The Central Virginia Volcanic-Plutonic Belt: An Island Arc of Cambrian(?) Age

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The Central Virginia Volcanic-Plutonic Belt: An Island Arc of Cambrian(?) Age

By LOUIS PAVLIDES

CONTRIBUTIONS TO THE GEOLOGY OF THE VIRGINIA PIEDMONT

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CONVERSION FACTORS

Metric unit		Inch-Pound equivalent
Length		
millimeter (mm)	= 0.03937	inch (in)
meter (m)	= 3.28	feet (ft)
kilometer (km)	= .62	mile (mi)
Area		
square meter (m^2)	= 10.76	square feet (ft^2)
square kilometer (km^2)	= .386	square mile (mi^2)
hectare (ha)	= 2.47	acres
Volume		
cubic centimeter (cm^3)	= 0.061	cubic inch (in^3)
liter (L)	= 61.03	cubic inches
cubic meter (m^3)	= 35.31	cubic feet (ft^3)
cubic meter	= .00081	acre-foot (acre-ft)
cubic hectometer (hm^3)	=810.7	acre-feet
liter	= 2.113	pints (pt)
liter	= 1.06	quarts (qt)
liter	= .26	gallon (gal)
cubic meter	= .00026	million gallons (Mgal or 10^6 gal)
cubic meter	= 6.290	barrels (bbl) (1 bbl=42 gal)
Weight		
gram (g)	= 0.035	ounce, avoirdupois (oz avdp)
gram	= .0022	pound, avoirdupois (lb avdp)
metric tons (t)	= 1.102	tons, short (2,000 lb)
metric tons	= 0.9842	ton, long (2,240 lb)
Specific combinations		
kilogram per square centimeter (kg/cm^2)	= 0.96	atmosphere (atm)
kilogram per square centimeter	= .98	bar (0.9869 atm)
cubic meter per second (m^3/s)	= 35.3	cubic feet per second (ft^3/s)

Metric unit		Inch-Pound equivalent
Specific combinations—Continued		
liter per second (L/s)	= .0353	cubic foot per second
cubic meter per second per square kilometer [(m^3/s)/km^2]	= 91.47	cubic feet per second per square mile [(ft^3/s)/mi^2]
meter per day (m/d)	= 3.28	feet per day (hydraulic conductivity) (ft/d)
meter per kilometer (m/km)	= 5.28	feet per mile (ft/mi)
kilometer per hour (km/h)	= .9113	foot per second (ft/s)
meter per second (m/s)	= 3.28	feet per second
meter squared per day (m^2/d)	= 10.764	feet squared per day (ft^2/d) (transmissivity)
cubic meter per second (m^3/s)	= 22.826	million gallons per day (Mgal/d)
cubic meter per minute (m^3/min)	=264.2	gallons per minute (gal/min)
liter per second (L/s)	= 15.85	gallons per minute
liter per second per meter [(L/s)/m]	= 4.83	gallons per minute per foot [(gal/min)/ft]
kilometer per hour (km/h)	= .62	mile per hour (mi/h)
meter per second (m/s)	= 2.237	miles per hour
gram per cubic centimeter (g/cm^3)	= 62.43	pounds per cubic foot (lb/ft^3)
gram per square centimeter (g/cm^2)	= 2.048	pounds per square foot (lb/ft^2)
gram per square centimeter	= .0142	pound per square inch (lb/in^2)
Temperature		
degree Celsius (°C)	= 1.8	degrees Fahrenheit (°F)
degrees Celsius (temperature)	=[(1.8×°C)+32]	degrees Fahrenheit

THE CENTRAL VIRGINIA VOLCANIC-PLUTONIC BELT: AN ISLAND ARC OF CAMBRIAN(?) AGE

By LOUIS PAVLIDES

ABSTRACT

Pre-Ordovician, probable Early Cambrian metavolcanic and somewhat younger meta-intrusive rocks form a linear belt in the central Virginia Piedmont. On the basis of the geologic and geochemical features of these rocks in the Fredericksburg area, and insofar as this area is representative of the entire belt, it is concluded that this belt constitutes an ancient island-arc sequence. The westernmost Chopawamsic Formation consists of a tholeiitic island-arc suite and associated calcalkaline metavolcanic rocks. Prior to Upper Ordovician time, low-potassic tonalitic plutons of plagiogranitic (pretectonic) and trondhjemitic (late-tectonic) affinities were intruded into the Chopawamsic terrane. The tholeiitic amphibolites of the Ta River Metamorphic Suite are considered to be an eastern, oceanward facies of the Chopawamsic Formation.

The James Run Formation of Maryland is probably a northern lateral equivalent of the central Virginia volcanic-plutonic belt. It may have formed as part of the ancient Virginia belt or along a penecontemporaneous but independent volcanic arc. The metavolcanic rocks and associated plutons of the Carolina slate belt in the southeast Piedmont are considered to have formed independently of the central Virginia volcanic-plutonic belt and perhaps in a different tectonic environment.

INTRODUCTION

The central Virginia volcanic-plutonic belt of pre-Ordovician age consists of (1) irregularly interlayered metavolcanic and metasedimentary rocks that trend northeast in northeastern and central Virginia and (2) metamorphosed intrusive rocks believed to be closely associated temporally and tectonically with the metavolcanic rocks (fig. 1). The volcanic nature of the belt was first recognized by Lonsdale (1927, pl. 1), who distinguished amphibolite, greenstone schist, and crystalline schist immediately beneath the Quantico Slate of the usage of Watson and Powell (1911). The Quantico Slate of Watson and Powell (1911) has been renamed the Quantico Formation (Pavlides, 1980a). Most of the volcanic rocks now assigned to the Chopawamsic Formation (Southwick and others, 1971) were shown as Peters Creek quartzite on the 1928 geologic map of Virginia (Virginia Geological Survey, 1928) but on the 1963 geologic map of Virginia (Virginia Division of Mineral Resources, 1963) a belt of rocks that includes the Chopawamsic Formation is shown as "metamorphosed volcanic and sedimentary rocks." The name Chopawamsic Formation was first applied to the belt of metavolcanic rocks immediately below the Quantico Formation in the Quantico Quadrangle (Mixon and others, 1972) by Southwick and others (1971), who designated Chopawamsic Creek, about 40 km south of Washington, D.C., as the type section.

The Chopawamsic Formation, and its more mafic eastern equivalent, the Ta River Metamorphic Suite (Pavlides, 1980a), and the rocks intrusive into and tectonically associated with these formations in the Fredericksburg area (fig. 1), are the only units within the central Virginia volcanic-plutonic belt for which extensive chemical and petrographic data are presently available. The interpretation presented here of the paleotectonic environment of the whole belt is thus based on the data of these rocks alone. The general geology of the Fredericksburg area has been described elsewhere (Pavlides, 1976, 1980a) and is not discussed further in this paper. Because of their particular relevance to the paleotectonic history, the discussion emphasizes the felsic meta-intrusive rocks of the belt. The associated mafic and ultramafic rocks briefly mentioned in this report will be discussed elsewhere.

The purpose of this paper is to describe briefly and characterize the geology of the central Virginia volcanic-plutonic belt and to interpret new geochemical data that bear on the origin, tectonic setting, and general regional geologic relations of these ancient metamorphosed volcanic and plutonic rocks. The James Run Formation and Carolina slate-belt metavolcanic rocks are also briefly described and evaluated as to their

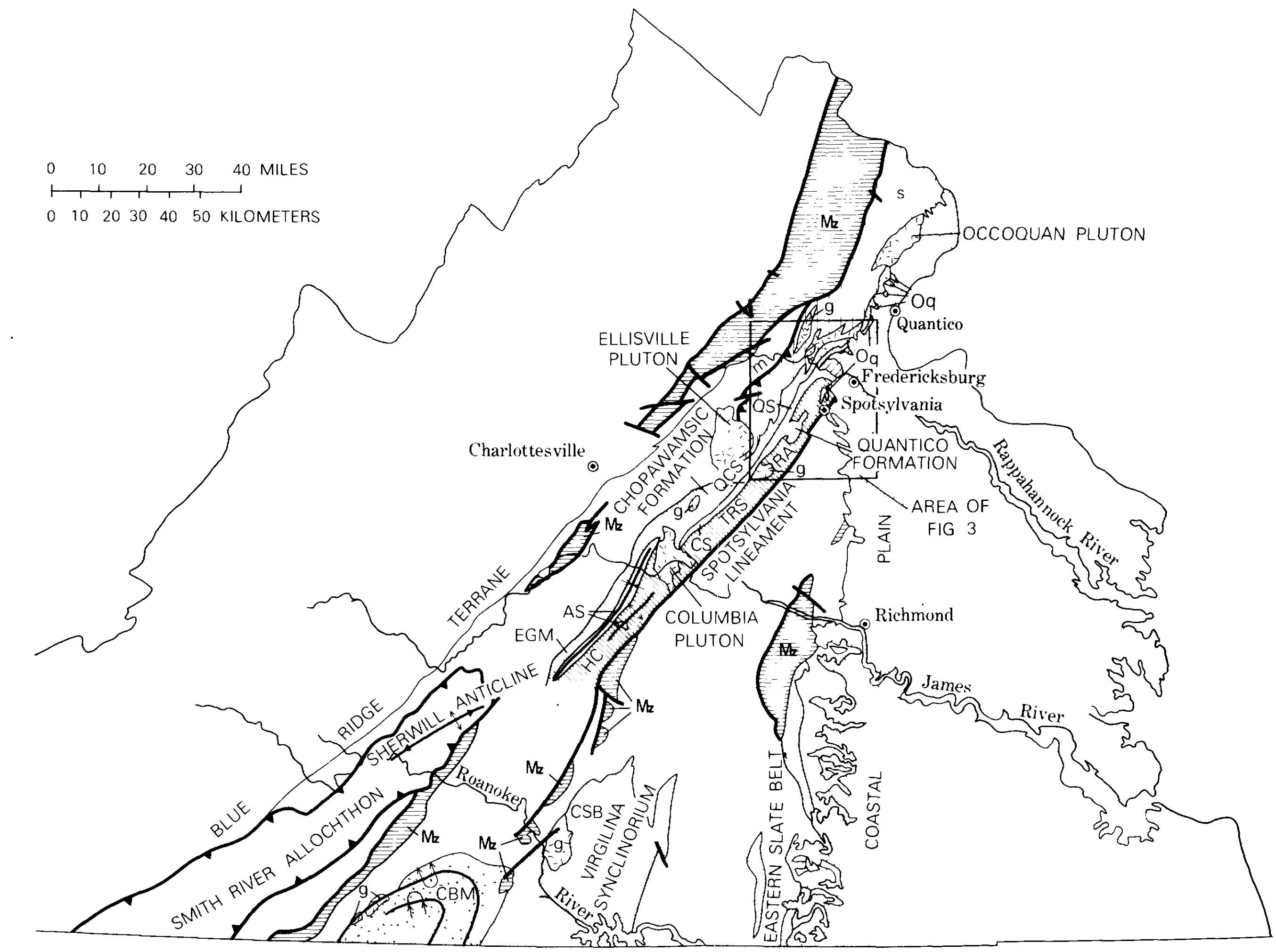


FIGURE 1.–Generalized geologic map showing the distribution of the Chopawamsic Formation and other rocks in central Virginia. Arvonia Slate within the Arvonia syncline (AS), Charlotte belt metavolcanic rocks (CBM), Columbia syncline (CS), Carolina slate belt (CSB), Evington Group metavolcanic rocks (EGM), granitoid plutons (g), Hatcher Compex of Brown (1969) (HC), melange zone (m), Mesozoic basins (Mz), Quantico-Columbia synclinorium (QCS), Quantico syncline (QS), Quantico Formation (Oq), Ta River Metamorphic Suite (TRS), Rappahannock anticlinorium (RA)–includes terrane of HC and TRS, and schist (s) stratigraphically and structurally beneath the Chopawamsic Formation.

correlativeness with the central Virginia volcanic-plutonic belt.

ACKNOWLEDGMENTS

I am particularly indebted to my former colleague S. Linda Cranford, who helped compile and prepare the illustrations and tables used in this report and also contributed modal analyses of some of the granitoid suites. Discussions with numerous geologists helped formulate some of the ideas expressed in this report. Especially helpful were David Gottfried and Joseph G. Arth, who freely gave of their time to discuss, as well as to share their knowledge of, the geochemistry of volcanic and associated plutonic rocks. The helpful reviews of this manuscript by N. L. Hatch, Jr., M. W. Higgins, and G. W. Leo are greatly appreciated.

AREAL DISTRIBUTION

The central Virginia volcanic-plutonic belt of the Virginia Piedmont includes metavolcanic rocks underlying the Quantico Formation and the Arvonia Slate within the Quantico-Columbia synclinorium and the Arvonia synclinorium. Presently available geologic mapping indicates that it extends from the Coastal Plain boundary in northeastern Virginia southwestward into the central Piedmont of Virginia at least as far as midway between the James and Roanoke Rivers (fig. 1). The exact nature and location of its southwest extent is not presently known.

The main characterizing unit of the central Virginia volcanic-plutonic belt is the Chopawamsic Formation. Different segments of the Chopawamsic have been mapped by Southwick and others (1971), Seiders and others

(1975), Pavlides (1976, 1980a), Pavlides and others (1974), Good and others (1977), and Conley and Johnson (1975). Metavolcanic rocks of the Evington Group along the northwest limb of the Arvonia synclinorium stratigraphically beneath the Arvonia Slate and beneath the Arvonia Slate in the Long Island syncline (Brown, 1969, pl. 1; Smith and others, 1964, pl. 1) are now considered to belong to the Chopawamsic Formation (Brown, 1976, p. 142; Conley, 1978, fig. 1). Southwick and others (1971, p. D9) originally suggested that the Evington Group metavolcanic rocks were possibly coeval with the Chopawamsic Formation.

More controversial is the correlation of the Chopawamsic Formation with the amphibolites of the Hatcher Complex of Brown (1969) that are found along the southeast side of the Arvonia and Columbia synclines. Chopawamsic metavolcanic rocks have been mapped around the southwest end of the Columbia syncline and reported as merging into and being interlayered with some of the amphibolitic rocks of Brown's Hatcher Complex (Conley and Johnson, 1975; Good and others, 1977; Conley, 1978, p. 134). Pavlides (1980a) considered the amphibolites and amphibolite gneisses of the Ta River Metamorphic Suite, along the southeast limb of the Quantico-Columbia synclinorium mostly south of the Rappahannock River, as a coeval eastern, more mafic facies of the Chopawamsic Formation. The Ta River Metamorphic Suite is an apparent northeast continuation of Brown's Hatcher amphibolitic rocks, and both terranes have the same magnetic signature (Neuschel, 1970). Figure 2 summarizes the correlations of the metavolcanic units assigned to the central Virginia volcanic-plutonic belt.

The Holly Corner Gneiss (fig. 2) is also believed to be a more metamorphosed eastern facies of the Chopawamsic (Pavlides, 1980a). The Holly Corner and an intrusive sill-like pluton, the Falls Run Granite Gneiss, crop out northwest of Fredericksburg along the Rappahannock River (fig. 1). Because the Holly Corner is allochthonous (Pavlides, 1979, p. 51) and more tenuously correlated with the Chopawamsic Formation, it is not discussed in this report.

ENCLOSING ROCKS

The Chopawamsic Formation is underlain conformably by pebbly gneiss (diamictite) in the Quantico area of Virginia (Southwick and others, 1971). The diamictite of northern Virginia does not extend much farther south than the area studied by Southwick and others (1971, fig. 1). Rather, for a considerable distance along strike to the southwest the Chopawamsic has been intruded by plagiogranitic rocks and locally by mafic rocks of the mafic complex at Garrisonville (fig. 3; Pavlides, 1976) and related plutons. Farther southwest, beyond the belt of plagiogranitic intrusions, the Chopawamsic grades downward into schist and silty schist that locally may contain thin and sparse layers of metavolcanic rocks.

The substrate on which the Ta River Metamorphic Suite lies is not exposed. Locally, it is assumed to be in

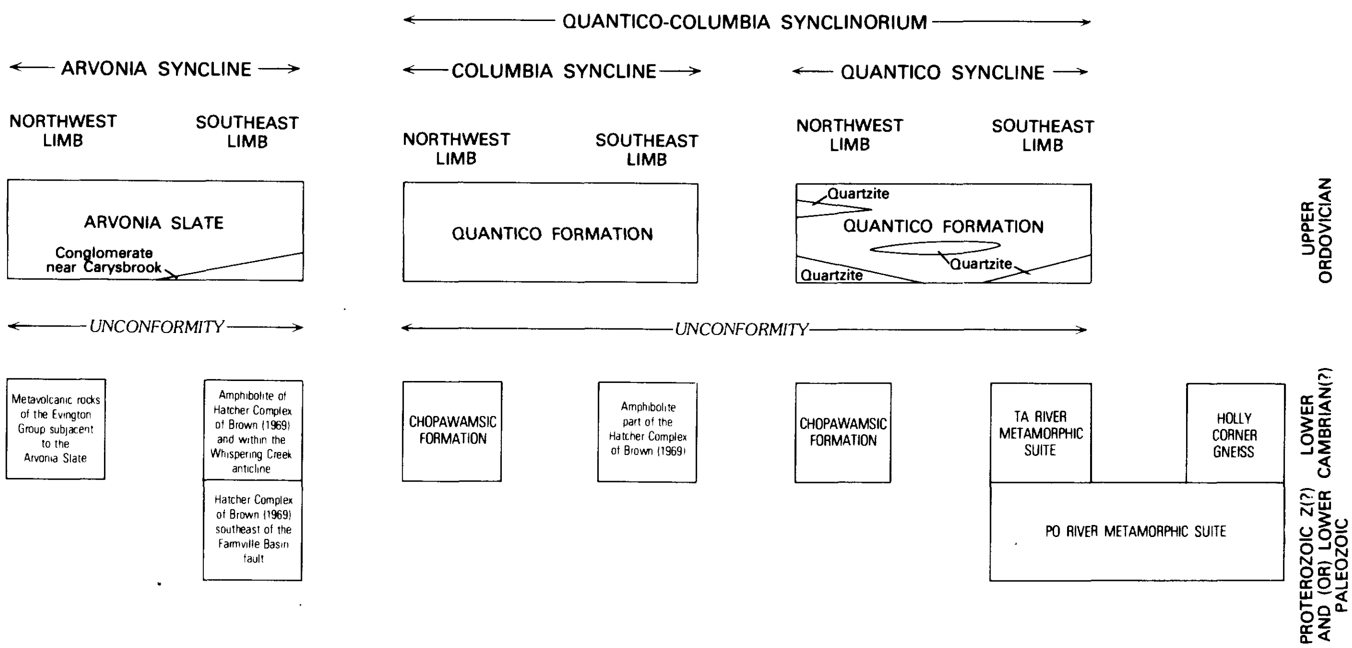


FIGURE 2.—Correlation chart of the Chopawamsic Formation and related metavolcanic rocks and their enclosing formations in Virginia.

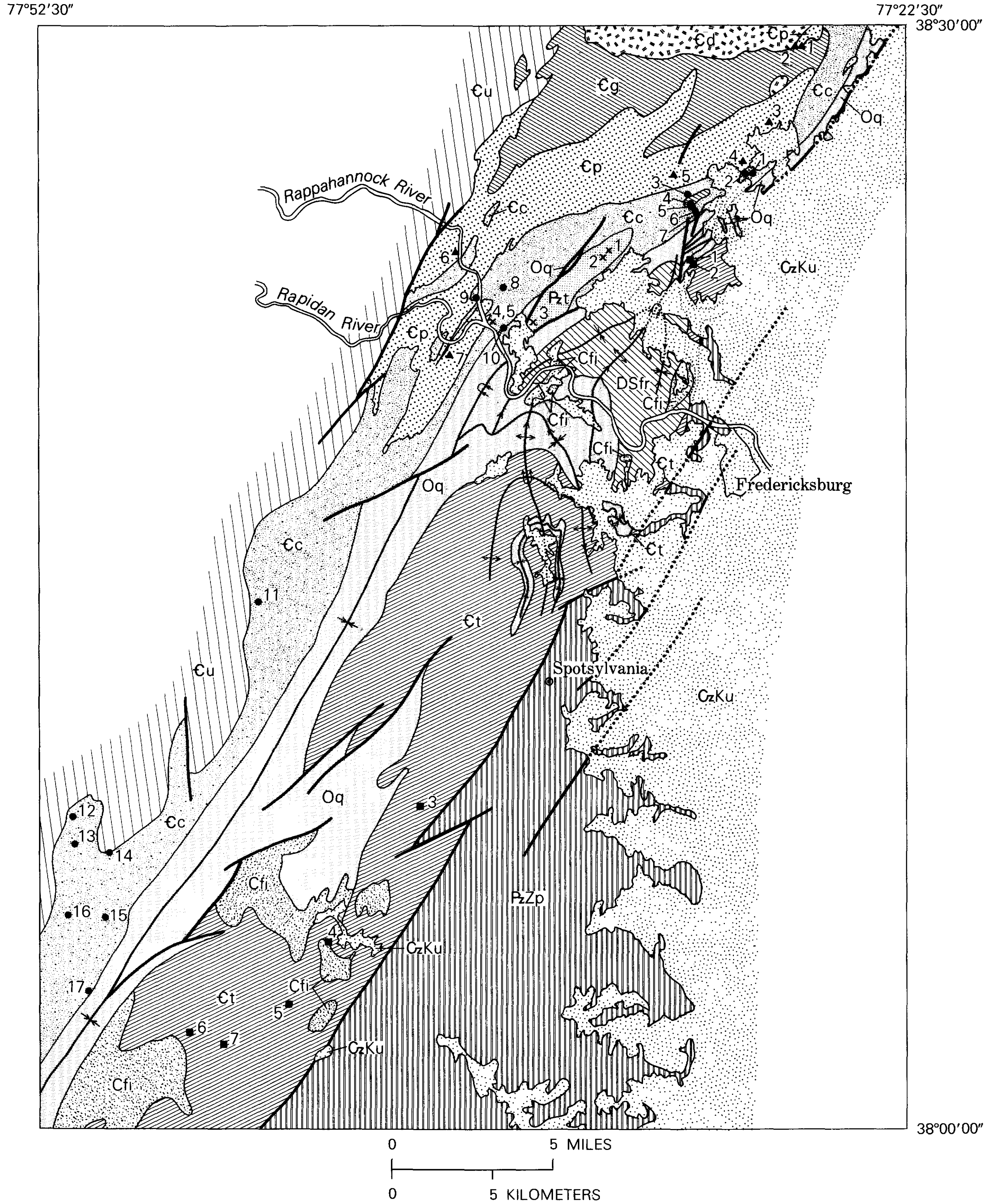
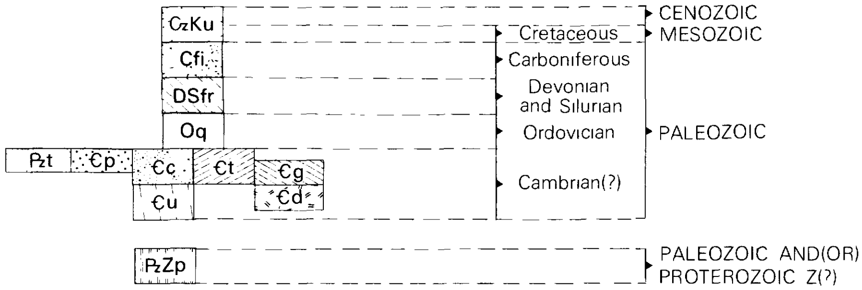


FIGURE 3.–Generalized geologic map of the Fredericksburg area, Virginia, showing location of samples discussed in text. Circles, Chopawamsic Formation; squares, Ta River Metamorphic Suite; triangles, plagiogranitic metatonalite; crosses, trondhjemitic metatonalite.

EXPLANATION



CzKu — Coastal Plain sediments: Unconsolidated, upland sand and gravel, terrace, and alluvium and swamp deposits

Cfi — Falmouth Intrusive Suite: Dikes and sills and small plutons of fine- to medium-grained granitoids, mainly monzogranite to granodiorite and less commonly tonalite

DSfr — Falls Run Granite Gneiss Coarse-grained, well-foliated, microcline granite gneiss (including Holly Corner Gneiss (Lower Cambrian?) Fine- to medium-grained, well-foliated, hornblende-biotite gneiss)

Oq — Quantico Formation: Gray to black graphitic slate and phyllite to staurolitic schist and biotite-muscovite garnetiferous schist in areas of increased metamorphism Lenses of micaceous quartzite occur within and locally at its base.

Ꞓc — Chopawamsic Formation Chiefly metavolcanic rocks of felsic, intermediate, and mafic compositions interlayered with lesser amounts of meta-epiclastic volcanic rocks and schist

Ꞓt — Ta River Metamorphic Suite: Chiefly amphibolite and amphibolitic gneiss with lesser amounts of biotitic gneiss and schist.

Ꞓp — Plagiogranitic metatonalite Medium- to coarse-grained leucocratic to mesocratic quartz-rich meta-intrusive granitoid.

Pzt — Trondhjemitic metatonalite. Fine-grained, allotriomorphic granular, leucocratic granitoid, locally having granophyric texture

Ꞓg — Mafic complex at Garrisonville Metamorphosed mafic plutonic rocks, chiefly amphibolite and hornblendite

Ꞓd — Diamictite Dark-gray granitelike metasedimentary rocks characterized by quartz lumps and clasts of schist and gneiss randomly scattered in a micaceous quartz- and plagioclase-rich matrix.

Ꞓu — Undifferentiated schists, metasiltstones, and graywackes

PzZp — Po River Metamorphic Suite: Chiefly biotite gneiss with lesser amounts of hornblende gneiss and schist

CONTACT—Commonly inferred, dotted where concealed.

FAULT—Commonly inferred, dotted where concealed

ANTIFORM—Showing trace of crestal plane and direction of plunge Dotted where concealed

OVERTURNED UPRIGHT

SYNFORM—Showing trace of trough plane and direction of plunge Dotted where concealed.

OVERTURNED UPRIGHT

FIGURE 3.—Continued.

stratigraphic contact with the Po River Metamorphic Suite of Paleozoic to Precambrian age, but mostly it is in fault contact with the Po River (Pavlides, 1980a, pl. 1). No direct information is available as to the nature of the rocks that may underlie the coeval parts of the Hatcher Complex of Brown (1969).

The Chopawamsic Formation is described by Southwick and others (1971, p. D3) as being conformably and gradationally overlain in the Quantico area by the Quantico Formation of Ordovician age. Within the area shown in figure 3, there is evidence for an unconformity between the Chopawamsic and the Quantico (Pavlides, 1973). This unconformity is placed stratigraphically below an impure quartzitic unit that occurs discontinuously at the base of the Quantico. The unconformity is believed to be the same as that between the Arvonia Slate and subjacent metavolcanic rocks of the Evington Group (Chopawamsic Formation) in the Arvonia syncline (see fig. 2). This unconformity has now been recognized near Quantico (Pavlides and others, 1980), where heretofore the contact between the Chopawamsic and the Quantico was considered gradational and concordant (Seiders and others, 1975).

AGE

The rocks of the central Virginia volcanic-plutonic belt do not contain recognized fossils and thus can be dated, at present, only by isotopic methods. However, both the Quantico Formation and the Arvonia Slate that unconformably overlie the Chopawamsic Formation or its equivalents contain Late Ordovician fossils and thus establish a minimum age for these subjacent metavolcanic rocks. The Chopawamsic and the coeval James Run Formation were dated as about 550 m.y. (million years) old on the basis of zircons from felsic layers within these formations (Tilton and others, 1970; Higgins and others, 1971, p. 320). A controversy ensued, however, as to the meaning of such discordant zircon ages from the Piedmont (Higgins, 1976; Higgins and others, 1977; Seiders, 1978a; Zartman, 1978) following the report by Seiders and others (1975, p. 492–495) that the Dale City pluton near Quantico, which gave discordant zircon ages of about 560 m.y., intruded the Quantico Formation. Seiders and others concluded from these relations that the age of the Quantico had to be Early Cambrian or older. However, the age of the Quantico has been reestablished by fossils as post-Cambrian and most likely Late Ordovician, and the Dale City pluton has been demonstrated to be unconformable beneath the Quantico (Pavlides and others, 1980). Therefore, the zircon ages of the Dale City pluton, which I consider to be an intrusive into the Chopawamsic volcanic pile, are not in conflict with the known regional geologic relationships. In view of this, I conclude that the discordant ages obtained from zircons of such rocks as the Dale City pluton (about 560 m.y.) and the Chopawamsic Formation (about 550 m.y.) are probably significant, and an Early Cambrian(?) age is provisionally accepted for the Chopawamsic Formation. However, the nature of the available data is such that an Ordovician, pre-Quantico age for the Chopawamsic cannot entirely be ruled out.

METAVOLCANIC ROCKS

LITHOLOGY AND PETROGRAPHY

CHOPAWAMSIC FORMATION

In the type area along Chopawamsic Creek (Southwick and others, 1971) the Chopawamsic Formation is a sequence of interbedded metavolcanic and metasedimentary rocks about 1,820–3,040 m thick. This estimate assumes that the section is free of structural complication and is essentially homoclinal. Southwick and others (1971) divided the Chopawamsic into three principal units, all of which are metamorphosed at least to greenschist facies: (1) Medium- to thick-bedded mafic to intermediate metavolcanic rocks derived from andesitic to basaltic flows, coarse breccias, and finer tuffaceous clastic rocks; (2) medium- to thick-bedded felsic metavolcanic rocks derived from flows and associated volcaniclastic sediments; and (3) thin- to medium-bedded metavolcaniclastic rocks of felsic to mafic composition, locally containing felsic to mafic flows and beds of nonvolcanic quartzose metagraywacke and green to gray phyllite. Units 1 and 2 grade vertically and laterally into unit 3 and appear to be tongues or lenses within a complex volcanic-sedimentary pile. A few thin beds of specular hematite, interlayered with felsic metavolcanic rocks, occur within the upper part of the Chopawamsic Formation in Chopawamsic Creek (A. R. Bobyarchick, oral commun., 1979). Immediately to the northeast of the Quantico area, Seiders and others (1975, p. 483) reported that the Chopawamsic consists of about 2,500 m of metasedimentary and metavolcanic rocks.

The Fredericksburg area (fig. 3) in part overlaps and extends contiguously to the southwest of the area described by Southwick and others (1971). The Chopawamsic here also consists of a series of intertonguing lenses of metasedimentary and metavolcanic rocks, but the distribution of these lenses appears to be more random than in the type area of Southwick and others. The thickness varies but may be as much as 3,000 m. The metavolcanic rocks of the Chopawamsic in the Fredericksburg area are mostly nonfragmental. Volcanic breccias and conglomerates are rare, although lithic and crystal tuffs or mixed tuffs have been recognized.

Near Mineral, Va., coarse-grained fragmental metavolcanic rocks are present in diamond-drill cores (Gair, 1978, p. 32–52) but are seldom found in surface outcrops, suggesting that the fragmental volcanic rocks are more susceptible to weathering than are some of the other volcanic rocks in the section. Nonetheless, even in drill cores, which actually penetrate only narrow parts of the Chopawamsic belt, such coarse-grained fragmental volcanic rocks probably constitute only about 5 percent of the section, according to Gair (oral commun., Jan. 1979).

In the Fredericksburg area metavolcanic rocks of the Chopawamsic belt are mostly felsic and intermediate in composition. Felsic rocks are commonly light gray and have visible small phenocrysts of quartz and (or) feldspar. Some felsic rocks are highly sodic (keratophyres) and contain fine-grained feldspar and quartz insets in a finely crystalline quartzofeldspathic matrix. Epidote occurs as a minor alteration of some plagioclase phenocrysts in felsic rocks having plagioclase that was originally more calcic than albitic. Dark-green metavolcanic rocks are of intermediate composition, as indicated by their SiO_2 content, which ranges from about 55 to 65 percent. In thin section, they commonly have a nematoblastic groundmass texture formed by alined prismatic amphibole intergrown with fine-grained quartz and feldspar. Blue-green actinolitic amphibole locally forms fine-grained porphyroblasts that, in some rocks, are arranged in small bundles (fascicles). Epidote, chlorite, and accessory magnetite are common minor constituents of these amphibolitic rocks. Locally, carbonate- and (or) quartz-filled vesicles or amygdules are present. Pillow lavas have been observed only in two small outcrops (Pavlides, 1976). Greenstones composed of quartz, chlorite, generally albitic plagioclase, and blue-green amphibole, some with relict basaltic textures, are interpreted as metabasalt.

Metavolcanic tuffs and conglomerates are sparse. Where present, the clasts in tuffs commonly consist of both volcanic rocks and individual, generally well-formed feldspar crystals, suggesting that the rocks may have originated as mixed lithic and crystal tuffs. Epiclastic volcanic conglomerate is rare and consists of volcanic clasts and rounded quartz grains having slightly embayed margins set in a fine-grained quartz-feldspar groundmass.

Epivolcaniclastic rocks in the northern part of the area are generally sparse and consist of relatively amphibole-free quartzose and schist layers that interfinger or lie between amphibole-rich quartzose streaks or thin layers. Ironstone or ferruginous metasedimentary rock has not been recognized within the Chopawamsic Formation in the Fredericksburg area. However, Good and others (1977, fig. 2) showed ferruginous quartzite as being locally present in Chopawamsic within the Columbia syncline.

TA RIVER METAMORPHIC SUITE

Amphibolite is the characterizing lithology of the Ta River Metamorphic Suite, described and named by Pavlides (1980a). These rocks are generally conformably layered with granitoid rocks and smaller amounts of biotite gneiss and schist in the northern part of the Fredericksburg region (fig. 3). To the southwest, along strike, the Ta River contains more biotite gneiss and schist and smaller amounts of amphibolite gneiss. Regional metamorphic grade also increases to the southwest, and the associated granitoid bodies are generally more felsic than are those in the northeast part of the Ta River Metamorphic Suite. Some of the granitoid rocks are of Carboniferous age (Pavlides and others, 1979) and are not part of the plutonic rocks temporally related to the central Virginia volcanic-plutonic belt.

The amphibolites of the Ta River contain green hornblende (commonly poikiloblastic) and plagioclase, both twinned and untwinned, ranging from andesine to bytownite. In general, textures in thin section range from granoblastic to foliated. Epidote normally is present in subhedral grains and is very abundant in some rocks. Sphene is commonly a fine-grained anhedral accessory. Quartz is locally abundant.

The Ta River, like the Chopawamsic Formation within the Fredericksburg area, also appears to lack ironstone beds. However, ironstone layers are locally present to the southwest in the amphibolitic gneisses (Gair, 1978, p. 32–52) on the southwest side of the Arvonia syncline, which are considered to be coeval with the Ta River Metamorphic Suite and the Chopawamsic Formation.

GEOCHEMISTRY

GENERAL STATEMENT

In geologically old volcanic terranes, particularly those that have been structurally deformed and metamorphosed, the original chemical composition of the volcanic protoliths has generally been modified. The central Virginia volcanic-plutonic belt is such a terrane. Diagenesis, hydrothermal alteration, weathering, metamorphism, and metasomatism are among the processes through which the bulk chemical composition of the original rock may be modified.

Table 1 is a partial list of the relative mobility of elements during some of these processes. This compilation shows that most major and many minor elements

TABLE 1.—*Element mobility during weathering, hydrothermal alteration, and metamorphism*

[+, element gained; –, element lost; ( ), minor gain or loss; 0, element immobile; ×, element mobile]

Element	Marine weathering							Hydrothermal alteration		Zeolite metamorphism		Greenschist facies metamorphism					Amphibolite facies metamorphism	
References	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18[1]
Si	–		–							–			+			–		
Al	0		(–)							–			–					
Fe	+		(–)					+					+					
Mg	–	–	–							–								
Ca	–	–	–						–				–	–				
Na	+		–									+	+			–		
K	+	+	+				+	–		+	0	–		–	×		(–)	
Ti	+						0	0		0				0			0	
P	+		+					0		0					×			
Mn	+		(–)															
Rb				+			+	–		+				–			(–)	
Ba				+				–										
Sr								–	–	+	0			–	×			
Th								0										
Zr				(+)			0	0	0	0	0			0	0		0	
Hf								0		0								
Nb							0	0		0	0			0	0		0	
Ta										0								
Cu				+					–									
Li				+														
Cr									0									
Ga				–														
B				+														
Zn				+														
V									0									
LREE[2]					–	–		0		+								
HREE[3]					0	0		0										
Y							0		0	0	0			0	0			

[1] Amphibolite grade metamorphism considered isochemical and isovolumetric.
[2] Light rare-earth elements: La, Ce, Pr, Nd, Pm, Sm.
[3] Heavy rare-earth elements: Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu.

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11, 15. Morrison (1978).
12. Melson and Van Andel (1966).
13. Cann (1969).
16, 18. Kerrich and others (1977).

are mobile under different alteration processes. Only a few elements such as zirconium, hafnium, niobium, tantalum, the heavy rare-earth elements (HREE), and, in part, Al_2O_3, titanium, and phosphorus appear to be immobile or relatively immobile. Various diagrams have been constructed using combinations of elements, some stable and some mobile, to characterize the tectonic environments in which various relatively unaltered and generally basaltic volcanic assemblages formed (see, for example, those of Pearce and Cann, 1973, and Floyd and Winchester, 1975, 1978). However, the use of such paleotectonic discrimination diagrams may sometimes be inconclusive or misleading (Morrison, 1978; Smith and Smith, 1976; Gottfried and others, 1977). In this paper a combination of "immobile" minor elements in conjunction with rare-earth element (REE) patterns that have internally consistent distribution characteristics are used to identify magma types involved in the formation of the Chopawamsic and the Ta River volcanic rocks and some of the associated intrusive granitoids characterized by a low potassium content. Paleotectonic environments are also deduced within the limitations of the analytical data base. Such limitations are severe in that only a small number of analyses are available as a consequence of the extensive weathering and generally poor exposure that characterize this part of the Virginia Piedmont. Also the stratigraphic position of samples for such analyses is not always certain because of the structural complexity of the region. Therefore, the results and conclusions presented below are of necessity preliminary and subject to revision as more data become available. Finally, in the discussions of the geochemistry of the metavolcanic and metaintrusive rocks of the Fredericksburg area, only those elements are emphasized that are generally considered to have little or no mobility during alteration processes.

ANALYTICAL METHODS

All chemical analyses cited in this report were made in the analytical laboratories of the U.S. Geological Survey in Reston, Va. Major element oxides were determined either by rapid rock methods described by Shapiro (1975) or by X-ray spectroscopy. The rapid-rock method is supplemented by atomic-absorption spectrometry. Abundances of 10 major constituents were determined from a single solution obtained by a nitric acid dissolution of a sample fused with lithium metaborate-lithium tetraborate. CaO, MgO, and Na_2O contents were determined by atomic-absorption spectrometry; SiO_2, Al_2O_3, Fe_2O_3, TiO_2, P_2O_5, and MnO contents were determined spectrophotometrically. Separate sample portions were used to determine FeO, H_2O (+ and −), and CO_2 contents.

Where major elements were determined by X-ray spectroscopy, 700 mg of ground (<200 mesh) sample was mixed with 5.600 g $Li_2B_4O_7$ flux and 700 mg La_2O_3 heavy absorber and fused in a platinum gold crucible at 1,100°C. The molten flux was then poured into a disc-shaped mold and cooled. Sample discs were analysed on a diano model 8600 fully automated X-ray fluorescence spectometer using discs prepared from U.S. Geological Survey (USGS) standard rocks as calibration standards.

Niobium and nickel content were determined by a spectrophotometric method (Greenland and Campbell, 1974). After decomposition by hydrofluoric acid and evaporation to volatilize silica, the samples were fused with pyrosulfate and dissolved in hydrochloric acid-tartaric acid. After separation by a thiocyanate extraction with amyl alcohol and back-extraction with dilute hydrofluoric acid, the niobium was reacted with 4-(2-pyridylazo)-resorcinol. Analytical error, calculated on the basis of replicate anaylses of eight USGS standard rocks, ranges from 2.9 to 6.4 percent in the concentration range 10–27 ppm (parts per million).

Synthetic standards and USGS standard rocks BCR-1, W-1, and AGV−1 (Flanagan, 1973) were used to establish the analytical curve for the element concentrations determined spectrographically.

Instrumental neutron activation was used to determine concentrations of large cation trace elements, minor ferromagnesian elements, and some of the rare-earth elements (La, Ce, Nd, Sm, Eu, Tb, Yb, and Lu). Three 0.15-g replicate samples packed in polyethylene vials were irradiated for two hours at a flux of 5×10^{13} neutrons $cm^{-2}sec^{-1}$ at the National Bureau of Standards reactor, Gaithersburg, Md. A standard was synthesized from an analyzed obsidian that was doped with solutions of selected trace elements, dried, reground, and calibrated relative to seven USGS standard rocks: BCR-1, G−2, AGF−1, GSP−1, PCC-1, DTS-1, and W−1 (Flanagan, 1973). The samples and standards were counted on a Ge(Li) detector one week and six weeks after irradiation. The tantalum content was determined by counting on a low-energy photon detector five months following irradiation. The spectral data were processed on an IBM 370[1] computer by means of the program SPECTRA (Baedecker, 1976).

CHOPAWAMSIC FORMATION

Metavolcanic rocks of a wide composition range that includes silicic, intermediate, and mafic types make up the Chopawamsic Formation. Table 2 lists chemical analyses of samples from the Chopawamsic, whose geographic distribution is shown in figure 3. The analyses are grouped into three suites based on the striking distribution differences of high-valence cations, particularly niobium and the rare-earth elements (REE). The suites also correspond to geographic groupings, in that most of the rocks of suite A are from the northern part of the Chopawamsic belt, suite C is from the southern part of the belt, and the two samples that constitute suite B lie between suites A and C (fig. 3). Some of the rocks in the southern part of the belt (samples 13 and 14) have chemical similarities to suite A and are included with that suite (table 2). The small number of samples that make up suites B and C, as compared with suite A, reflect the differences in degree of saprolitization and depth of stream incision through the saprolite in the geographic areas of the various suites. Suite A samples come mostly from streams near the Piedmont-Coastal Plain contact or from the lower part of streams tributary to the Rappahannock River that mostly flow on bedrock within the area of figure 3. On the other hand, suites B and C are from areas of more pervasive weathering, where fewer fresh-rock exposures are available. Furthermore, the fact that suites B and C appear to contain only silicic rocks (table 2) is, in part, an artifact of sampling and may not truly represent the compositional makeup of these suites. Intermediate and mafic metavolcanic rocks, too weathered to be analyzed for meaningful results, also occur in the geographic areas of suites B and C. In general, however, the central and southern parts of the Chopawamsic belt in the Fredericksburg area (fig. 3) are composed mostly of silicic rocks.

Suite A is highly sodic and locally contains keratophyres (table 2), which may result from alteration rather than primary magmatic composition. However, Coleman and Donato (1979, p. 161–162) suggested that keratophyres may be the effusive equivalents of plagiogranite and hence of magmatic and not metasomatic origin. In any event, mobility of K_2O in suites B and C

[1] Any use of trade names in this publication is for descriptive purposes only and does not constitute endorsement by the U.S. Geological Survey.

TABLE 2.—*Chemical and normative composition of the Chopawamsic Formation*

Suites	A											B		C			
Sample No	1	3	13	10	8	4	5	14	6	7	2	11	9	17	16	15	12
Field No	P-71-9	P-70-73	P-76-142A	P-73-13	P-72-150	P-70-67	P-70-64	P-76-124	P-70-63	P-70-61	P-71-7	P-77-37	P-70-128	P-76-117	P-76-139	P-76-141	P-76-145
Major oxide composition (weight percent)																	
SiO_2	50.8	51.5	51.69	53.4	55.0	56.5	59.0	64.40	64.5	76.0	78.3	72.2	73.6	61.72	73.54	73.86	76.75
Al_2O_3	19.2	17.0	15.20	15.6	15.3	14.6	13.8	14.72	11.4	12.7	11.6	13.17	12.7	15.90	13.38	13.56	12.40
Fe_2O_3	1.4	.50	8.2	2.8	5.5	3.6	5.2	3.2	3.5	2.4	.61	1.3	1.1	2.3	1.6	1.5	1.8
FeO	8.3	10.2	6.1	10.7	7.5	7.6	6.7	4.2	6.4	.38	1.9	2.0	2.3	5.8	.16	1.1	1.0
MgO	7.1	7.0	3.18	5.4	3.9	3.5	3.0	2.11	2.6	.16	.43	.61	1.4	2.15	.00	.01	.00
CaO	4.1	4.7	7.25	3.8	6.8	6.2	2.5	2.85	3.8	1.2	.27	.19	.50	2.32	.17	.67	.34
Na_2O	4.9	5.0	3.40	4.8	4.1	4.4	5.7	3.26	4.6	5.6	5.2	1.43	5.7	2.41	.04	3.07	4.20
K_2O	.12	.25	.23	.08	.19	.15	.15	.64	.15	.80	.13	6.68	.85	2.31	8.91	3.88	1.22
H_2O^+	3.4	2.5	1.3	2.1	.86	1.0	1.6	1.7	.80	.34	1.2	.87	1.0	1.6	.74	.58	.56
H_2O^-	.07	.14	.39	.16	.11	.07	.22	.22	.03	.03	.14	.30	.05	.37	.07	.10	.09
TiO_2	.36	.87	2.06	1.6	1.5	1.5	1.6	1.30	1.5	.21	.14	.55	.59	.87	.24	.29	.20
P_2O_5	.06	.10	.12	.25	.22	.26	.23	.18	.24	.07	.04	.07	.19	.18	.04	.06	.01
MnO	.25	.25	.19	.24	.11	.22	.30	.14	.22	.03	.03	.06	.04	.22	.02	.05	.06
CO_2	.05	.08	.01	.04	.02	.05	.05	.01	.05	.02	.05	.01	.02	.01	.00	.01	.02
Total	100.11	100.09	99.32	100.97	101.11	99.75	100.0	98.93	99.79	99.94	100.04	99.44	100.04	98.16	98.91	98.74	98.65
Normative mineral composition (weight percent) [Based on analyses recalculated to 100 percent water-free oxides]																	
Q	----	----	12.9	2.9	9.6	10.7	13.6	33.8	24.6	37.9	45.8	37.0	33.9	28.8	39.1	40.5	47.9
C	3.8	0.4	----	1.4	----	----	.3	4.1	----	.7	2.5	3.5	2.0	5.9	3.3	3.3	3.7
or	.7	1.5	1.4	.5	1.1	.9	.9	3.9	.9	4.7	.8	40.2	5.1	14.2	53.6	23.4	7.3
ab	42.9	43.4	29.4	41.2	34.6	37.8	49.1	28.4	39.3	47.6	44.6	12.3	48.7	21.2	1.2	26.5	36.2
an	20.7	22.7	26.1	17.2	22.7	19.9	11.1	13.3	10.1	5.4	1.1	.4	1.1	10.7	.6	2.9	1.5
wo	----	----	4.1	----	3.9	4.0	----	----	3.1	----	----	----	----	----	----	----	----
en	10.3	5.3	8.1	13.6	9.7	8.8	7.6	5.4	6.5	.4	1.1	1.5	3.5	5.5	----	.1	----
fs	8.1	5.3	1.4	15.3	7.0	9.1	6.0	3.3	6.9	----	2.8	1.8	2.4	8.0	----	.4	.1
fo	5.6	8.9	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----
fa	4.9	9.7	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----
mt	2.1	.7	12.2	4.1	8.0	5.3	7.7	4.8	5.1	.7	.9	1.9	1.6	3.5	----	2.2	2.7
hm	----	----	----	----	----	----	----	----	----	1.9	----	----	----	----	1.6	----	----
il	.7	1.7	4.0	3.1	2.8	2.9	3.1	2.5	2.9	.4	.3	1.1	1.1	1.7	.4	.5	.4
ru	----	----	----	----	----	----	----	----	----	----	----	----	----	----	.1	----	----
ap	.2	.2	.3	.6	.5	.6	.6	.4	.6	.2	.1	.2	.5	.4	.1	.1	.1
cc	----	.2	.1	.1	.1	----	----	.1	----	.1	----	.1	.1	.1	----	.1	.1
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
di	----	----	7.8	----	7.7	7.9	----	----	6.1	----	----	----	----	----	----	----	----
di-wo	----	----	4.1	----	3.9	4.0	----	----	3.1	----	----	----	----	----	----	----	----
di-en	----	----	3.1	----	2.2	1.9	----	----	1.5	----	----	----	----	----	----	----	----
di-fs	----	----	.6	----	1.6	2.0	----	----	1.5	----	----	----	----	----	----	----	----
hy	18.4	10.6	5.9	29.0	12.9	14.0	13.6	8.7	10.4	0.4	3.9	3.4	6.0	13.6	----	0.5	0.1
hy-en	10.3	5.3	5.0	13.6	7.5	6.9	7.6	5.4	5.1	.4	1.1	1.6	3.5	5.6	----	.1	----
hy-fs	8.1	5.3	.9	15.4	5.4	7.1	6.0	3.3	5.3	----	2.8	1.8	2.5	8.0	----	.4	.1
ol	10.5	18.5	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----
ol-fo	5.6	8.8	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----
ol-fa	4.9	9.7	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----
DI	43.7	44.9	43.7	44.6	45.3	49.4	63.7	66.2	64.8	90.3	91.2	89.5	87.7	64.2	93.9	90.4	91.5
Trace-element abundances (parts per million)																	
Large cations[2]																	
Rb	----	----	----	----	----	----	----	----	----	12	3	197	26	138	143	79	27
Ba	----	48	42	43	77	46	24	132	----	172	80	803	222	262	863	534	362
Sr	113	110	159	77	147	201	67	311	----	114	29	43	65	119	56	67	71
K/Rb	----	----	----	----	----	----	----	----	----	537	324	281	270	139	517	408	374
Ba/Rb	----	----	----	----	----	----	----	----	----	14	24	4	8	2	6	7	13
High-valence cations[3]																	
Th	----	1.7	0.9	1.5	1.1	1.4	1.6	3.0	----	2.5	1.6	21.9	20.6	12.0	10.7	9.4	6.6
U	----	----	1.0	.4	.6	.3	1.5	1.0	----	.8	.3	5.0	4.3	4.6	2.4	1.8	1.4
Zr	----	30	60	62	63	55	120	70	----	150	76	500	480	160	200	200	150
Hf	----	1.0	2.1	1.7	1.7	1.5	3.3	2.2	----	3.8	2.6	12.8	13.2	4.2	5.5	5.5	3.7
Nb[4]	----	2.7	6.7	4.7	4.7	6.7	6.0	7.1	----	4.5	4.4	34	27	17	13	11	11
Ta	----	----	.12	----	----	.21	.32	.44	----	.41	.20	2.31	2.12	1.18	1.06	.88	.76
Th/U	----	----	.9	3.8	1.8	4.7	1.1	3.0	----	3.1	5.3	4.4	4.8	2.6	4.5	5.2	4.7
Zr/Hf	----	76	29	36	37	37	36	32	----	40	12	39	36	38	36	36	40
Nb x 100/Ti	----	.1	.1	.1	.1	.1	.1	.1	----	.4	.6	1	.8	.3	.9	.6	.9
Nb/Ta	----	----	55.8	----	----	31.9	18.8	16.1	----	11.0	22.0	15	13	14	12	12	14
Ferromagnesian elements[5]																	
Co	----	42.8	28.9	28.6	29.7	33.6	65.2	7.4	----	2.3	1.4	1.7	4.5	12.0	0.2	2.5	1.0
Ni[4]	----	81	12	6	1	12	5	----	----	1	1	----	2	27	----	----	----
Zn	----	166	124	175	63	120	172	174	----	44	24	54	35	104	90	52	37
Cr	----	258.5	14.4	7.2	----	5.7	----	----	----	----	----	3.0	4.4	----	----	----	----
Sc	----	44.25	38.83	36.56	37.85	35.48	32.78	23.87	----	9.78	7.80	11.34	12.80	15.35	11.83	7.60	9.43
Ni/Co	----	1.9	.4	.2	----	.4	.1	----	----	.4	.7	----	.4	2.2	----	----	----

TABLE 2.—*Chemical and normative composition of the Chopawamsic Formation*—Continued

Suites	A											B		C			
Sample No	1	3	13	10	8	4	5	14	6	7	2	11	9	17	16	15	12
Field No	P-71-9	P-70-73	P-76-142A	P-73-13	P-72-150	P-70-67	P-70-64	P-76-124	P-70-63	P-70-61	P-71-7	P-77-37	P-70-128	P-76-117	P-76-139	P-76-141	P-76-145
Rare-earth elements[5,6]																	
La	----	3	7	5	5	7(2)	9(2)	12	----	11	8(2)	66	56	42(2)	31(2)	27(2)	15
Ce	----	7	12	10	12	16(2)	17(2)	22	----	28	14(2)	138	124	63(2)	54(2)	58(2)	42
Nd	----	5	11	9	9	10(2)	16(2)	12	----	16	14(2)	67	55	41(2)	28(2)	24(2)	14
Sm	----	1.9	4.2	3.2	3.5	3.2(2)	5.3(2)	3.5	----	5.3	4.8(2)	13.9	12.3	7.6(2)	5.8(2)	5.8(2)	4.4
Eu	----	.62	1.61	1.05	.96	1.10(2)	1.48(2)	1.01	----	1.05	1.13(2)	1.88	1.75	1.40(2)	1.08(2)	1.02(2)	.79
Tb	----	----	1.05	.86	.84	.70(2)	1.25(2)	.76	----	1.16	1.16(2)	1.89	1.85	.88(2)	.78(2)	.98(2)	.85
Yb	----	2.2	3.3	3.6	3.1	2.9(2)	5.4(2)	2.2	----	5.2	5.4(2)	7.0	7.5	1.8(2)	3.1(2)	4.2(2)	4.1
Lu	----	.30	.49	.57	.60	.40(2)	.80(2)	.33	----	.81	.80(2)	1.00	1.14	.50(2)	.42(2)	.59(2)	.67
Y[7]	----	29	60	42	43	44	84	31	87	61	45	84	85	45	36	38	44
La/Yb	----	1.4	2.1	1.4	1.6	2.4	1.7	5.5	----	2.1	1.5	9.4	7.4	24	10.0	6.5	3.6
Nb/Y	----	.09	.11	.11	.11	.15	.07	.23	----	.07	.10	.40	.32	.38	.36	.29	.25

[1] Major elements determined by
1. X-ray spectroscopy: P-77-37, P-76-124, P-76-172A, P-76-145, P-76-117, P-76-139, P-76-141; P. Hearn and S. Wargo, analysts.
2. Rapid rock analysis:
   a. P-70-64, P-70-67, P-70-63, P-71-7, and P-71-9; P. Elmore, H. Smith and J. Kelsey, analysts;
   b. P-70-61, P-70-128, P-70-73, P-72-150, and P-70-13; Lowell Artis, analyst.
3. H_2O^+, H_2O^-, and CO_2; N. Skinner, analyst.

[2] Large cations determined by several methods listed below. Values listed in tables list arithmetic averages of elements determined by two different methods:
1. Rb and Sr: X-ray fluorescence, W. P. Doering, analyst; instrumental neutron activation analysis, L. J. Schwarz, analyst.
2. Ba and Sr: X-ray spectroscopy (Ba), J. Lindsay, B. McCalland, George Sellers, analysts; X-ray fluorescence (Sr), W. B. Doering, analyst.
3. Ba and Rb: Instrumental neutron activation analysis; L. J. Schwarz, analyst.

[3] High-valence cations (excluding Nb) determined by instrumental neutron activation analysis; L. J. Schwarz, analyst.
[4] Nb: Spectrophotometric analysis; E. Campbell, analyst.
[5] Ferromagnesian and rare-earth elements: Instrumental neutron activation analysis; L. J. Schwarz, analyst.
[6] Numbers in parentheses indicate number of analyses averaged to give cited value.
[7] Y: Quantitative spectrographic analysis; N. Rait, analyst.

DESCRIPTION OF SAMPLES

1. Metabasalt: quartz-chlorite-amphibole gneiss: Stafford Quadrangle at lat 38°25'57" N. and long 77°27'45" W.
2. Meta-quartz keratophyre: quartz-albite-chlorite-amphibole gneiss: Stafford Quadrangle at lat 38°25'58" N. and long 77°28'02" W.
3. Metabasalt: quartz-albite-chlorite-amphibole gneiss: Storck Quadrangle at lat 38°25'27" N. and long 77°30'02" W.
4. Meta-andesite: quartz-albite-amphibole gneiss: Stafford Quadrangle at lat 38°25'06" N. and long 77°29'51" W.
5. Metafelsite: quartz-albite-amphibole gneiss: Stafford Quadrangle at lat 38°24'58" N. and long 77°29'48" W.
6. Interior of metamorphosed pillow: Stafford Quadrangle at lat 38°24'57" N. and long 77°29'48" W.
7. Metafelsite: quartz-albite gneiss: Storck Quadrangle at lat 38°24'52" N. and long 77°29'44" W.
8. Meta-andesite: quartz-epidote-plagioclase-amphibole gneiss: Storck Quadrangle at lat 38°23'03" N. and long 77°36'22" W.
9. Metafelsite: quartz-albite-chlorite-mica porphyritic gneiss: Storck Quadrangle at lat 38°22'16" N. and long 77°37'13" W.
10. Meta-andesite: quartz-albite-amphibole gneiss: Salem Church Quadrangle at lat 38°21'57" N. and long 77°36'24" W.
11. Metafelsite: muscovite-biotite-plagioclase-quartz porphyritic gneiss: Brokenburg Quadrangle at lat 38°14'28" N. and long 77°44'55" W.
12. Metafelsite: muscovite-plagioclase-quartz gneiss: Belmont Quadrangle at lat 38°08'36" N. and long 77°51'18" W.
13. Metafelsite: amphibole-biotite-chlorite-quartz gneiss: Belmont Quadrangle at lat 38°07'49" N. and long 77°51'12" W.
14. Metabasalt: quartz-albite-amphibole gneiss: Belmont Quadrangle at lat 38°08'34" N. and long 77°50'00" W.
15. Metafelsite: muscovite-biotite-potassic feldspar-quartz gneiss: Lake Anna West Quadrangle at lat 38°05'47" N. and long 77°50'11" W.
16. Metafelsite: muscovite-potassic feldspar-quartz gneiss: Lake Anna West Quadrangle at lat 38°05'49" N. and long 77°51'28" W.
17. Meta-epivolcaniclastic rock: garnet-biotite-feldspar-quartz gneiss: Lake Anna West Quadrangle at lat 38°03'45" N. and long 77°50'46" W.

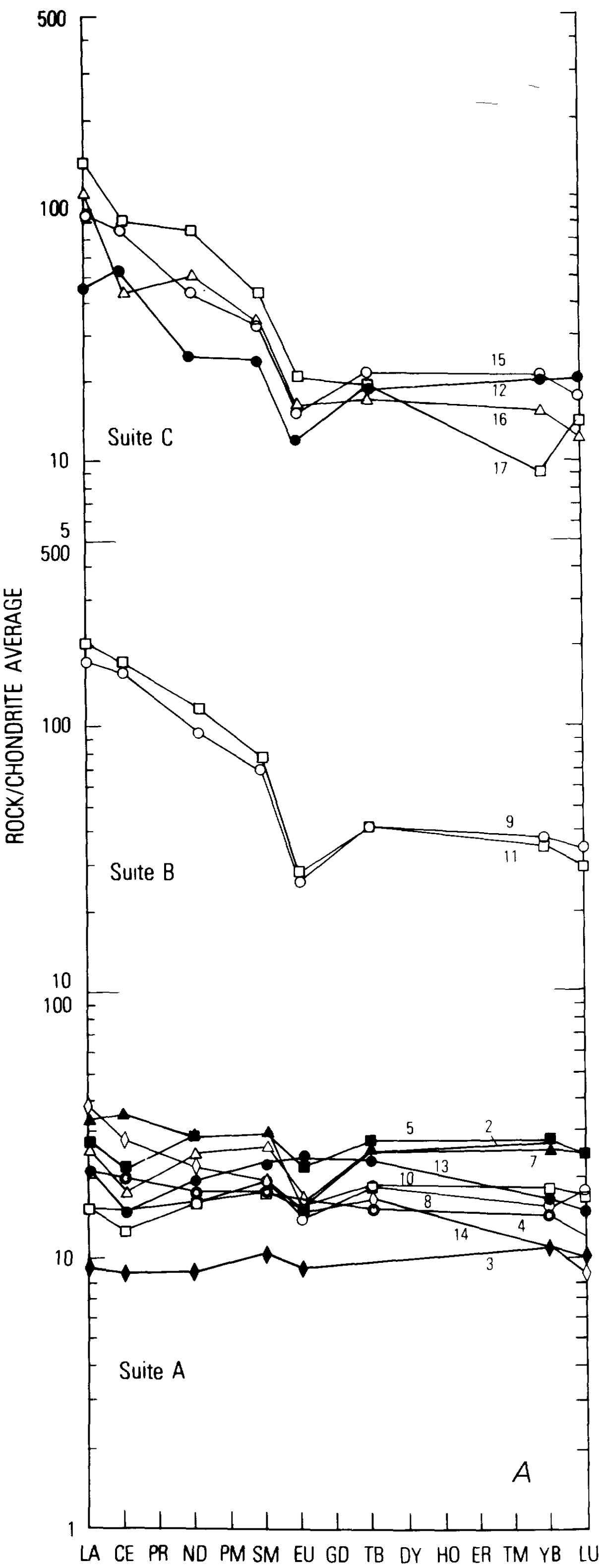
since the time these rocks were erupted is demonstrated by the marked reversals of K_2O abundances in some of the metafelsites having about the same SiO_2 content (table 2, samples 9, 11, and 16). Within suite A, scandium varies inversely with respect to silica content, a relationship characteristic of fractionation, which suggests that silicon and scandium were not affected by major mobilization processes, as were some of the other elements within the Chopawamsic rocks.

Table 2 also shows that the high-valence cations have characteristic abundance groupings in each of the three suites. For example, suite A rocks, whose major-element chemistries and SiO_2 content range from basalt to keratophyre, have niobium contents of only 2.7–7.1 ppm. Suites B and C, although only represented by silicic rocks because of the sampling problems discussed, are also clearly separable from each other and suite A by their high-valence cation content, such, for example, as that of niobium in the range 27–34 ppm in suite B and 11–17 ppm in suite C. Suites B and C are not considered to be more fractionated differentiates of suite A because all three suites have similar silicic rocks (see Jakeš and White, 1972, p. 36), namely SiO_2 >70 percent and distinctive minor element and REE abundances.

The REE patterns of the three suites of table 2 are given in figure 4. The REE patterns of suite A rocks are generally flat and similar to chondritic or primitive patterns. Generally they have a 10–30 fold enrichment of rare-earth elements above those of chondrites. These patterns are similar to those of the tholeiitic island-arc suites of Jakeš and Gill (1970) and Jakeš and White (1969; 1971; 1972, p. 34). The La/Yb value of most of the suite A samples (table 2) is also within the 1–2 range described as characteristic of tholeiitic island-arc suites (Jakeš and Gill, 1970, table 1). The REE patterns of suites B and C are characteristic of more highly fractionated rocks of calcalkaline affinities (Jakeš and White, 1972, p. 36).

TA RIVER METAMORPHIC SUITE

The same limitations imposed by weathering and poor exposure as described for the Chopawamsic Formation



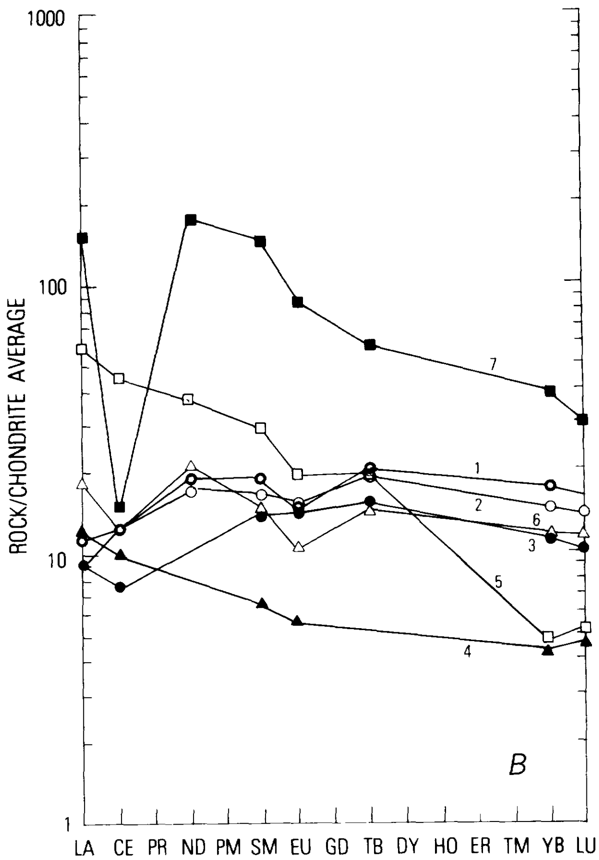


FIGURE 4.–Chondrite-normalized rare-earth element patterns for (*A*) rocks of suites A, B, and C of the Chopawamsic Formation and (*B*) amphibolites of the Ta River Metamorphic Suite.

also hamper the geochemical sampling and analysis of the Ta River amphibolites. Table 3 lists the chemical and normative analyses of seven amphibolites from the Ta River. Although considered an eastern mafic facies of the Chopawamsic Formation, the Ta River amphibolites show no chemical similarities to suites B and C of the Chopawamsic and have only some geochemical similarities to suite A (compare table 2 with 3). Except for sample 6 (table 3) the SiO_2 content of the Ta River amphibolites is within the basaltic range (< 53 percent). However, as noted in the sample description of table 3, sample 6 is cut by quartz-feldspar dikelets, which may have introduced SiO_2 into this rock. Also, analyses of samples 3 and 7 should be considered with caution because of the massive epidote replacement in sample 3, as refelcted in its high CaO content (21.6 percent) and the quartz veining present in sample 7 (see table 3). In contrast with suite A of the Chopawamsic Formation (table 2), the Ta River amphibolites are not markedly sodic (table 3). Al_2O_3 and TiO_2 in table 3 have too wide a compositional range for meaningful comparison with standard ocean-ridge, island-arc, and continental-

TABLE 3.—*Chemical and normative composition of amphibolites from the Ta River Metamorphic Suite*

Sample No	3	5	4	1	7	2	6
Field No	P-76-53	P-76-71	P-76-61	P-70-51	P-76-80	P-70-50	P-76-78
Major oxides composition (weight percent)[1]							
SiO_2	43.60	47.20	47.70	48.90	49.00	50.20	55.17
Al_2O_3	16.09	16.63	21.30	14.84	14.19	14.49	14.02
Fe_2O_3	5.86	1.89	2.02	3.06	6.87	4.65	3.36
FeO	3.5	4.9	4.6	8.8	5.7	6.4	7.3
MgO	6.98	8.93	6.47	7.72	6.80	6.05	4.1
CaO	21.61	17.00	14.53	9.96	13.68	11.65	7.76
Na_2O	.46	1.14	1.26	2.45	.51	2.23	3.48
K_2O	.15	.45	.30	.21	.27	.32	.11
H_2O^+	.57	.53	.81	.71	.84	.94	.70
H_2O^-	.15	.08	.13	.15	.30	.31	.15
TiO_2	.81	.44	.28	1.50	.75	1.30	1.04
P_2O_5	.04	.14	.03	.09	.06	.10	.07
MnO	.23	.17	.13	.22	.26	.24	.20
CO_2	.00	.00	.00	.01	.00	.00	.01
Total	100.05	99.50	99.56	98.62	99.23	98.88	97.47
Normative mineral composition (weight percent) [Based on analyses recalculated to 100 percent water-free oxides]							
Q	----	----	----	0.3	11.0	5.8	11.5
or	----	2.7	1.8	1.3	1.6	1.9	.7
ab	----	8.3	10.8	21.2	4.4	19.3	30.5
an	41.7	39.4	52.3	29.5	36.3	29.3	23.1
lc	.7	----	----	----	----	----	----
ne	2.1	.8	----	----	----	----	----
wo	25.9	18.8	8.6	8.5	13.5	12.2	6.8
en	17.5	13.1	16.1	19.7	17.3	15.4	10.6
fs	.7	4.1	6.6	11.8	4.1	6.4	9.6
fo	----	6.6	.1	----	----	----	----
fa	----	2.3	.1	----	----	----	----
cs	1.2	----	----	----	----	----	----
mt	8.6	2.8	3.0	4.5	10.2	6.9	5.0
il	1.5	.8	.5	2.9	1.5	2.5	2.0
ap	.1	.3	.1	.2	.1	.3	.2
cc	----	----	----	.1	----	----	----
Total	100	100	100	100	100	100	100
di	39.0	36.0	16.6	16.6	25.8	23.6	13.4
di-wo	20.8	18.8	8.6	8.5	13.5	12.2	6.8
di-en	17.5	13.1	5.7	5.1	9.9	8.0	3.5
di-fs	.7	4.1	2.3	3.0	2.4	3.3	3.1
hy	----	----	14.7	23.4	9.1	10.4	13.6
hy-en	----	----	10.5	14.6	7.3	7.4	7.1
hy-fs	----	----	4.2	8.8	1.8	3.0	6.5
ol	----	8.9	.2	----	----	----	----
ol-fo	----	6.6	.1	----	----	----	----
ol-fa	----	2.3	.1	----	----	----	----
wo	5.1	----	----	----	----	----	----
DI	2.8	11.8	12.6	22.8	17.0	27.0	42.7
Trace-element abundances (parts per million) Large cations[2]							
Rb	17	18	16.5	21	19.5	16	13
Ba	7	174	35	61	16	172	18
Sr	373	928	321	125	228	185	113
Ba/Rb	.4	9.7	2.1	2.9	.8	10.2	1.4
High-valence cations[3,4]							
Th	----	2.5(3)	1.1(3)	0.4(2)	----	0.4	1.0(3)
Zr	50	60	10	80	40	70	70
Hf	1.4(3)	1.6(3)	.8(2)	2.6(3)	1.0(3)	2.1(3)	1.7(3)
Nb	3.1	3.6	1.6	4.4	3.5	3.5	6.4
Ta	----	----	----	.14(3)	----	.13(3)	.06(3)
Zr/Hf	37	37	12	31	40	33	41
Nb × 100/Ti	.06	.14	.09	.05	.08	.04	.10
Nb/Ta	----	----	----	44	----	27	107

TABLE 3.—*Chemical and normative composition of amphibolites from the Ta River Metamorphic Suite*—Continued

Sample No / Field No	3 P-76-53	5 P-76-71	4 P-76-61	1 P-70-51	7 P-76-80	2 P-70-50	6 P-76-78
Ferromagnesian elements[5]							
Co	43.5(3)	28.7(3)	29.9(3)	48(3)	27.6(3)	35.4(3)	28.8(3)
Ni	250	54	37	110	220	59	2
Zn	100(3)	104(3)	78(3)	138(3)	136(3)	117(3)	118(3)
Cr	265.3(3)	103.6(3)	115.8(3)	239.7(3)	385.4(3)	149.2(3)	----
Sc	40.4(3)	61.5(3)	35.2(3)	45.3(3)	40.8(3)	36.6(3)	33.3(3)
Ni/Co	5.8	1.9	1.2	2.3	8.0	1.7	.07
Rare-earth elements[5]							
La	3(3)	19(3)	4(3)	4(3)	48(3)	3(3)	6(3)
Ce	6(3)	36(3)	8(3)	10(3)	12(3)	10(3)	10(3)
Nd	28(3)	21(3)	----	11	102(3)	10	12
Sm	2.6(3)	5.4(3)	1.2(3)	3.5(3)	27.3(3)	3.1(3)	2.8(3)
Eu	.99(3)	1.34(3)	.38(3)	1.01(3)	6.04(3)	1.05(3)	.72(3)
Tb	1.01(3)	1.22(3)	----	.98(3)	2.80(3)	.92(3)	.68(2)
Yb	2.3(3)	1.0(3)	.9(3)	3.6(3)	8.3(3)	3.0(3)	2.4(3)
Lu	.35(3)	.18(3)	.16(3)	.55(3)	1.05(3)	.47(3)	.39(3)
Y	27	12	14	48	67	38	31
La/Yb	1.3	19	4.4	1	5.8	1	2.5

[1] Major elements determined by X-ray spectroscopy: P. Hearn and S. Wargo, analysts; except for FeO, H_2O^+, H_2O^-, and CO_2 determined by rapid rock analysis, N. Skinner, analyst.
[2] Large cations: Rb is average of values (2) determined by instrumental neutron activation analysis, L. J. Schwarz, analyst, and X-ray spectroscopy, George Sellers, B. McCall, and J. Lindsay, analysts. Ba and Sr determined by X-ray spectroscopy, George Sellers, B. McCall, and J. Lindsay, analysts.
[3] High valence cations (excluding Nb) determined by instrumental neutron activation analysis, L. J. Schwarz, analyst. Nb determined by spectrophotometric analysis, E. Campbell, analyst.
[4] Numbers in parentheses indicate number of analyses averaged to give cited value.
[5] Ferromagnesian and rare-earth elements (except Ni) determined by instrumental neturon activation analysis, L. J. Schwarz, analyst. Ni determined by spectrographic analysis, S. Berman, analyst.

DESCRIPTION OF SAMPLES

1. Strongly foliated amphibolite with small-scale folds and with small segregation veins of quartz and quartz-feldspar. Layering consists of green amphibole-rich layers interleaved with quartz-plagioclase-rich layers. Stafford Quadrangle at lat 38°23′39″ N. and long 77°29′52″ W.
2. Similar to P-70-51 above: Stafford Quadrangle at lat 38°23′37″ N. and long 77°29′49″ W.
3. Foliated amphibolite composed mostly of green amphibole, smaller amounts of untwinned plagioclase and accessory sphene granules. Epidote is abundant and locally forms massive replacement of the amphibolite: Brokenburg Quadrangle at lat 38°08′51″ N. and long 77°39′26″ W.
4. Foliated and layered (on a fine scale) amphibolite. Irregular laminae of green amphibole intergrown with calcic well-twinned plagioclase are interleaved with amphibolitic layers or are interspersed with them. Epidote and sphene are accessory: Lake Anna East Quadrangle at lat 38°05′08″ N. and long 77°42′40″ W.
5. Foliated amphibolite. Green amphibole and andesine with enclosed and partial (metamorphic) twinning. Amphibole poikilitically encloses small-size grains of plagioclase. Epidote is a minor accessory: Lake Anna East Quadrangle at lat 38°03′27″ N. and long 77°43′51″ W.
5. Foliated amphibolite. Green amphibole and andesine with enclosed and partial (metamorphic) twinning. Amphibole poikilitically encloses small-size grains of plagioclase. Epidote is a minor accessory: Lake Anna East Quadrangle at lat 38°03′27″ N. and long 77°43′51″ W.
6. Finely layered and strongly foliated amphibolite locally cut by quartz-feldspar dikelets and, in places, containing feldspathic segregation clots. Green amphibole locally encloses small grains of quartz and plagioclase. Plagioclase occurs as twinned and untwinned grains. Quartz is a minor constituent and fine-grained granular sphene is accessory: Lake Anna West Quadrangle at lat 38°02′38″ N. and long 77°47′23″ W.
7. Fine-grained foliate amphibolite laced by very thin quartz veinlets. Amphibole poikilitically encloses small grains of epidote, quartz, and untwinned plagioclase. Epidote is abundant, quartz occurs mostly in stringers and generally untwinned plagioclase is a minor constituent: Lake Anna West Quadrangle at lat 38°02′20″ N. and long 77°46′12″ W.

margin basalts described in some reports (Gottfried and others, 1977, table 4; Garcia, 1978, table 2; Jakeš and White, 1971, table 2). However, the high-valence cations within the Ta River amphibolites show few differences from suite A of the Chopawamsic, except that the Ta River rocks are generally lower in the zirconium-hafnium pair (compare table 2 with 3). The Ta River rocks generally contain more of the ferromagnesian elements cobalt, nickel, and chromium than do the suite A Chopawamsic rocks. No major abundance differences are apparent in REE content between these two suites of rocks. The chondrite-normalized REE data for Ta River amphibolites is shown in figure 4*B*. The REE patterns of the Ta River amphibolites are not so definitive as those of the three suites of the Chopawamsic Formation. The unusual pattern for sample 7 (fig. 4*B*) may result from the altered nature of this rock (see description in table 3), as possibly reflected by its high Fe_2O_3 content (6.9 percent). Samples 7 and 5 have REE patterns with light rare-earth element (LREE) enrichment comparable with some calcalkaline rocks, whereas 1 and 2 have trends comparable with ocean-ridge basalt, namely, flat distribution of heavy rare-earth elements (HREE) and depleted LREE. Samples 6 and 3 have patterns generally similar to those of 1 and 2, except that lanthanum shows relative enrichment rather than a continuing depletion (fig. 4*B*).

META-INTRUSIVE ROCKS

GENERAL STATEMENT

Metamorphosed plutonic rocks of felsic, mafic, and ultramafic composition intrude or occur within the belt of metavolcanic rocks of the Fredericksburg area. In this paper only the felsic intrusive rocks, believed to be temporally and tectonically related to the metavolcanic rocks of this part of the central Virginia volcanic-plutonic belt, are discussed. The metamorphosed mafic and ultramafic rocks are only briefly summarized. Also, the Carboniferous felsic meta-igneous rocks of the Falmouth Intrusive Suite (Pavlides and others, 1979) are not discussed because they are tectonically and temporally unrelated to the early history of the central Virginia volcanic-plutonic belt.

METAMORPHOSED MAFIC AND ULTRAMAFIC ROCKS

The metavolcanic rocks of both the Chopawamsic Formation and the Ta River Metamorphic Suite shown in the southern part of figure 3 contain small masses of serpentinite and metapyroxenite(?) (not shown in fig. 3) that because of poor exposure are provisionally considered intrusive. Near Fredericksburg, the Chopawamsic is intruded by metagabbro (Pavlides, 1976, p. 6, p. 34–36). The mafic complex at Garrisonville (fig. 3) is the largest metamafic mass in the area and is considered to be a sphenolith-like intrusion (Pavlides and others, 1974, p. 575). It consists of a variety of metamorphosed mafic rocks including hornblendite, amphibolite, metapyroxenite, metawebsterite(?), and metanorite (Pavlides, 1976, p. 6, p. 12–14). However, because the contact of the Garrisonville mafic complex with its enclosing rocks is not exposed, the possibility that the Garrisonville was structurally emplaced into its present position cannot be ruled out.

TRONDHJEMITIC AND PLAGIOGRANITIC METATONALITES

Two petrographically dissimilar and metamorphosed granitoid rocks (here called metatonalites) occur in plutons and associated dikes of different ages within the Chopawamsic belt near Fredericksburg (fig. 3). Both plutons and their related dikes are of pre-Late Ordovician age, as they have not been observed to intrude the Quantico Formation. For reasons given in following paragraphs, a trondhjemitic protolith is suggested for the younger pluton and its associated dikes, whereas the older more metmorphosed and more deformed pluton is interpreted as having close compositional affinities to plagiogranite. However, because the granitoid rocks from both plutons and their related dikes now have color indices >10 they cannot be classed as trondhjemite or plagiogranite under strict usage of these terms. Nonetheless, the overall mineral and chemical features of these granitoid rocks from the Fredericksburg area suggest affinities to such rock types, and they are, therefore, classified as belonging to trondhjemitic and plagiogranitic suites. Because trondhjemites and plagiogranites are defined in several ways by different petrologists, a brief discussion of the terminology used in this report is provided.

The general characterisitics of trondhjemite have been reviewed by Barker (1979b), and many papers describing trondhjemite are presented by other investigators in a volume edited by Barker (1979a). Petrographically, trondhjemite is a leucotonalite having a color index <10 and contains sodic plagioclase in the range albite to oligoclase. Chemically, it is characterized by a low K_2O content, which, under Barker's usage, may be as much as 2.5 percent. SiO_2 content is high, generally 68 percent or more. O'Connor (1965) published a very useful normative diagram (fig. 5) that differentiates trondhjemites from other granitoid rocks. All the rocks of the Fredericksburg area considered to have affinities to trondhjemite fall in the trondhjemite field of the O'Connor diagram (fig. 5). On the Coleman and Peterman modal diagram (fig. 6) they lie along the quartz-plagioclase tieline entirely within the trondhjemite-tonalite field. For these reasons and because of their other chemical features, described in the section Geochemistry (p. A18–A20), they are classed as trondhjemitic metatonalite in this report.

Plagiogranite has been used as a synonym with trondhjemite by some petrologists (Streckeissen, 1975, p. 14). Plagiogranite, like trondhjemite, also generally has a color index <10 and contains sodic plagioclase. Chemically, however, it contains <1 percent K_2O, and SiO_2 is generally 70 percent or more. Coleman and Peterman (1975) recognized a special class of plagiogranite closely associated with transported ophiolite sequences that they termed oceanic plagiogranite. Oceanic plagiogranite occurs in small masses believed to have been derived through fractionation from the associated ophiolitic rocks. In contrast, plagiogranite not genetically related to ophiolites has been reported in batholithic dimensions in the Sayan geosyncline of Siberia by Popolitov and others (1973). Here quartz-plagioclase rocks containing very low K_2O and SiO_2 of about 73 percent has been termed plagiogranite. These rocks cover several thousand square kilometers in area and have been emplaced into lower Paleozoic volcanic rocks formed on ocean crust. The plagiogranitic rocks of the Fredericksburg area are more closely similar to those of the Sayan belt than to oceanic plagiogranite.

Coleman and Peterman (1975, fig. 1) introduced a ternary diagram, modified from Streckeissen (1973, fig. 1A) that is useful for classifying plagiogranites irrespective of their genetic relationships. This is reproduced in figure 6. The plagiogranite suite falls along the tieline Q-P and can range in composition from quartz-rich granitoid rock, to tonalite-trondhjemite, and to diorite in composition (see Coleman and Peterman, 1975, fig. 1). In the Fredericksburg area, all the granitoid rocks considered to be of plagiogranitic composition lie along

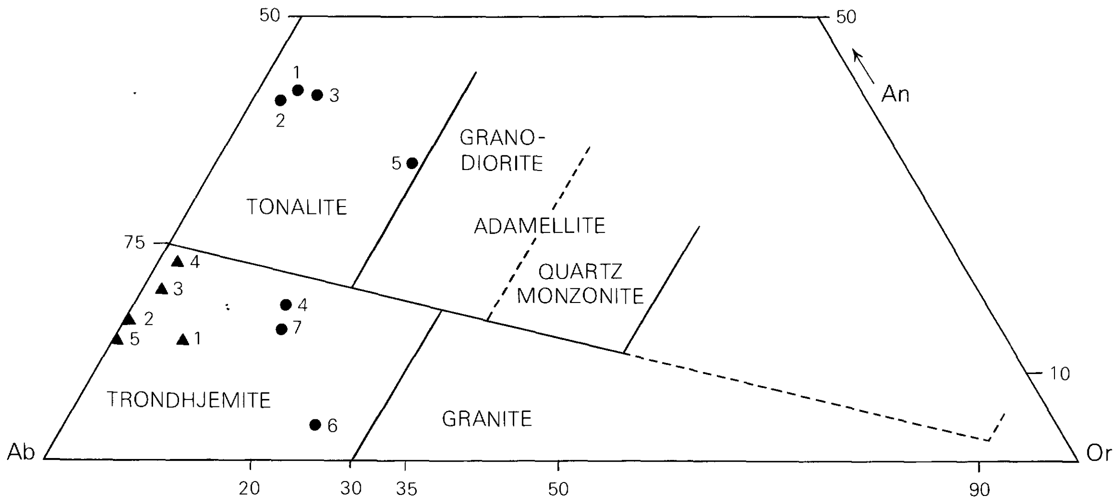


FIGURE 5.—Normative Ab-Or-An diagram showing fields of siliceous plutonic rocks (O'Connor, 1965) and plots of rocks of the trondhjemitic metatonalite suite (triangles) and the plagiogranitic metatonalite suite (circles) from the Fredericksburg area, Virginia.

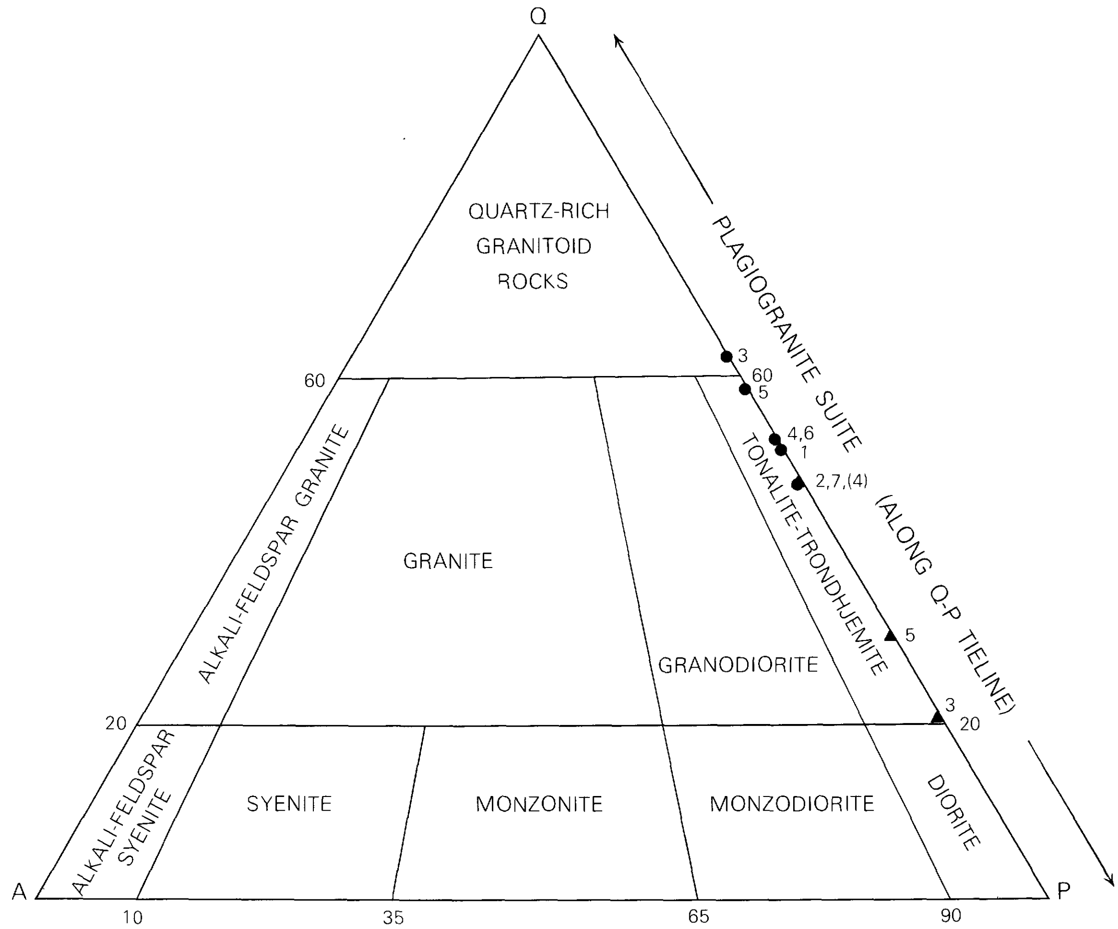


FIGURE 6.—Modal plots of A (potassic feldspar)-P (plagioclase, including albite)-Q (quartz) for rocks of the plagiogranitic metatonalite suite (circles) and the trondhjemitic metatonalite suite (triangles) from the Fredericksburg area, Virginia. Sample (4) is a trondhjemitic metatonalite that falls on two plagiogranitic metatonalite sample points. Diagram taken from Coleman and Peterman (1975, fig. 1).

the **Q-P** tieline (plagiogranite suite), and all but one (sample 3) fall along the **Q-P** tieline of the tonalite-trondhjemite field. Sample 3, which falls along the tieline of the quartz-rich granitoid field, is still close to tonalite in composition. Therefore, these rocks of the older pluton are termed plagiogranitic metatonalite. The additional chemical features that characterize these rocks as plagiogranitic in composition are discussed in the section Geochemistry (p. A20–A21).

LITHOLOGY AND PETROGRAPHY

TRONDHJEMITIC METATONALITE SUITE

A small pluton of trondhjemitic metatonalite intrudes the Chopawamsic Formation immediately north of the Rappahannock River (fig. 3). It was originally assumed to be intrusive into both the Chopawamsic and the Quantico Formations (Pavlides, 1976), but new mapping indicates it intrudes only the Chopawamsic and is in fault contact with the Quantico. Similar rock is also common as plugs and dikes within the Chopawamsic Formation near this pluton. The pluton and its associated dikes and plugs are characterized by a weak to locally imperceptable foliation, by granophyric texture consisting of albitic plagioclase (An <10 percent by flat stage measurements) graphically intergrown with quartz, and by blue-green amphibole that appears to be a sodic hornblende in the sodic edenite series (Malcom Ross, oral commun., 1978). This amphibole may form as much as 36 percent of some rocks. Table 4 lists chemical, normative, and modal analyses of granitoid rocks of the trondhjemitic metatonalite suite from the pluton and from plugs and dikes intruding the Chopawamsic Formation. The normative analyses of table 4 are plotted on the normative Ab-Or-An diagram (fig. 5) of O'Connor (1965), and all fall in the trondhjemite field.

PLAGIOGRANITIC METATONALITE SUITE

Coarse-grained, quartz-rich metatonalites extensively intrude the Chopawamsic Formation in the Fredericksburg area (fig. 3). The granitoid rocks are highly foliated and were emplaced into the Chopawamsic and deformed with it, as they share the same foliation. In contrast the trondhjemitic metatonalite suite of rocks described, having weaker foliation, were emplaced later. The plagiogranitic-metatonalite-suite granitoid rocks of the Fredericksburg area have a modal quartz range of 41–48 percent (table 5). Characteristically they contain granoblastic-textured aggregates of quartz, as well as single discrete grains of quartz and plagioclase, generally with chlorite, epidote, and, in places, white-mica alteration. Biotite and amphibole are common accessories; garnet is rare, and opaque minerals are minor. Some of the quartz is blue.

TABLE 4.—*Chemical, normative, and modal composition of trondhjemitic metatonalite in the Fredericksburg area, Virginia*

Sample No	3	4	5	1	2
Field No	P-73-1	P-73-5	P-73-6	P-72-41	P-72-190
Major oxide composition (weight percent)[1]					
SiO_2	69.7	74.1	75.1	75.8	77.4
Al_2O_3	13.2	12.1	11.9	12.0	11.5
Fe_2O_3	3.9	3.7	2.4	1.3	.78
FeO	3.5	2.6	1.1	2.0	1.7
MgO	.49	.33	.15	.33	.53
CaO	2.4	2.4	1.7	[2]1.5	[2]2.9
Na_2O	5.2	4.2	5.5	[2]4.6	[2]5.2
K_2O	.15	.13	.05	[2].54	[2].02
H_2O^+	.66	.36	.37	.60	1.1
H_2O^-	.20	.10	.06	.23	.24
TiO_2	.46	.38	.29	.23	.28
P_2O_5	.14	.11	.05	.06	.01
MnO	.16	.31	.06	.00	.00
CO_2	.04	.06	.02	.01	.01
Total	100.2	100.88	98.75	99.2	101.57
Normative mineral composition (weight percent) [Based on analyses recalculated to 100 percent water-free oxides]					
Q	32.5	43.1	40.0	43.2	41.0
C	.5	1.1	----	1.3	----
or	.9	.8	.3	3.2	.1
ab	44.3	35.4	47.3	39.7	43.0
an	10.8	10.8	7.7	7.1	8.4
wo	----	----	.1	----	2.4
en	1.2	.8	.4	.8	1.3
fs	2.8	1.7	----	2.2	2.0
mt	5.7	5.3	3.0	1.9	1.1
hm	----	----	.4	----	----
il	.9	.7	.6	.4	.5
ap	.3	.2	.1	.1	.1
cc	.1	.1	.1	.1	.1
Total	100.0	100.0	100.0	100.0	100.0
di	----	----	0.2	----	4.9
di-wo	----	----	.1	----	2.4
di-en	----	----	.1	----	1.0
di-fs	----	----	----	----	1.5
hy	4.0	2.5	.2	3.1	.9
hy-en	1.2	0.8	.2	.8	.4
hy-fs	2.8	1.7	----	2.3	0.5
DI	77.7	79.2	87.6	86.0	84.1
Modal analysis (percent)[3]					
Quartz	14.90	25.51	21.67	----	----
Quartz (granophyric)	9.93	3.54	18.08	----	----
Plagioclase	49.86	23.96	27.04	----	----
Plagioclase (granophyric)	7.62	3.83	22.79	----	----
Biotite	----	.78	----	----	
Amphibole	12.86	35.68	1.12	----	----
Chlorite	.99	.16	----	----	----
Garnet	1.66	.32	.11	----	----
Epidote	.61	1.77	6.77	----	----
Opaque minerals	1.75	5.22	1.62	----	----
Total	100.00	99.99	99.98	----	----
Color index[4]	17.87	43.15	10.4	----	----
Trace-element abundances (parts per million)					
Large cations[5,6]					
Rb	6	17	----	12(2)	2
Ba	45	229	----	138(2)	21
Sr	163(2)	100	98.3	153	36(2)
Ba/Rb	8	13	----	11	10
High valence-cations[7]					
Th	3.0	2.7	----	4.7	2.8(2)
Zr[8]	160	160	----	180	120
Hf	4.4	4.6	----	5.8	3.6(2)
Nb[9]	3.3	2.4	----	4.4	2.4
Ta	.32	.21	----	.38	.22(2)
Zr/Hf	36	35	----	31	33
Nb × 100/Ti	.12	.10	----	.31	.14
Nb/Ta	10	11	----	12	11
Ferromagnesian elements[10]					
Co	2.2	1.9	----	1.3	2.2(2)
Zn	66	49	----	31	58(2)
Sc	16	13.15	----	9.94	9.89(2)
Rare-earth elements[1]					
La	10	11	----	9	4(2)
Ce	25	27	----	45	11(2)
Nd	17	18	----	17	8(2)
Sm	5.7	5.1	----	5.4	2.6(2)

TABLE 4.—*Chemical, normative, and modal composition of trondhjemitic metatonalite in the Fredericksburg area, Virginia*—Continued

Sample No	3	4	5	1	2
Field No	P-73-1	P-73-5	P-73-6	P-72-41	P-72-190
Rare-earth elements—Continued					
Eu	1.6	1.49	----	1.08	.68(2)
Tb	1.16	1.06	----	1.21	.81(2)
Yb	6.3	12.3	----	7.4	5.0(2)
Lu	.92	2.01	----	1.04	.74(2)
Y[11]	63	82	----	81	52
La/Yb	1.6	.89	----	1.2	.8
Nb/Y	.05	.03	----	.05	.05

[1] Major elements determined by rapid rock analysis:
1. P-73-1, P-73-5, and P-73-6, Lowell Artis, analyst.
2. P-72-41 and P-72-190, H. Kirschenbaum and S. Botts, analysts.

[2] Rapid rock analysis; Leonard Shapiro, analyst.

[3] Modal analysis by S. L. Cranford.

[4] Color index from Streckeisen, A., (1975).

[5] Large cations: Determined by several methods listed as follows. Values cited in tables list arithmetic averages for elements determined by two different methods:
1. Rb and Ba: P-73-1, P-73-5, P-72-190, X-ray spectroscopy, B. McCall, J. Lindsay, G. Sellers, and S. Wargo, analysts. P-72-41, instrumental neutron activation analysis, L. J. Schwarz, analyst; X-ray spectroscopy, B. McCall, J. Lindsay, G. Sellers, and S. Wargo, analysts.
2. Sr: P-73-1 and P-72-190, X-ray fluorescence, W. P. Doering, analyst; X-ray spectroscopy, B. McCall, J. Lindsay, G. Sellers, and S. Wargo, analysts. P-73-5 and P-72-41, X-ray spectroscopy, B. McCall, J. Lindsay, G. Sellers, and S. Wargo, analysts. P-73-6, X-ray fluorescence, W. P. Doering, analyst.

[6] Numbers in parentheses indicate number of analyses averaged to give cited value.

[7] High valence cations (excluding Zr and Nb) determined by instrumental neutron activation analysis, L. J. Schwarz, analyst.

[8] Zr: Emission spectroscopy, S. Berman, analyst.

[9] Nb: Spectrophotometric analysis, E. Campbell, analyst.

[10] Ferromagnesian and rare-earth elements (excluding Y): instrumental neutron activation analysis, L. J. Schwarz, analyst.

[11] Y: Emission spectroscopy, N. Rait, analyst.

DESCRIPTION OF SAMPLES

1. Mesocratic, granophyric garnet-amphibole bearing trondhjemitic metatonalite: Salem Church Quadrangle at lat 38°22′09″ N. and long 77°35′05″ W.
2. Mesocratic granophyric magnetite-amphibole bearing trondhjemitic metatonalite: Salem Church Quadrangle at lat 38°22′02″ N. and long 77°36′48″ W.
3. Mesocratic, granophyric amphibole-epidote bearing trondhjemitic metatonalite: Salem Church Quadrangle at lat 38°22′02″ N. and long 77°36′48″ W.
4. Cataclastic, muscovite-biotite-chlorite bearing trondhjemitic metatonalite dike: Storck Quadrangle at lat 38°23′58″ N. and long 77°32′50″ W.
5. Leucocratic, hypidiomorphic-granular chlorite-muscovite bearing trondhjemitic metatonalite dike: Storck Quadrangle at lat 38°23′47″ N. and long 77°33′01″ W.

Figure 6 is a modal plot of the metatonalites of the Fredericksburg area on the A-Q-P diagram of Coleman and Peterman (1975). As stated earlier, the rocks fall along the plagioclase suite tieline between Q and P. Normative analyses of these rocks, however, plot in both the tonalite and trondhjemite fields of O'Connor's Ab-An-Or diagram (fig. 5). Normally plagiogranitic rocks should plot close to the Ab-An tieline of the O'Connor diagram, as do samples 1, 2, and 3. The fact that samples 4, 5, and 7 plot considerably away from this tieline is attributed to metamorphic alteration.

GEOCHEMISTRY

TRONDHJEMITIC METATONALITE SUITE

Although weakly foliated as well as metamorphosed, the trondhjemitic metatonalites of the Fredericksburg area have granophyric textures consisting of intergrowths of albitic plagioclase and quartz. Granophyric texture is generally considered to form from cotectic precipitation of feldspar and quartz in magmatic rocks (Barker, 1970). Granophyric texture involving intergrowths of sodic plagioclase and quartz has also been interpreted as a late-stage crystallization producing plagiogranites from K_2O-poor magmas (Coleman and Donato, 1979, p. 153–154). The granophyric texture in the trondhjemitic metatonalite suite of the Fredericksburg area is, therefore, interpreted as indicative of a magmatic origin of these rocks. The inverse variation of scandium with SiO_2 (table 4) is consistent with the fractionation trend of this element and thus implies that mobility of SiO_2 in these rocks, if it did take place, was minor.

The weakly foliated and metamorphosed trondhjemitic metatonalite suite of rocks of the Fredericksburg area includes both corundum-normative and diopside-normative samples regardless of its SiO_2 content (table 4). This contrasts with the observation that in calcalkaline magmas there is a change from diopside normative to corundum normative where SiO_2 content is in the mid-60's (Cawthorn and others, 1976). The fact that both high-alumina ($Al_2O_3 > 15$ percent) and low-alumina ($Al_2O_3 < 15$ percent) trondhjemites are generally corundum normative (Barker, 1979b, p. 5) suggests that the corundum-normative trondhjemites are not dependent on an original high-aluminum bulk chemistry. The trondhjemitic metatonalites of the Fredericksburg area all contain substantially < 15 percent Al_2O_3 and are thus similar to low-alumina trondhjemites, according to the definition of Barker and Arth (1976) modified by Barker (1979b, p. 6–7). Arth (1979) has subdivided trondhjemites into oceanic and continental varieties on the basis of their Al_2O_3 and ytterbium contents, as plotted on a semilogarithmic graph (fig. 7). On this diagram, in which Arth separates the high- and low-alumina fields at 14.5 percent Al_2O_3, all the trondhjemitic metatonalites of the Fredericksburg area plot in the low Al_2O_3, oceanic field (fig. 7).

The REE patterns of the Fredericksburg area trondhjemitic metatonalites are shown in figure 8*A*. In general the patterns are flat except for HREE enrichment shown by sample 4 and the cerium enrichment of sample 1. If we exclude these apparent local enrichments, the LREE show values about 15–33 fold above chondrite values, whereas the HREE show an enrichment of 21–30 fold above chondrite values. The REE patterns of the Fredericksburg area trondhjemitic metatonalites are similar to patterns obtained from Cenozoic and Mesozoic trondhjemites found in island arcs and are strikingly dissimilar to patterns of trondhjemites in continental margins, continental interiors, and ophiolites (Arth, 1979, fig. 1). They differ from the patterns of the trondhjemite of the Mule Mountain stock that intrudes Devonian metavolcanic rocks of the West Shasta district in California, in that the Mule Mountain trondhjemite

TABLE 5.—*Chemical, normative, and modal composition of plagiogranitic metatonalite in the Fredericksburg area, Virginia*

Sample No	2	1	5	3	7	4	6
Field No	P-71-55	P-71-38	P-70-81	P-71-27	P-70-240	P-71-18	P-70-179
Major oxide composition (weight percent)[1]							
SiO_2	70.4	72.7	73.1	75.1	75.2	76.6	77.7
Al_2O_3	14.9	12.2	13.1	11.2	12.8	12.6	12.3
Fe_2O_3	1.6	2.2	1.3	1.1	.78	1.2	1.3
FeO	2.6	2.6	2.2	2.7	1.2	1.3	.60
MgO	1.0	1.1	.64	1.0	.45	.72	.30
CaO	4.1	3.8	3.3	3.5	2.3	1.6	.48
Na_2O	3.1	2.8	2.6	2.5	3.7	3.2	4.0
K_2O	.20	.26	1.5	.38	1.2	1.0	2.0
H_2O^+	1.1	1.5	1.4	1.3	1.2	1.2	.61
H_2O^-	.27	.04	.07	.07	.05	.12	.08
TiO_2	.42	.49	.20	.52	.13	.33	.16
P_2O_5	.11	.00	.00	.02	.00	.06	.00
MnO	.08	.13	.12	.11	.08	.07	.11
CO_2	----	----	----	----	0.70	----	----
Total	99.9	99.8	99.5	99.5	98.6	100.0	99.6
Modal analysis (percent)[2]							
Quartz	41.0	41.7	48.1	44.9	41.8	47.2	46.2
Plagioclase	44.0	38.6	33.9	26.4	46.5	41.3	41.1
Amphibole	4.6	----	----	----	----	----	----
Biotite	.7	.4	5.3	1.2	----	2.2	.3
Muscovite	.3	.1	4.1	1.7	7.5	6.3	12.0
Chlorite	4.8	7.2	.8	6.3	2.2	.8	----
Epidote	3.6	10.1	7.3	19.0	.2	.6	.1
Garnet	.1	----	.3	----	----	----	----
Calcite	----	----	----	----	1.5	----	----
Opaque minerals	.7	1.8	----	.5	.1	1.5	.4
Total	99.8	99.9	99.8	100.0	99.8	99.9	100.1
Color index[3]	14.8	19.6	17.8	28.7	11.5	11.4	12.8
Normative mineral composition (weight percent) [Based on analyses recalculated to 100 percent water-free oxides]							
Q	41.0	45.4	43.9	49.7	45.4	50.2	45.9
C	2.5	.5	1.3	.5	2.9	3.7	2.8
or	1.2	1.6	9.1	2.3	7.2	6.0	11.9
ab	26.6	24.1	22.4	21.5	31.8	27.4	34.2
an	19.6	18.9	16.4	17.2	7.1	7.3	2.1
en	2.5	2.9	1.6	2.5	1.1	1.8	.8
fs	3.0	2.4	2.9	3.5	1.5	1.0	----
mt	2.4	3.2	1.9	1.6	1.1	1.8	1.8
hm	----	----	----	----	----	----	.1
il	.8	.9	.4	1.0	.3	.6	.3
ap	.3	----	----	.1	----	.1	----
cc	.1	.1	.1	.1	1.6	.1	.1
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0
hy	5.5	5.2	4.5	6.0	2.6	2.8	0.8
hy-en	2.5	2.8	1.6	2.5	1.1	1.8	.8
hy-fs	3.0	2.4	2.9	3.5	1.5	1.0	----
DI	68.8	71.1	75.3	73.5	84.3	83.6	92.0
Trace-element abundances (parts per million)							
Large cations[4,5]							
Rb	6(2)	8	----	12(2)	----	32	----
Ba	47	42	----	86	----	206(2)	----
Sr	162	119	----	105	----	84	----
Ba/Rb	8	5	----	7	----	6	----
High-valence cations[6]							
Th	0.8	0.8(2)	----	1.3	----	2.1	----
Zr[7]	----	20	----	60	----	240	----
Hf	.6	.6(2)	----	1.8	----	5.5	----
Nb[8]	1.9	3.9	----	5.0	----	----	----
Ta	.12	.25	----	.16	----	.27	----
Zr/Hf	----	33	----	33	----	44	----
Nb x 100/Ti	.08	.13	----	.16	----	----	----
Nb/Ta	16	16	----	31	----	----	----

TABLE 5.—*Chemical, normative and modal composition of plagiogranitic metatonalite in the Fredericksburg area, Virginia*—Continued

Sample No	2	1	5	3	7	4	6
Field No	P-71-55	P-71-38	P-70-81	P-71-27	P-70-240	P-71-18	P-70-179
Ferromagnesian elements[9]							
Co	6.0	7.6(2)	----	6.8	----	5.9	----
Ni[7]	4	----	----	4	----	----	----
Zn	98	84	----	52	----	28	----
Cr	2.8	10.9(2)	----	10.1	----	----	----
Sc	6.56	21.08(2)	----	10.93	----	7.66	----
Ni/Co	.7	----	----	.6	----	----	----
Rare-earth elements[10]							
La	5	5(2)	----	6	----	8	----
Ce	8	12(2)	----	11	----	15	----
Nd	6	8(2)	----	6	----	7	----
Sm	1.2	2.6(2)	----	1.4	----	1.6	----
Eu	.77	.84(2)	----	.63	----	.54	----
Tb	.26	.45	----	.23	----	.25	----
Yb	.8	1.7(2)	----	.9	----	2.3	----
Lu	.09	.26(2)	----	.15	----	.38	----
Y[10]	13	28	----	14	----	18	----
La/Yb	6.25	2.94	----	6.67	----	3.48	----
Nb/Y	.15	.14	----	.36	----	----	----

[1] Major elements determined by rapid rock analysis:
1. P-71-55, P. Elmore, H. Smith, J. Kelsey, and J. Glenn, analysts.
2. P-71-38, P-70-81, P-71-27, P-70-240, and P-70-179, P. Elmore, H. Smith, J. Kelsey, J.Glenn, and G. Chloe, analysts.
3. P-71-18, P. Elmore, H. Smith, and J. Kelsey, analysts.

[2] Modal analysis by S. L. Cranford.

[3] Color index from Streckeisen, A., 1975.

[4] Large cations determined by several methods listed as follows. Values cited in tables list arithmetic averages for elements determined by two different methods:
1. Rb: P-71-55, X-ray spectroscopy, B. McCall, J. Lindsay, G. Sellers, and S. Wargo, analysts; X-ray spectroscopy, J. S. Wahlberg. P-71-38, X-ray spectroscopy, B. McCall, J. Lindsay, G. Sellers, and S. Wargo, analysts. P°71-27 and P-71-18, X-ray spectroscopy, B. McCall, J. Lindsay, G. Sellers, and S. Wargo, analysts; instrumental neutron activation analysis, L. J. Schwarz, analyst.
2. Ba: P-71-55 and P-71-38, X-ray spectroscopy, B. McCall, J. Lindsay, G. Sellers, and S. Wargo, analysts. P-71-27 and P-71-18, X-ray spectroscopy, B. McCall, J. Lindsay, G. Sellers, and S. Wargo, analysts; instrumental neutron activation analysis, L. J. Schwarz, analyst.
3. Sr: P-71-55, X-ray spectroscopy, B. McCall, J. Lindsay, G. Sellers, and S. Wargo, and J. S. Wahlberg, analysts. P-71-38, P-71-27, and P-71-18, X-ray spectroscopy, B. McCall, J. Lindsay, G. Sellers, and S. Wargo, analysts.

[5] Numbers in parentheses indicate number of analyses averaged to give cited value.

[6] High-valence cations (excluding Zr and Nb) determined by instrumental neutron activation analysis, L. J. Schwarz, analyst.

[7] Zr and Ni: Emission spectroscopy, E. Silk, analyst.

[8] Nb: Spectrophotometric analysis, E. Campbell, analyst.

[9] Ferromagnesian and rare-earth elements: instrumental neutron activation analysis, L. J. Schwarz, analyst.

[10] Y: Emission spectroscopy, N. Rait, analyst.

DESCRIPTION OF SAMPLES

1. Quartz-feldspar-hornblende metatonalite: Stafford Quadrangle at lat 38°29′12″ N. and long 77°26′26″ W.
2. Chlorite-hornblende-quartz mesocratic tonalite, small intrusion in Garrisonville mafic complex: Stafford Quadrangle at lat 38°29′28″ N. and long 77°26′02″ W.
3. Biotite-quartz granitoid: Storck Quadrangle at lat 38°25′58″ N. and long 77°30′30″ W.
4. Quartz-plagioclase-clinozoisite-chlorite-biotite plagiogranitic metatonalite: Stafford Quadrangle at lat 38°27′21″ N. and long 77°27′08″ W.
5. Plagioclase-quartz-muscovite-chlorite plagiogranitic metatonalite: Chancellorsville Quadrangle at lat 38°21′06″ N. and long 77°38′17″ W.
6. Biotite-muscovite-chlorite-epidote-magnetite plagiogranitic metatonalite: Stafford Quadrangle at lat 38°26′17″ N. and long 77°28′01″ W.
7. Quartz-plagioclase-muscovite-biotite plagiogranitic metatonalite: Richardsville Quadrangle at lat 38°23′54″ N. and long 77°38′05″ W.

has a marked depletion of LREE (Barker and others, 1979, fig. 7).

PLAGIOGRANITIC METATONALITE SUITE

The plagiogranitic rocks of the large intrusion in the Fredericksburg area have SiO_2 contents ranging approximately from 70 to 77 percent. Some of the silica of these rocks may have been introduced during alteration processes, particularly metamorphism. This interpretation may be supported by the nonsystematic variation of scandium with respect to SiO_2 (table 5), which contrasts with the systematic variation of these two components in the trondhjemitic tonalites described.

The plagiogranitic tonalites of the Fredericksburg area are all corundum normative even though they contain < 15 percent Al_2O_3 and in this respect are similar to the earlier described trondhjemitic tonalites of the area. They also contain from 0.20 percent to as much as 2.0 percent K_2O (table 5). However, the samples containing more than 1 percent K_2O also contain the largest amount of metamorphic micas (for example, samples 4, 5, 6, and 7, table 5), suggesting that these higher K_2O values probably result from postemplacement alteration processes. For this reason, samples 1, 2, and 3 (table 5), which contain 0.20–0.38 percent K_2O, may be more representative of the original K_2O content of these rocks. The apparent absence of potassic feldspar in these metatonalites also suggests an original low K_2O content, because this mineral if formed magmatically in tonalites should still be present, even in relict form.

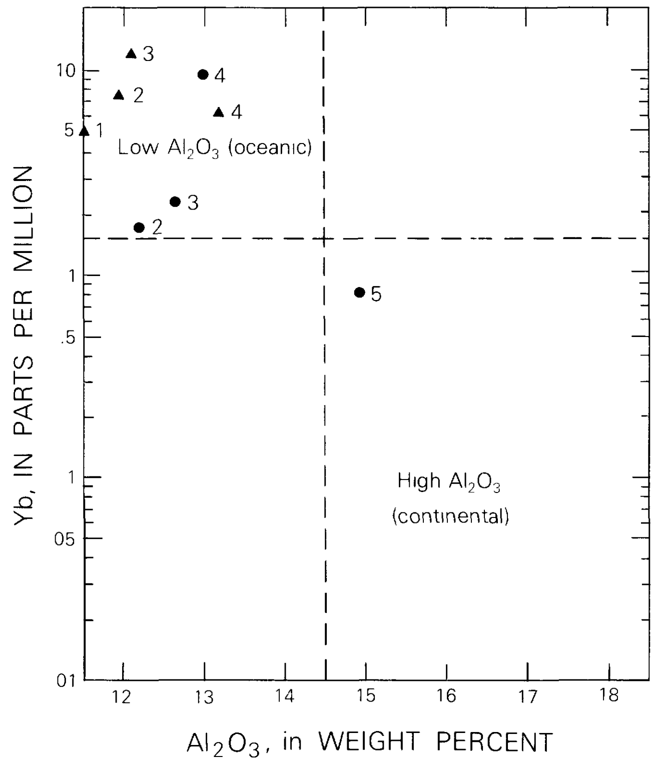


FIGURE 7.—Plot of Al_2O_3 against ytterbium as a discriminant diagram for oceanic in contrast with continental trondhjemite. Rocks of the trondhjemitic metatonalite suite (triangles) and plagiogranitic metatonalite suite (circles) of the Fredericksburg area, with one exception, plot in the oceanic field. Diagram taken from Arth (1979, fig. 2).

The rare-earth elements of the plagiogranitic tonalites (table 5) are plotted in figure 8*B*. Compared with chondrite they have a 15–25 fold enrichment of lanthanum and a 3–11 fold enrichment of lutetium. The plagiogranitic metatonalite REE patterns contrast with the trondhjemitic metatonalite patterns (compare fig. 8*A* with 8*B*) in two important aspects. Rather than the flat patterns of the trondhjemitic rocks with their negative europium anomaly, the plagiogranitic tonalites show a calcalkaline trend that has an enrichment of LREE with respect to the HREE. They also have a positive europium anomaly in contrast to the negative europium anomaly of the trondhjemitic rocks. Oceanic plagiogranites from Cyprus (Coleman and Peterman, 1975, fig. 7) and Oman (Coleman and Donato, 1979, fig. 8) have REE patterns with LREE depletion and negative europium anomalies. The plagiogranitic metatonalites from the Fredericksburg area (fig. 8B), however, have calcalkaline patterns similar to the silicious (> 65 percent SiO_2) trondhjemites from Finland (Arth, 1979, figs. 4, 5), including a positive europium anomaly. Such fractionated REE patterns with positive europium anomalies generally characterize continental trondhjemites, which are also rocks high in Al_2O_3. Thus, although the Fredericksburg area plagiogranitic rocks have REE patterns similar to continental tonalitic rocks, their relatively low Al_2O_3 content resembles oceanic tonalitic rocks. They generally also plot in the oceanic field of trondhjemites on the basis of their ytterbium-Al_2O_3 contents (fig. 7). Possibly they are transitional between oceanic and continental trondhjemitic-plagiogranitic tonalites, because the field boundaries between continental and oceanic types are also transitional, depending on the stage of tectonic development in which they formed (Arth, 1979, p. 125). LREE are reported to be somewhat mobile under certain rock alteration processes (table 1). Alternatively, the REE patterns of the plagiogranitic metatonalites of the Fredericksburg area may have been slightly modified during the shearing and metamorphism these rocks have undergone, which is greater than that present in the younger trondhjemitic metatonalites.

REGIONAL RELATIONSHIPS

The Chopawamsic Formation has been tentatively correlated with the volcanic rocks of the Carolina slate belt (Glover, 1974, p. 757), and Higgins (1972, p. 1020) assigned the volcanic rocks of the Chopawamsic, the James Run, and the Carolina slate belt to the "Atlantic Seaboard volcanic province." Neither the slate-belt correlation nor the Atlantic Seaboard volcanic province assignment are considered appropriate in light of recent work on the Chopawamsic Formation. Figure 9 shows the distribution of the central Virginia volcanic-plutonic belt with respect to other belts of volcanic rocks in the Piedmont.

JAMES RUN FORMATION

The James Run Formation as defined by Higgins (1972) includes a belt of metavolcanic and metavolcaniclastic rocks that are exposed near the Fall Line in the Maryland Piedmont (fig. 9). Higgins (1972) included within the James Run Formation the James Run Gneiss of Southwick and Fisher (1967), as well as felsic rocks considered by others to be intrusive. The Relay Quartz Diorite of Hopson (1964), originally considered a pluton differentiated from Hobson's Baltimore Gabbro and silicified and albitized by its own residual fluids, was reinterpreted (Higgins, 1972, p. 1007) as an assemblage of felsic metavolcanic and metavolcaniclastic rocks. He also suggested (p. 1000–1001) that parts of the Port Deposit Gneiss may be metavolcanic rocks of the James Run Formation, the rest being part of a pluton that intruded its own volcanic pile. Southwick (1979) divided the Port Deposit Gneiss, which he considered polygenetic, into five units, among

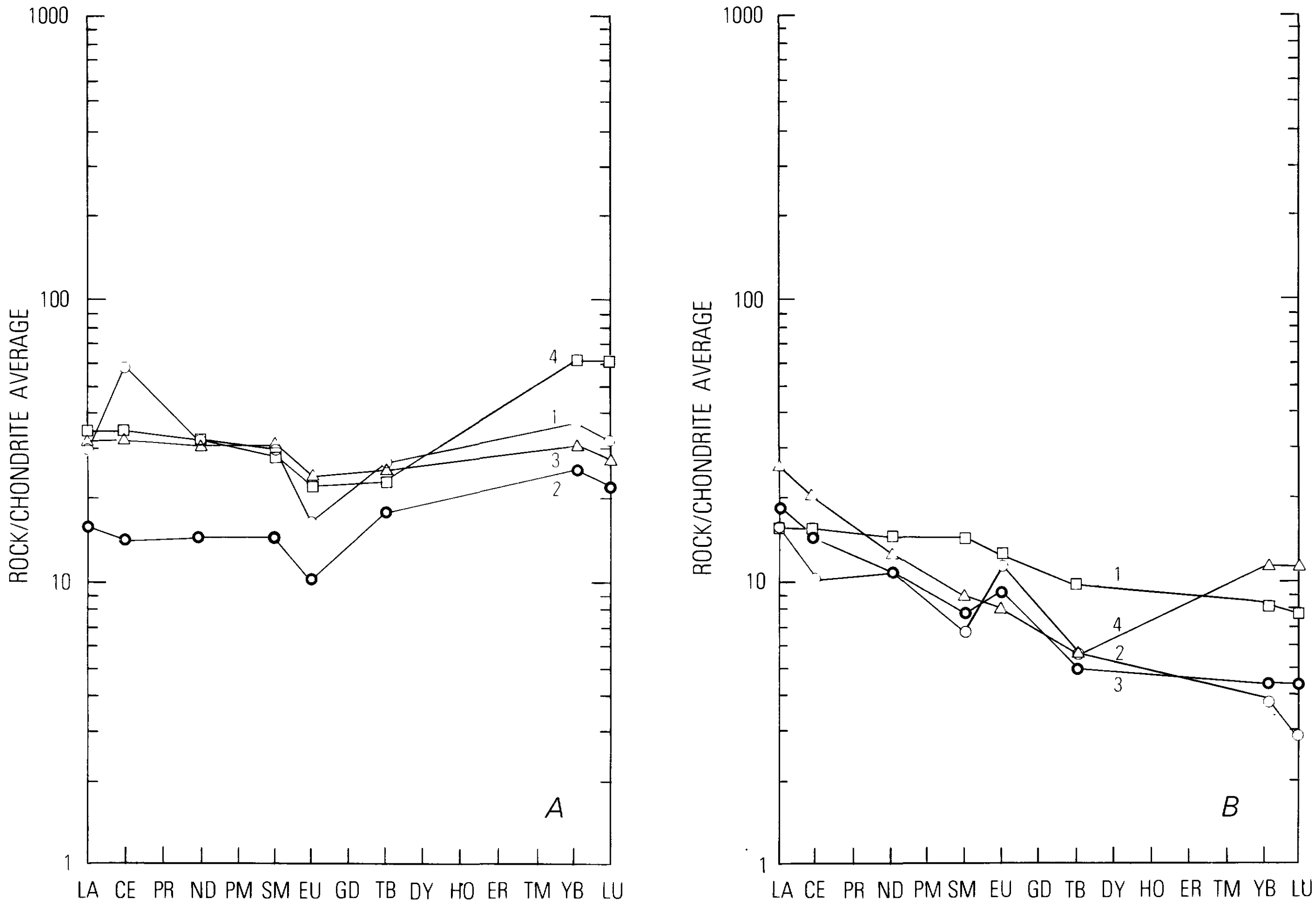


FIGURE 8. – Chondrite-normalized plot of rare-earth elements in metatonalitic rocks of the Fredericksburg area. Data from table 4. *A*, trondhjemitic metatonalite; *B*, plagiogranitic metatonalite.

which are metasedimentary rocks, plutonic rocks in the form of sheets or thick sills, metavolcanic rocks composed of dacite flows and tuff sheets, and a leucocratic quartz augen gneiss interpreted to be a metamorphosed trondhjemitic pluton. Southwick assigned the metadacite and associated metavolcanic rocks to the James Run Formation. The presence of trondhjemitic rocks within the James Run terrane is analogous to the situation in the Chopawamsic terrane of the Fredericksburg area in Virginia.

Crowley (1976) assigned amphibolite and biotite-quartz-plagioclase gneiss within tectonically transported rocks in the Baltimore area to the James Run Formation. He mapped the James Run Formation as conformably overlying amphibolite and ultramafic rocks of his Baltimore Mafic Complex (Crowley, 1976, Geologic Map of Baltimore County and City, in pocket). However, in his more generalized geologic map (Crowley, 1976, plate 2, in pocket), he suggested that the James Run and his Baltimore Mafic Complex may be separated by a thrust fault, the James Run being on the upper plate. The fact that the youngest member of the James Run, Crowley's (1976) Relay Gneiss Member, is juxtaposed against Crowley's Baltimore Mafic Complex further supports the fault interpretation. Crowley divided the James Run of the Baltimore area into three members, the uppermost of which is his Relay Gneiss Member, thereby agreeing with Higgins (1972, 1976) that Hopsons' Relay Quartz Diorite is a metavolcanic rock.

Higgins (1972, p. 1001–1002) originally subdivided the James Run Formation in Cecil County, Md., into four informal units but has subsequently refined the subdivision of the James Run into six formal members and an unnamed member (Higgins, 1977). Three coeval or nearly coeval members occur at the base of the James Run and consist generally of felsic metavolcanic and metavolcaniclastic rocks and subordinate mafic metavolcanic rocks. Locally some of these units grade into probably metasedimentary biotite gneiss. Diamictite is inter-

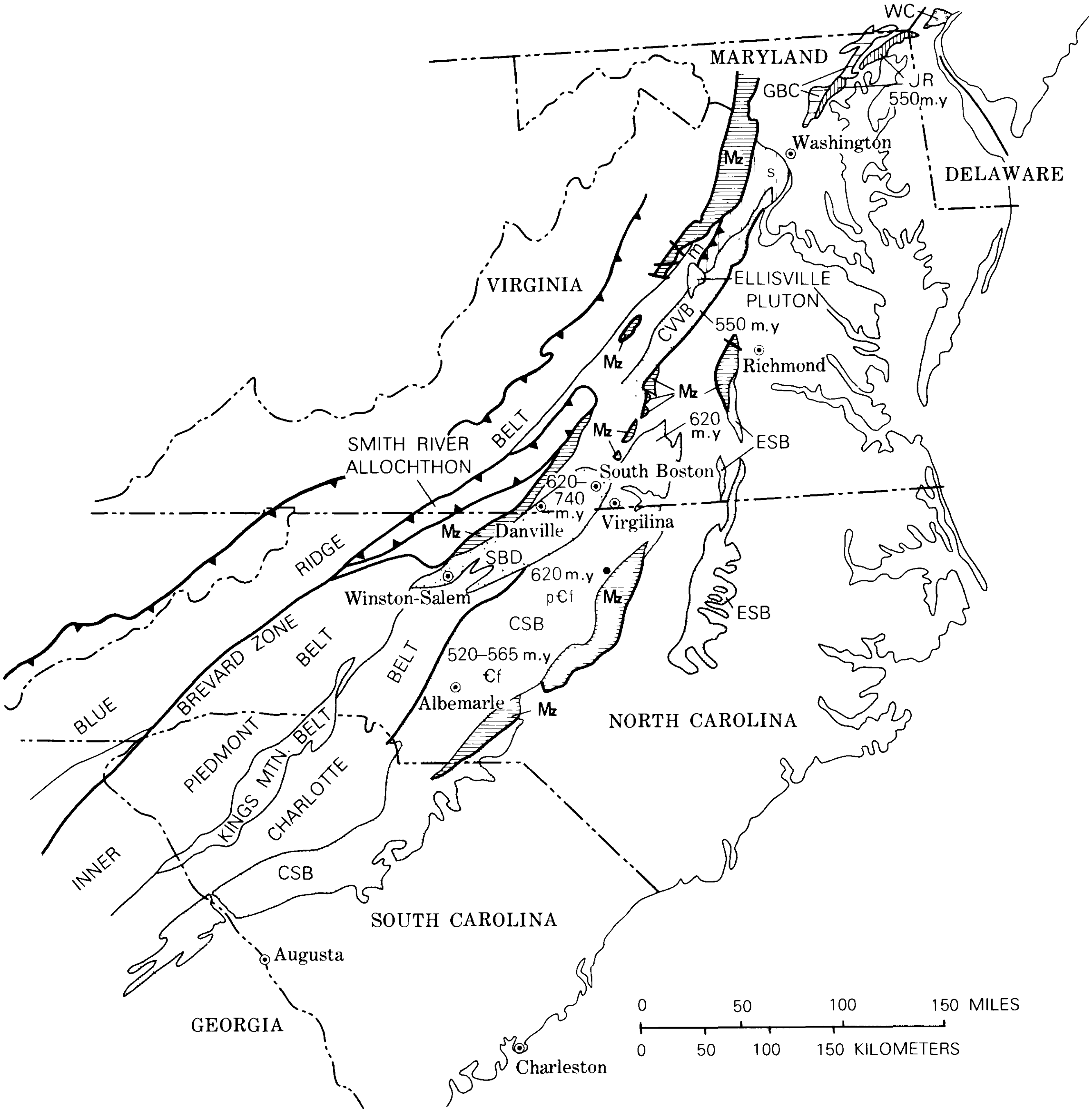


FIGURE 9. – Generalized geologic map of the Piedmont showing the distribution of the Carolina slate belt (CSB), Eastern slate belt (ESB), central Virginia volcanic-plutonic belt (CVVB), South Boston-Danville area (SBD), James Run belt (JR), and Wilmington complex (WC). Also shown are Mesozoic basins (Mz), gabbro of the Baltimore Complex (GBC) of Maryland, melange zone (m), schist beneath the Chopawamsic Formation (s), and other features as identified on the map. Isotopic ages reported for some of these metavolcanic rocks are also shown. Єf and pЄf are the Early Cambrian and Precambrian fossil localities, respectively, from within CSB.

calated with some of the metavolcanic rocks, as also reported by Southwick (1979). The Gilpin Falls Member (Higgins, 1971, p. 322–323) overlies the three basal members of the James Run. It consists of metamorphosed basalt, which in its basal part is characterized by pillow lavas and aquagene tuff. The Gilpin Falls Member is a very distinctive unit that is widely distributed within the James Run terrane of Cecil County, Md. Overlying the Gilpin Falls Member are three other coeval to nearly coeval members containing metamorphosed mafic and felsic rocks that originally were probably volcanic and volcaniclastic accumulations interlayered with sediments. Higgins (1977, p. 126) stated that one of these (Big Elk Creek Member) appears gradational with metagraywackes of the Wissahickon Formation, a relationship that is difficult to understand because it would make one of the upper members of the James Run Formation gradational with the stratigraphically underlying Wissahickon. Structural or stratigraphic complications do not appear to be involved, as the Big Elk Creek Member is shown in its correct stratigraphic order and then in contact with the Wissahickon Formation (Higgins, 1977, fig. 3). The Principio Creek Member above the Gilpins Fall Member is in turn overlain by undescribed "unnamed felsite member." However, the Principio Creek Member is described as underlying pelitic schist of the Wissahickon Formation (Higgins, 1977, p. A127 and fig. 3). Here again an anomalous situation occurs, in that rocks stratigraphically high in the James Run stratigraphic section are reported to underlie the rocks (Wissahickon Formation) that are stratigraphically beneath the James Run. In any event, the James Run Formation of Cecil County appears to be composed of a complex pile of laterally and vertically grading volcanic and volcaniclastic rocks that show marked lithologic changes along strike both locally within Cecil County, as well as regionally with the James Run of the Baltimore area described by Crowley (1976). Of particular interest, however, is the presence of the pillow lavas of the Gilpin Falls Member in Cecil County, described by Higgins as emplaced in water shallower than 0.5 km on the basis of the size and percentage of amygdules in the pillow lavas of this unit (Higgins, 1971). Pillow lavas are not recognized in the James Run Formation from elsewhere in Maryland and are extremely rare in the Chopawamsic Formation of Virginia, being confined to two localities of outcrop size (Pavlides, 1976).

Southwick and Fisher (1967) had originally described rocks of the James Run Formation as the James Run Gneiss, and Southwick (1969) proposed that metavolcanic rocks of the Baltimore area and parts of the Wilmington Complex described by Ward (1959) in Delaware were similar. Later Southwick and others (1971) correlated the James Run areas with the Chopawamsic Formation of Virginia, a correlation also accepted by Higgins (1972).

The correlation between the James Run and the Chopawamsic Formations was based largely on what appeared to be coeval but discordant Cambrian zircon ages. Because of the uncertainties introduced by the debate on the significance of zircon ages in the Piedmont (Higgins and others, 1977) this age correlation is not conclusive. However, the James Run and the Chopawamsic generally occur along strike, albeit in widely separated areas and probably belong to the same tectonic province. They may be coeval and possibly have been essentially coextensive at one time. Alternatively, they may have been parts of different volcanic chains of about the same age and within the same tectonic regime.

CAROLINA SLATE BELT

Correlation of the Carolina slate-belt rocks with what is now defined as the Chopawamsic has been proposed by Glover (1974, p. 757). Stratigraphic comparisons between the two districts, however, are handicapped by the controversies that exist among geologists as to the stratigraphic succession present within the Carolina slate belt. Briggs and others (1978, p. 511) suggested that two separate stratigraphic sequences are within the Carolina slate belt. The oldest of these is the sequence within the Virgilina synclinorium of the Virgilina district (figs. 1, 9), as originally defined by Laney (1917) and somewhat modified by later workers. It consists of, from top to bottom, Laney's Virgilina Greenstone, Aaron Slate, and Hyco Quartz Porphyry. These rocks generally give discordant zircon ages of 740–620 m.y. (Precambrian) and according to Briggs and others (1978, p. 511) are the older of two sequences that once occurred within the Virgilina area of Virginia and North Carolina. The younger sequence is now believed to be represented in the Albemarle area of North Carolina (Glover, 1974; Briggs and others, 1978, p. 511), where tuffaceous rocks determined as younger than 565 m.y. (Early Cambrian) by Fullagar (1971) are present (fig. 9). In the Virgilina area, the Roxboro Granodiorite of Glover and Sinha (1973, p. 242–244), which has discordant zircon ages of about 565 m.y., intrudes folded rocks of the Carolina slate belt and is assumed to be a plutonic root of the younger volcanic sequence, namely the temporal equivalent of the 565 m.y.-old metavolcanic rocks near Albemarle, N.C., that have since been removed by erosion in the Virgilina area. The two fossil localities from within the Carolina slate belt (fig. 9) are also consistent with an Early Cambrian to Late Precambrian age span for these rocks.

The nature of the contact between the Carolina slate-belt rocks in the Virgilina area of Virginia and the higher grade gneisses of the South Boston-Danville area immediately to their west (fig. 9) is also controversial. Laney (1917) considered the contact between these two terranes to be either a fault or an unconformity. Tobisch and Glover (1971) mapped recumbent nappes west of the Carolina slate belt in the South Boston area of Virginia, which they believed were rooted near the Carolina slate-belt contact, and considered the gneisses and schists in the nappes to be more highly metamorphosed equivalents of the Carolina slate belt. Henika (1977) has mapped gneisses and schists in the Danville area of Virginia as a sequence of polydeformed metavolcanic rocks that appear to structurally merge to the east (figs. 1, 9) with the nappes mapped by Tobisch and Glover (1971). Tobisch and Glover (1969) have considered the contact between the upper amphibolite-grade metavolcanic rocks of the nappes in the South Boston area and the greenschist-facies metavolcanic rocks of the Carolina slate-belt volcanic rocks in the Virgilina synclinorium to be essentially a closely compressed metamorphic gradient increasing in grade from east to west. Conley (1978) cited the unpublished data of R. D. Kreisa in the South Boston area of Virginia as supporting conformable contact between the Carolina slate belt and higher grade metavolcanic rocks to the west (gneisses of the nappes of Tobisch and Glover, 1971), which Conley considered to be coeval with the Chopawamsic, with the implication that the 620–740 m.y. zircon ages from the South Boston area of gneiss are anomalous and "might be the product of contamination of younger rocks by older zircons" (Conley, 1978, p. 137). Conley (1978, p. 138, and Explanation, fig. 1) concluded that the slate-belt rocks of the Virgilina synclinorium are younger and stratigraphically overlie the higher grade metavolcanic rocks to their east. On this reasoning, the Chopawamsic Formation, which Conley considered coeval with these amphibolite-grade metavolcanic rocks, is hence considered to be older than the Carolina slate belt.

Obviously many stratigraphic and geochronologic problems remain to be resolved within the slate belt metavolcanic rocks and their presumed equivalents to the west, as well as in the Chopawamsic. However, Pavlides (1976, p. 24) has indicated that despite these problems sufficient stratigraphic, chemical, and geophysical differences exist between the Chopawamsic rocks and the Carolina slate-belt metavolcanic rocks to preclude their having been part of a single volcanic province or even coextensive. The Carolina slate belt has a distinctive stratigraphy at various places along its belt of outcrop. The tripartite stratigraphy for the Carolina slate belt in the Virgilina synclinorium as first established by Laney (1917) and generally adopted and refined by Glover and Sinha (1973) cannot be duplicated anywhere within the Chopawamsic belt.

The chemistry of the volcanic rocks in the Carolina slate belt is different from that of the rocks in the Chopawamsic Formation. Major element chemistry for Carolina slate-belt metavolcanic rocks in the Albemarle area of North Carolina (fig. 9) demonstrates that they are strongly bimodal, about 17 percent mafic, 80 percent felsic, and 3 percent intermediate, as well as being generally calcalkaline (Seiders, 1978b). This is in contrast to the Chopawamsic features described earlier. Whitney and others (1978) also concluded that the metavolcanic rocks of the "Little River Series" of the Carolina slate belt at the Georgia-South Carolina border area are bimodal and predominantly felsic. On the basis of major element chemistry they considered them to be comparable with a tholeiitic island-arc suite. They correlated the "Little River" sequence with the lower part of the metavolcanic sequences in the Albemarle area of North Carolina. The number of presently available chemical analyses from the Chopawamsic is small but contains minor element and REE analyses, which include elements generally stable under metamorphic conditions. In contrast, such stable-element data have not been published as of this writing for Carolina slate-belt rocks. Therefore, the conclusion by Whitney and others (1978) that the major-element chemistry of the "Little River Series" represents primitive island-arc volcanism needs additional verification by stable-element data. The large number of analyses used by Seiders in determining the Peacock index despite the use of mobile elements, makes it statistically reasonable that the Carolina slate-belt sequence near Albemarle is calcalkaline. Although the data have a large scatter, they nonetheless form statistical clusters that permit reasonable graphs to be extrapolated through them (Seiders, 1978b, fig. 8). Hence, the volumetrically predominantly calcalkaline character of the Carolina slate-belt metavolcanic rocks, at least in the Albemarle area, contrasts with the character of the Chopawamsic Formation and the coeval amphibolites of the Ta River Metamorphic Suite described earlier. Laney's Hyco Formation of the Carolina slate belt, or unit II of Glover and Sinha (1973), is also reported as showing evidence of welding in tuffs (Glover and Sinha, 1973, p. 238) that suggests subaerial deposition. Furthermore, Glover and Sinha (1973, p. 239) reported conglomerate beds in their unit III containing volcanic, as well as quartzite, feldspathic quartzite, and, rarely, granite pebbles, suggesting a continental source for these deposits. Such lithologic features have not been recognized in the Chopawamsic.

The Eastern slate belt (fig. 9) is generally considered to be similar to the Carolina slate belt but has not been studied extensively. It is not discussed in this report.

Both the Carolina slate belt and the central Virginia volcanic-plutonic belt are characterized by positive magnetic anomalies. In general, however, the Chopawamsic magnetic signature is characterized by high-amplitude strongly linear patterns, whereas the Carolina slate belt has a broader, less linear, pattern. The Carolina slate belt overlies a large, broad, gravity high, presumably related to mafic rocks at some depth beneath the surface. In contrast, the Chopawamsic belt lacks such a directly related mafic substrate.

The stratigraphic, geochemical, and geophysical contrasts between the central Virginia volcanic-plutonic-belt and the Carolina slate-belt metavolcanic rocks are believed to reflect differences related to their formation in different tectonic belts and settings. The Carolina slate belt is part of the Avalonian province of eastern North America, which is characterized by "relatively undeformed and unmetamorphosed, chiefly terrestrial rocks of mainly late Precambrian age" (Williams, 1978).

ORIGIN AND TECTONIC SETTING OF THE CENTRAL VIRGINIA VOLCANIC-PLUTONIC BELT: DISCUSSION AND CONCLUSIONS

The tectonic setting in which the Chopawamsic Formation and its related rocks formed is difficult to evaluate, as it is in most ancient volcanic terranes. The linearity of the present belt probably reflects to some extent the paleogeographic linearity of the belt of volcanism during the Early Cambrian, at which time the Chopawamsic and associated rocks of the central Virginia volcanic-plutonic belt are believed to have formed, but subsequent tectonism could also account for some of this linearity. Few unequivocal data in the presently exposed metavolcanic rocks of this belt indicate whether these rocks formed subaerially or in water. Pillow lavas are rare and at best indicate local deposition either in lacustrine or marine waters. Ignimbritic tectures, which would suggest subaerial deposition, have not been recognized in this belt. Some of the volcaniclastic rocks were obviously water laid, but again no criteria are available as to whether such deposition was marine or terrestrial. Because the Chopawamsic grades downward into diamictite near Quantico, Va. (Southwick and others, 1971) and because such diamictite has been interpreted as having formed as a submarine slide (Hopson, 1964), it is assumed that the basal Chopawamsic probably formed initially in a marine environment. This interpretation is not inconsistent with the stratigraphic relationships to the southwest in the Fredericksburg area, where the Chopawamsic grades downward into a thick sequence of schist. All in all, however, the field evidence is equivocal as to the precise tectonic regime in which the Chopawamsic and its related rocks formed.

The geochemical features of the rocks of the central Virginia volcanic-plutonic belt in the Fredericksburg area are more indicative of their paleotectonic setting than are the stratigraphic features of these rocks. For example, as described on page A11, suite A of the Chopawamsic Formation has an REE composition (table 2, fig. 4) that is characteristic of tholeiitic island-arc suites (Jakeš and Gill, 1970; Jakeš and White, 1969, 1971, 1972). The closely associated calcalkaline rocks of the Chopawamsic suites B and C under the model of Jakeš and White may represent stratigraphically younger rocks or represent volcanics that formed on the continentward side of an island arc (see also Miyashiro, 1975, p. 185). However, the Chopawamsic tholeiitic and calcalkaline suites do not show a zonation parallel to the length of the volcanic belt, as do most examples cited by Jakeš and White for younger volcanic arcs. Instead, the zonation from a tholeiitic suite to a calcalkaline volcanic suite takes place along the volcanic belt rather than across it in the Fredericksburg area (see figs. 3 and 4 and table 2), comparable with the north to south increase in alkalinity of volcanic rocks in the Lesser Antilles island-arc chain (Arculus and Johnson, 1978, p. 120–121, fig. 3). Indeed, Arculus and Johnson argued that the island-arc tholeiitic-calcalkaline-alkaline zonation across island arcs in which alkalinity increases continentward, as suggested by Jakeš and White (1969, 1972) and Jakeš and Gill (1970), may not be a valid general model. Arculus and Johnson pointed out that the examples cited by Jakeš and his coworkers from Papua, New Guinea, and Vite Levu in the Fiji chain were based on incorrect concepts of the local geology. The geologic relationships in these areas have since been shown to be both different and more complex (Johnson and others, 1978; Gill, 1976a, b) than originally envisioned by Jakeš and his coworkers. Arculus and Johnson (1978) pointed out that the alkalic or shoshonitic volcanism in some of the cited examples of Jakeš and White is generally a late event, unrelated to a trench-subduction-zone process. Furthermore, calcalkaline and tholeiitic volcanic rocks on some volcanic islands, such as Martinique, are intercalated at several stratigraphic levels and do not fit a model of alkalinity increasing with time (Arculus and Johnson, 1978, p. 123). Indeed, Arculus and Johnson emphasized that tholeiitic, calcalkalic, and alkalic volcanism can take place essentially contemporaneously in different provinces of a volcanic terrane. Thus, it is also possible to consider suites A, B, and C of the Chopawamsic Formation as distinct tholeiitic and more alkalic suites that formed more or less contemporaneously but that were derived from chemically different magmas. These differences in source magmas are indicated by the differences in REE patterns (fig. 4) and high-valence cation abundances (table 2) among the three suites. The differences indicated by these elements are considered to be particularly relevant for the metamorphosed volcanic rocks of the Chopawamsic because of the general immobility, particularly of the high-valence cations, during postdepositional alteration. Regardless of the degree of applicability of the model of Jakeš and his coworkers, the geochemical features of the island-arc tholeiite suite seem valid and are found within suite A of the Chopawamsic Formation.

The trondjemitic and plagiogranitic tonalites intrusive into the Chopawamsic are analogous to similar tonalitic rocks in other ancient island arcs, as well as in modern island-arc chains. For example, trondhjemite in the Mule Mountain stock of the West Shasta district, California, intrudes a Devonian island-arc suite (Barker and others, 1979), the Twillingate Trondhjemite intrudes a lower Paleozoic island-arc sequence in northern Newfoundland (Payne and Strong, 1979), and Popilitov and others (1973) reported plagiogranites of batholitic dimensions intruding Cambrian metavolcanic rocks in the Sayan geosyncline of Siberia. Similarly, the Miocene-age rocks of the Izu-Bonin arc in Japan are intruded by low-potash tonalites and trondhjemites of the Tanzawa plutonic complex (Ishizaka and Yanagi, 1977). Additional examples of trondhjemites and related tonalitic rocks intruding Tertiary island-arc-chain volcanic rocks have been reported in the Pacific, such as in the Fiji chain (Band, 1968; Gill and Stork, 1979). Low-potash dacite, the effusive equivalent of trondhjemite, also occurs in the Tonga-Kermadec island-arc chain (Bryan, 1979), on Fiji (Gill and Stork, 1979), and on Saipan in the Marianas (Barker and others, 1969, 1975). Thus, as emphasized by many others, low-potash granitoids such as trondhjemites and plagiogranites are characteristic, although generally minor, rock types in island-arc assemblages.

The eastern temporal equivalent of the Chopawamsic Formation, the Ta River Metamorphic Suite, is less well characterizable by its REE chemical features. However, it has a few amphibolites showing generally primitive patterns and LREE depletion (see fig. 4) suggestive of oceanic tholeiites.

Many discriminant diagrams using immobile elements have been constructed recently to evaluate tectonic setting, principally of basaltic rocks. Some of the discriminant diagrams of Floyd and Winchester (1975, figs. 2, 5) and Pearce and Cann (1973, fig. 3) were used to evaluate the tectonic setting of the amphibolites (generally metabasalts) of the Ta River Metamorphic Suite. Most of the amphibolites of the Ta River plot in the field of oceanic tholeiitic basalt on the Floyd and Winchester diagrams (fig. 10*A*, *B*) and less convincingly within the ocean-floor-basalt field of Pearce and Cann (fig. 10*C*). Except for one analysis, they also plot in the subalkaline-basalt field (fig. 11) on the diagrams of Winchester and Floyd (1977, figs. 2, 4). All these are generally consistent with the proposed model that the Ta River amphibolites are an oceanward facies of the Chopawamsic Formation. (However, the proximity of the amphibolitic Ta River Metamorphic Suite to the lithologically dissimilar Chopawamsic Formation (fig. 3), without an intervening lithologic transition zone, poses a problem in considering these two formations as coeval facies equivalents. Possibly, the Ta River was structurally juxtaposed against the Chopawamsic by northwestward directed thrusting in pre-Quantico Formation time. Such an interpretation would necessitate the additional speculation that the trace of such a thrust is buried beneath the Quantico Formation that now intervenes in a synform between the Chopawamsic and the Ta River.)

Discriminant diagrams purporting to show tectonic setting are as yet not constructed for volcanic suites consisting of felsic rocks, as well as mafic rocks, such as those in the Chopawamsic Formation. However, as indicated earlier, suite A of the Chopawamsic has characteristics of the tholeiitic island-arc suite of Jakeš and Gill (1970), as indicated by some of its chemical features and particularly its REE pattern. The general protolithic character of these metavolcanic rocks of the Chopawamsic is suggested in part by their plot on the composition-field diagram (fig. 12) of Winchester and Floyd (1977, fig. 6). Suites B and C of the Chopawamsic Formation (table 2) plot in the rhyodacite-dacite field, whereas most of the suite A rocks plot as subalkaline basalt, although the SiO_2 content of some of these samples is greater than 53 percent (compare fig. 12 with table 2). The sodic nature of some of the felsic rocks, such as the keratophyres of suite A, poses a problem in the use of diagrams such as figure 12. If keratophyres can be derived from sodic magmas, as suggested by Coleman and Donato (1979, p. 150–151), then figure 12 is not usable for these rocks because it lacks a keratophyre field.

Although the rocks of the central Virginia volcanic-plutonic belt generally have features found in ensimatic island arcs, the possibility that they formed as chains along a continental margin having a thin sialic crust, perhaps as represented by the Po River Metamorphic Suite, cannot be excluded. However, irrespective of the precise tectonic environment within which these volcanic rocks formed, the oceanward side of the chain was apparently to the east.

The presence of a possible tectonic melange zone about 8 km northwest of the Chopawamsic Formation

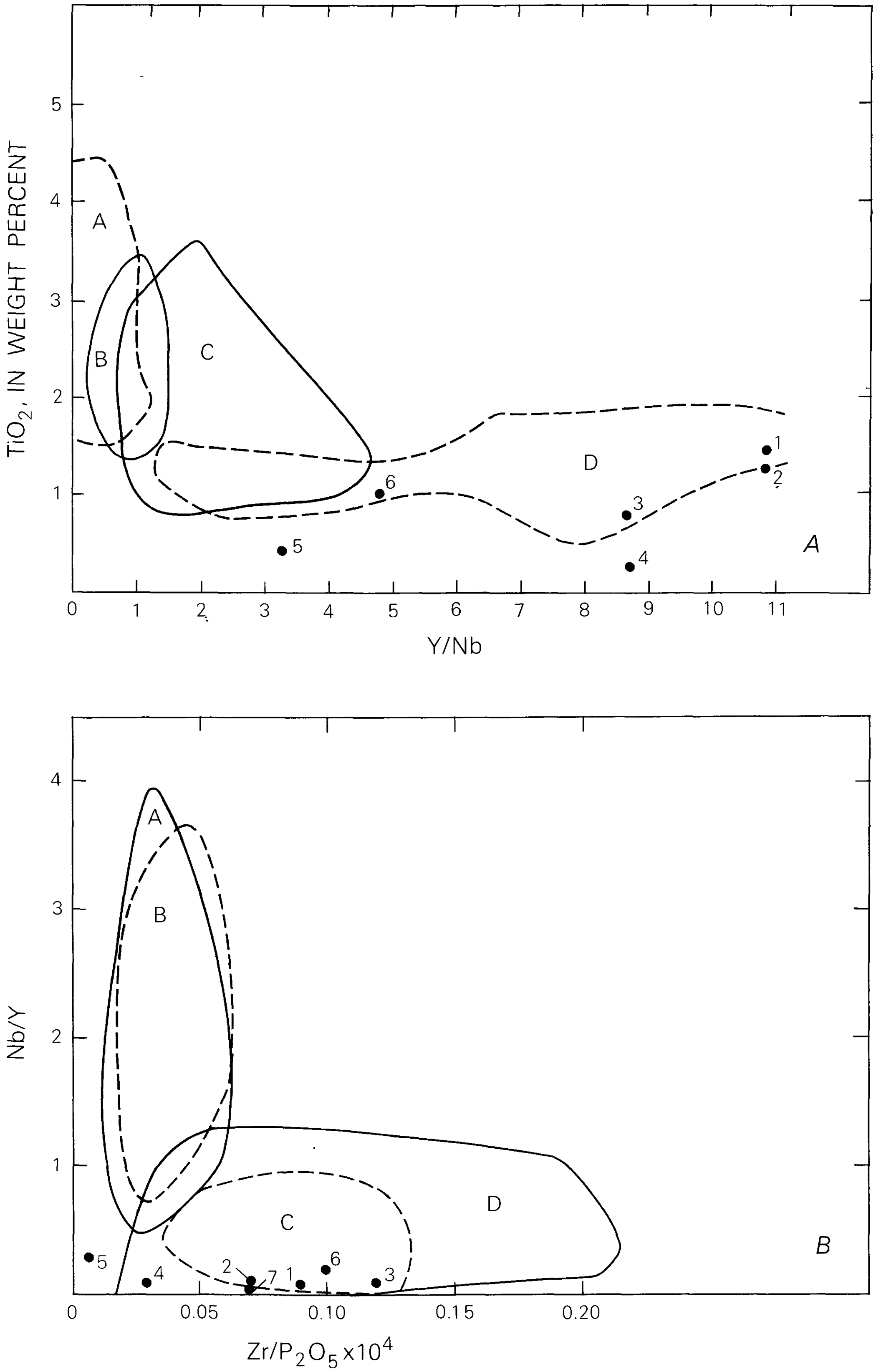


FIGURE 10.—Plot of amphibolites of the Ta River Metamorphic Suite on the discriminant diagrams of (*A*, *B*) Floyd and Winchester (1975, figs. 2, 5) and (*C*) Pearce and Cann (1973, fig. 3). Fields for *A* are **A**, oceanic alkali basalts; **B**, continental alkali basalts; **C**, continental tholeiitic basalts; and **D**, oceanic tholeiitic basalts. Fields for *B* are **A**, continental alkali basalts; **B**, oceanic alkali basalts; **C**, oceanic tholeiitic basalts; and **D**, continental tholeiitic basalts. Fields for *C* are **D**, ocean island or continental basalts; **B**, ocean-floor basalts; **A–B**, low-potassium tholeiites; and **C–B**, calc-alkali basalts. Numbered circles are of samples whose locations are shown on figure 3.

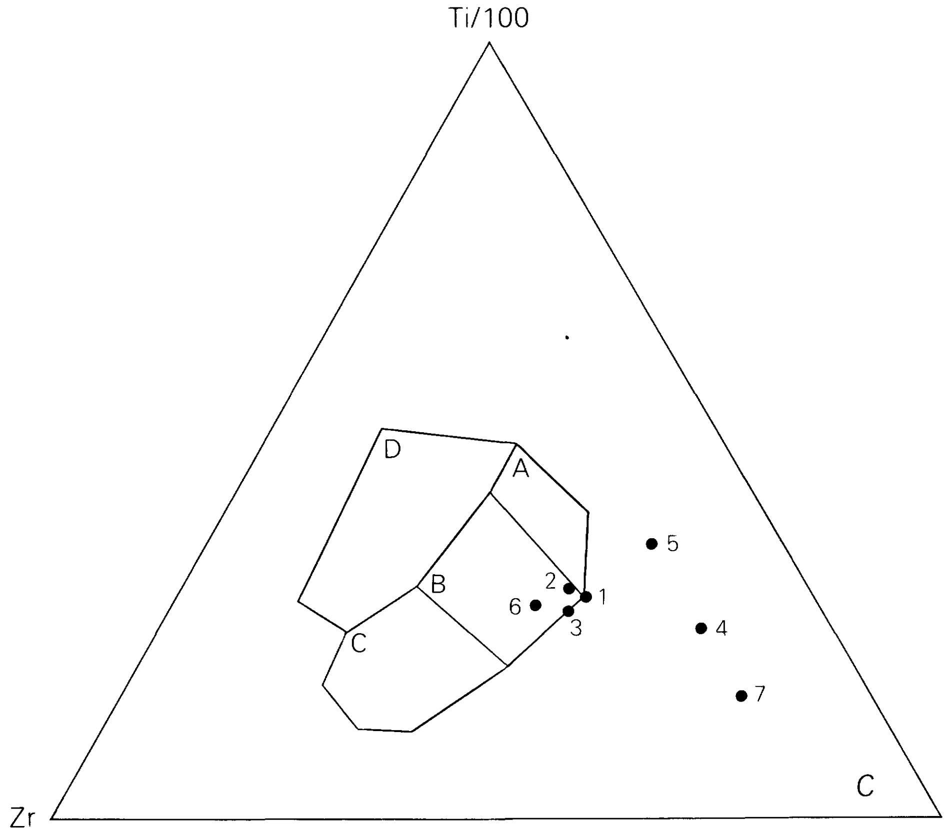


FIGURE 10. – Continued.

(fig. 1) in the Fredericksburg area suggests that the central Virginia volcanic-plutonic belt may be allochthonous and has been transported westward in early Paleozoic time (Pavlides, 1980b). I believe that the hypothesis of a Cambrian island-arc system composed of the central Virginia volcanic-plutonic belt and the James Run terrane of Maryland with a marginal basin on the west side is the model most compatible with the available data discussed in this paper. As stated under the discussion of the James Run Formation, the volcanic belt may not necessarily have had absolute linear continuity with the Virginia belt. Indeed, the proposed Cambrian island arc may have been an outer or even frontal arc system. This speculation finds some support in the nature of the melange northwest of the Chopawamsic Formation. The widely scattered blocks within this melange include serpentinite, metagabbro, metavolcanic rocks, and some metagraywacke and may be remnants of a tectonically disrupted island arc and marginal basin that lay to the west of the Chopawamsic Formation and its associated rocks. Mapping in progress may eventually provide data needed to evaluate this speculation. Brown (1976, p. 142) has described a tectonic melange(?) beneath the Chopawamsic near Shores, Va., along the James River. It may be a southwestward extension of the melange now recognized west of the Chopawamsic belt, which by convergence southeastward now lies beneath the Chopawamsic there. Bland and Brown (1977, p. 121–122) indicated that some of the greenstone blocks of the Shores melange plot as ocean-floor basalts on the titanium-zirconium-yttrium discriminant diagrams of Pearce and Cann (1973) and, also using other criteria, they suggested that the Shores melange may represent a collapsed and eastward subducted back-arc basin. Bland and Brown (1977) also suggested that the Chopawamsic volcanic rocks, which they characterize as calcalkaline there (Arvonia district), may have formed from this eastward subducting slab. I have no evidence with which to evaluate the polarity of a subduction zone, if one existed, with respect to the melange west of the Chopawamsic belt now recognized in northern Virginia. However, on the basis of the geochemical evidence cited that supports a model wherein the Ta River amphibolites are a mafic oceanward facies of the Chopawamsic, it can be assumed that a subduction zone, if present, lay east of this belt of rocks and dipped westward. The

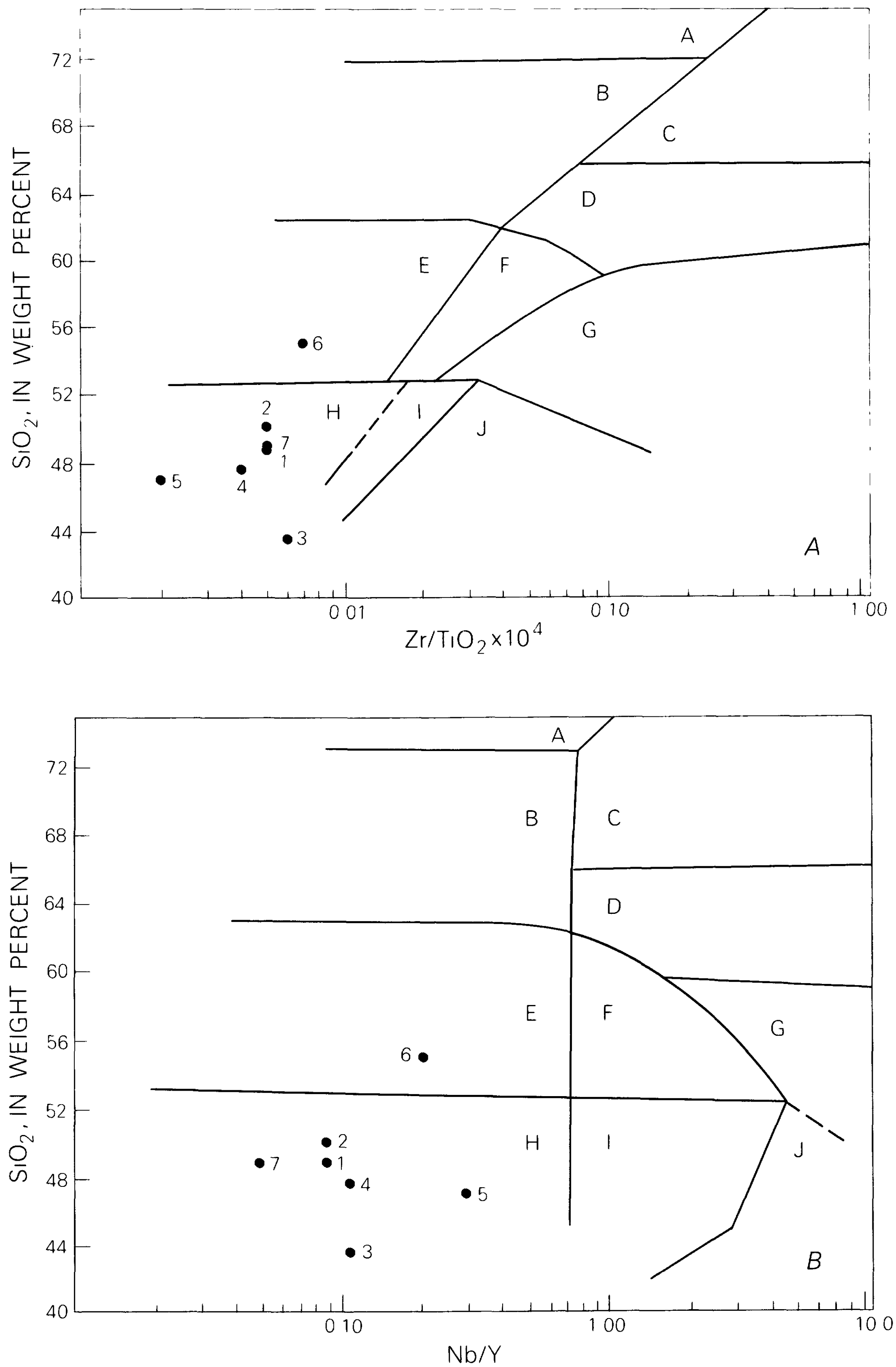


FIGURE 11.–Plot of amphibolites of the Ta River Metamorphic Suite on the discriminant diagrams of Winchester and Floyd (1977, figs. 2, 4). Fields for *A* are A, rhyolite; B, rhyodacite and dacite; C, comendite and pantellerite; D, trachyte; E, andesite; F, trachyandesite; G, phonolite; H, subalkaline basalt; I, alkali basalt; and J, basanite, trachybasanite, and nephelinite. Fields for *B* are A–I, same as for *A*; J, basanite and nephelinite. Numbered circles are of samples whose locations are shown on figure 3.

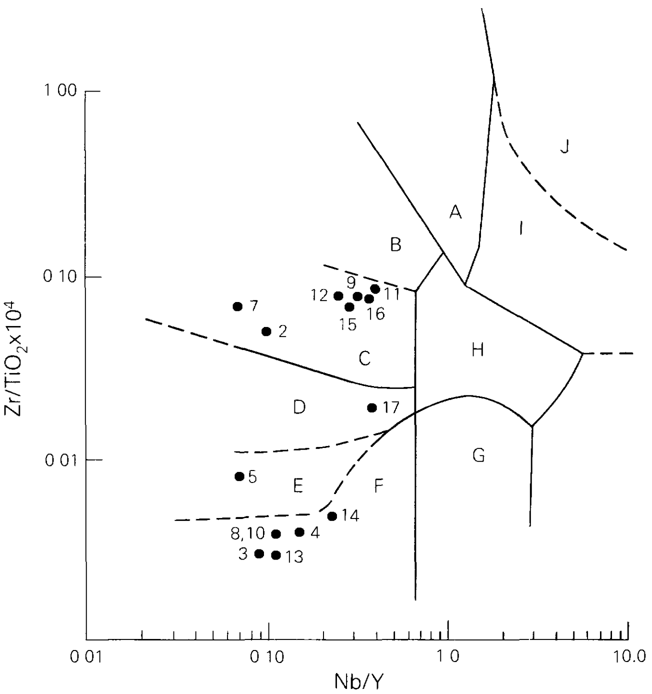


FIGURE 12.–Plot of metavolcanic rocks of the Chopawamsic Formation (table 2) on the composition-field diagram of Winchester and Floyd (1977, fig. 6). Fields are A, comendite and pantellerite; B, rhyolite; C,rhyodacite and dacite; D, andesite; E, andesite and basalt; F, subalkaline basalt; G, alkali basalt; H, trachyandesite; I, trachyte; and J, phonolite. Numbered circles are of samples whose locations are shown on figure 3.

difference in polarity of a subduction zone remains to be resolved between the model of Bland and Brown (1977) and the model suggested in this report.

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