GEOLOGIC MAP OF THE ROBERTSON RIVER IGNEOUS SUITE, BLUE RIDGE PROVINCE, NORTHERN AND CENTRAL VIRGINIA

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INTRODUCTION

The Robertson River Igneous Suite is composed of eight granitic units that are all Late Proterozoic in age and located within the Blue Ridge anticlinorium in northern and central Virginia (Index map). The suite includes a main dike-like batholith, at least two satellitic intrusive bodies, extrusive rhyolite, and numerous petrologically related dikes that intrude rocks of the main batholith and are enclosed within the surrounding Grenville-age (1.0-1.1 Ga) basement. The main batholith forms an elongate, narrow belt encompassing an area of more than 380 km^2 (137 mi^2) stretching from near Ashby Gap in northern Virginia southward nearly 120 km (72 mi) to the vicinity of Charlottesville. As such, the main batholith of the Robertson River Igneous Suite constitutes the largest body of Late Proterozoic anorogenic intrusive rocks in the Appalachian orogen (Bartholomew and Lewis, 1984; Rankin and others, 1990). Emplacement of the suite into Grenville-age orthogneisses and other metamorphic rocks of the Blue Ridge core zone occurred during an extended period of magmatic activity that coincided with the initial stages of the Late Proterozoic rifting of Laurentia (Rankin, 1975; 1976; Tollo and Aleinikoff, 1992).

Granitic rocks of the Robertson River Igneous Suite were originally named and described by Allen (1963), who referred to abundant exposures along the Robinson River (incorrectly designated as the Robertson River on the 1933 edition of the Madison quadrangle (Lukert and Banks, 1984)) in Madison County, Virginia. These and other granitic rocks that were either contiguous in outcrop exposure or could be correlated on a regional basis were later mapped as the Robertson River Pluton or Formation (Lukert and Nuckols, 1976; Lukert and Halladay, 1980; Clarke, 1984). However, Tollo and Arav (1992) proposed the term Robertson River Igneous Suite in order to emphasize the lithologic, petrologic, and geochemical diversity of the formation and Tollo (in press) presented detailed descriptions and nomenclature for the constituent units.

FIELD RELATIONS

Rocks assigned to the Robertson River Igneous Suite display numerous field characteristics that distinguish them from the adjacent basement lithologies. All of the Robertson River lithologic units lack the widespread pervasive foliation that is characteristic of the surrounding orthogneiss terrane of the Blue Ridge anticlinorium. However, localized zones of ductile deformation do occur on a variety of scales throughout most of the constituent units of the suite. Mitra (1979) referred to these features as ductile deformation zones and suggested that they are zones of high strain that developed during Late Paleozoic compression and account for a significant portion of the total shortening within the Blue Ridge core. More recently, Bailey and Simpson (1991) suggested that many fault structures, including numerous ductile features, preserve evidence of Late Proterozoic extension associated with rifting of the Laurentian margin.

Field evidence for the intrusive nature of the Robertson River Igneous Suite into the surrounding gneissic terrane includes: (1) dikes of Robertson River-type granitoid and felsite cutting the gneiss, (2) xenolith zones of gneiss within granitoid, and (3) large inliers of gneiss mapped within the principal outcrop belt of the Robertson River (Lukert and Nuckols, 1976; Lukert and Halladay, 1980; Clarke, 1984; Arav, 1989; Tollo and others, 1991). Furthermore, the exaggerated, elongate shape and general north-northeast alignment of the main body of the Robertson River are characteristics similar to those of numerous dikes of Late Proterozoic age that occur throughout the Blue Ridge province. Bartholomew (1992) suggested that this similarity indicates that the Robertson River Igneous Suite was emplaced as a large dike-like mass within an existing extensional environment.

LITHOLOGIC UNITS

The results of detailed field mapping, petrographic studies, and both geochemical and isotopic analyses indicate that the Robertson River Igneous Suite can be subdivided into eight major lithologic units (see descriptions below). These units can be distinguished on the basis of a variety of field and petrochemical criteria including: (1) rock type, (2) texture, (3) mineral assemblage, (4) bulk composition, and (5) inferred petrogenesis (table 1). Intrusive rocks are dominant; however, both subvolcanic felsite (term used herein to describe light-colored, fine-grained rocks that are not clearly extrusive in origin) and rhyolite occur associated with and are mapped as part of the Battle Mountain Alkali Feldspar Granite. The intrusive rock types of the Robertson River Igneous Suite range from granite to alkali feldspar granite to alkali feldspar syenite (figs. 1-8) and commonly display evidence of relatively high levels of emplacement including porphyritic textures, miarolitic cavities, and pegmatites. The subvolcanic rocks are exclusively rhyolitic and exhibit features including lithophysae and flow banding. The demonstrably extrusive rhyolites include both ash and volcaniclastic deposits. Most lithologic units display considerable variation and, as a result, the area assigned to each unit on the map includes all exposures that can be correlated on a lithologic basis with one of the designated type localities (table 2).

Manuscript approved for publication March 30, 1993.
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Table 1—Field and petrographic characteristics of the Robertson River Igneous Suite

Lithologic unit	Rock type	Texture; Grain size	Kspar:plag ratio	Ferromagnesian phase(s)	Distinguishing characteristics
Battle Mountain	Rhyolite	Porphyritic; very fine to aphanitic	Undeterminable	Biotite(?)	Rare euhedral phenocrysts Abundance of fluorite Volcaniclastic fabric
	Felsite	Allotriomorphic; fine	10:1 to >15(?):1	Aegirine	Fine grain size; local flow banding
	Alkali feldspar granite	Inequigranular; medium	10:1 to >15:1	Aegirine	Low color index; abundance of fluorite
Amissville	Alkali feldspar granite	Porphyritic; medium	9:1 to 20:1	Riebeckite, aegirine	Ferromagnesian assemblage; quartz phenocrysts
Hitt Mountain	Alkali feldspar syenite	Inequigranular; medium to coarse	6:1 to >100:1	Amphibole	Low quartz content; prominent amphiboles
Cobbler Mountain	Alkali feldspar quartz syenite	Porphyritic; medium	8:1 to 10:1	Amphibole, rare pyroxene	Mesoperthite phenocrysts; low quartz content
White Oak	Alkali feldspar granite	Inequigranular; coarse and fine	8:1 to >100:1	Amphibole	Associated coarse- and fine-grain types; abundant prismatic amphibole
Arrington Mountain	Alkali feldspar granite	Equigranular; medium	4:1 to 40:1	Amphibole	Eu- to subhedral mesoperthite; equigranular texture
Laurel Mills	Granite	Inequigranular; coarse	1:1 to 4:1	Amphibole	Coarse grain size; coarse plagioclase
Rivanna	Alkali feldspar granite and granite	Equigranular; medium	3:1 to 10:1	Biotite, muscovite	Low color index; locally abundant fluorite

In the lithologic descriptions presented below and on the map, the alpha-numeric symbol given in parentheses following geographic localities refers to the horizontal (letters) and vertical (numbers) coordinate grid on the map. Names of the quadrangles (all U.S. Geological Survey 7.5-minute series) are given on the accompanying regional geology and quadrangle location map. The lithologic units are discussed below in order of decreasing age, as determined by U-Pb isotopic analysis of zircons collected from representative samples of each (Tollo and Aleinikoff, 1992; unpub. data).

Rivanna Granite

The distinctive Rivanna Granite (Zrr) is one of the more disjointed units in the Robertson River Igneous Suite. These rocks are restricted to several relatively small areas of exposure on the northeastern flank of Hitt Mountain (E4), the western edge of Arrington Mountain (F3) (too small to show at this map scale), a larger area north of Brightwood (F4), and a linear belt 8 km (4.8 mi) in length at the southernmost tip of the main batholith (H2–I2). Although relatively poorly exposed, the Rivanna Granite can be readily distinguished from other Robertson River units by its characteristically low color index (average is less than 5) and prominent clusters of well-defined biotite crystals.

In the field, the Rivanna is a white, medium-grained, equigranular alkali feldspar granite to granite (fig. 1) composed of light gray quartz, nearly inconspicuous plagioclase, perthitic alkali feldspar, and small clots of fine- to medium-grained, subhedral biotite. Most exposures of the Rivanna display abundant fluorite that is closely intergrown with the biotite clusters. Additionally, very careful examination of the biotite clusters will often reveal the presence of muscovite. Some Rivanna exposures display abundant, fine-scale, sinuous ductile deformation zones. At Reference Locality 1 (I2), the Rivanna contains miarolitic cavities (filled with quartz and pyrite) which are indicative of a relatively high level of emplacement. Also exposed at this locality are several large, garnet-bearing schistose xenoliths probably derived from the Grenvillian country rocks.

In thin section, the Rivanna displays a medium-grained, hypidiomorphic granular texture similar to that of the Arrington Mountain Alkali Feldspar Granite. Prominent mineral phases include medium-grained, anhedral quartz displaying undulatory extinction and metamorphic recrystallization textures; fine- to medium-grained, subhedral plagioclase; medium- to coarse-grained, anhedral to subhedral microcline-microperthite; and fine-grained, sub-

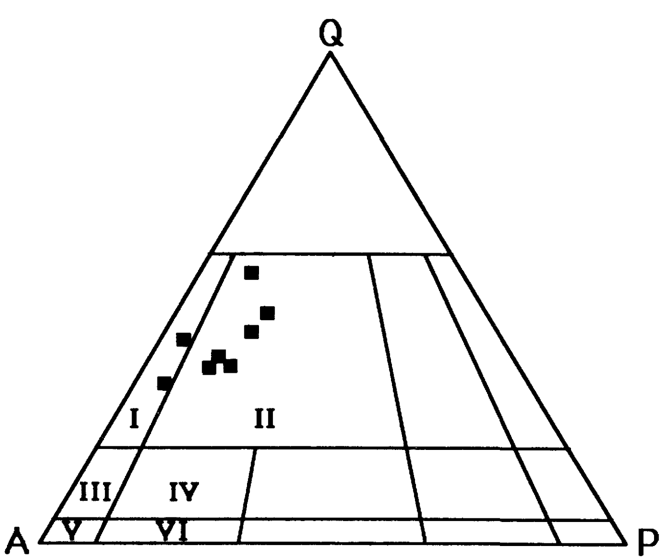

Figure 1.—Plot of modal quartz (Q), alkali feldspar (A), and plagioclase (P) for the Rivana Granite. Number of analyses = 8. Field labels include: I, alkali feldspar granite; II, granite; III alkali feldspar quartz syenite; IV, quartz syenite; V, alkali feldspar syenite; VI, syenite (after Le Maitre and others, 1989).

Table 2.—Lithologic type localities of the Robertson River Igneous Suite

Amissville Alkali Feldspar Granite: Massies Corner 7.5-minute quadrangle. Roadcut on US Highway 211 at intersection with Virginia Highway 640, 4.3 km (2.7 mi) west of Amissville. Light-gray, medium-grained, porphyritic aegirine + reibeckite-bearing alkali feldspar granite.

Arrington Mountain Alkali Feldspar Granite: Brightwood 7.5-minute quadrangle. Large outcrop on west side of southernmost crest of Arrington Mountain adjacent to trail from Virginia Highway 603. Gray, medium-grained, equigranular biotite-bearing alkali feldspar granite.

Battle Mountain Alkali Feldspar Granite: Massies Corner 7.5-minute quadrangle. Roadcut on north side of Virginia Highway 729, located 0.55 km (0.35 mi) east of intersection with Virginia Highway 618. Blue-gray, aphyric and weakly flow banded, aegirine-bearing felsite in contact with blue-gray, medium-grained, aegirine-bearing alkali feldspar granite. Castleton 7.5-minute quadrangle (Reference Locality 14 (E5)). Abandoned quarry (and immediate vicinity) on north side of Virginia Highway 615, located 2.7 km (1.6 mi) south of intersection with Virginia Highway 617 Light gray, aphanitic to sparsely porphyritic (feldspar phenocrysts), volcaniclastic rhyolite.

Cobbler Mountain Alkali Feldspar Quartz Syenite: Upperville 7.5-minute quadrangle. Roadcut on north side of Virginia Highway 55, 1.4 km (0.9 mi) west of intersection with US Highway 17. Dark gray, medium-grained alkali feldspar quartz syenite.

Hitt Mountain Alkali Feldspar Syenite: Brightwood 7.5-minute quadrangle. Series of small outcrops on southwest slope of Hitt Mountain west of Virginia Highway 607 approximately 1.4 km (0.9 mi) northeast of intersection of Virginia Highways 607 and 606. Light gray, coarse-grained, amphibole-bearing alkali feldspar syenite locally intruding darker gray, fine-grained, amphibole-bearing alkali feldspar syenite.

Laurel Mills Granite: Massies Corner 7.5-minute quadrangle. Roadcut on Virginia Highway 618, approximately 1.4 km (0.9 mi) south-southwest of Laurel Mills. Gray, coarse-grained, amphibole-bearing granite.

Rivanna Granite: Charlottesville East 7.5-minute quadrangle. Exposures on south side of spillway north of filtration plant on South Fork of Rivanna River. White, medium-grained, fluorite-bearing granite.

White Oak Alkali Feldspar Granite: Brightwood 7.5-minute quadrangle. Large roadcut on east side of Virginia Highway 638 approximately 0.24 km (0.15 mi) northeast of bridge crossing the Robinson River, 0.6 km (0.4 mi) northeast of confluence of Glebe Run and White Oak Run. White to light gray, coarse-grained, amphibole-bearing alkali feldspar granite closely associated with light gray, fine-grained, amphibole-bearing alkali feldspar granite.

hedral biotite (X=pale yellow-brown; Y=Z=light green-brown) occurring in clusters with fine-grained, subhedral muscovite and containing abundant inclusions of zircon. Accessory phases include metamict allanite rimmed by epidote; fine- to medium-grained, anhedral fluorite; fibrous orange-brown stilpnomelane; and fine-grained, anhedral zircon.

Although the Rivanna typically contains two micas, the unit is characterized by a metaluminous bulk composition and, as a result, the muscovite is interpreted as secondary in origin. In terms of major element composition and relative to the rest of the suite, the Rivanna displays high SiO_2 (average is 77.8 weight percent (wt pct)), low Al_2O_3 (12.1 wt pct), and low total alkalies (8.3 wt pct). Trace element contents in the Rivanna are elevated for Th and average for Nb, Zn, Ga, and Ce. The Ga/Al values of the Rivanna Granite (average is 4.8) are comparable to those of the other metaluminous units of the Robertson River Igneous Suite.

Laurel Mills Granite

The Laurel Mills Granite (Zrl) is exposed continuously along the western edge of the Robertson River outcrop belt for 35 km (21 mi) from the vicinity of Goose Creek (B6) southward to near Castleton (E5). Throughout this area of exposure, the Laurel Mills is in contact with numerous gneissic rocks to the west and with various units of the Robertson River Igneous Suite including the Battle Mountain Alkali Feldspar Granite, Amissville Alkali Feldspar Granite, and Cobbler Mountain Alkali Feldspar Quartz Syenite to the east. An inlier of gneiss (Yg) separates the Laurel Mills from the Cobbler Mountain unit for 17 km (10 mi) from near the Rappahannock River (C5) northward to the vicinity of Delaplane (B6). Contact relations are obscured by poor exposure throughout this area; nevertheless, the relative ages of the different lithologic units are apparent from cross-cutting relations. The Laurel Mills includes several small inliers of gneiss near Cresthill (C5) and Hume (C6) (Arav, 1989) and also south of the Rappahannock River (Lukert and Halladay, 1980). Dikes of Laurel Mills intrude the large inlier south of Delaplane (B6). A dike of amphibole-bearing felsite of the Battle Mountain unit intrudes the Laurel Mills Granite at Reference Locality 2 (D5) and a dike of Cobbler Mountain Alkali Feldspar Quartz Syenite intrudes the Laurel Mills at Reference Locality 3 (B6). Farther to the south near Novum (F4), a small area of Laurel Mills occurs along the western edge of the Robertson River outcrop belt. The Laurel Mills in this area is in contact with gneiss on both the west (country rock) and east (inlier) and with Arrington Mountain Alkali Feldspar Granite and Hitt Mountain Alkali Feldspar Syenite to the south. A dike of Hitt Mountain Alkali Syenite intrudes the Laurel Mills at Reference Locality 4 (F4). Laurel Mills Granite also occurs as a small body in contact with basement gneiss and both the Hitt Mountain and Arrington Mountain units along the western edge of the Robertson River outcrop belt near Haywood (F3) and as a small, isolated body located west of the Robertson River batholith at Naked Mountain (B6) northeast of

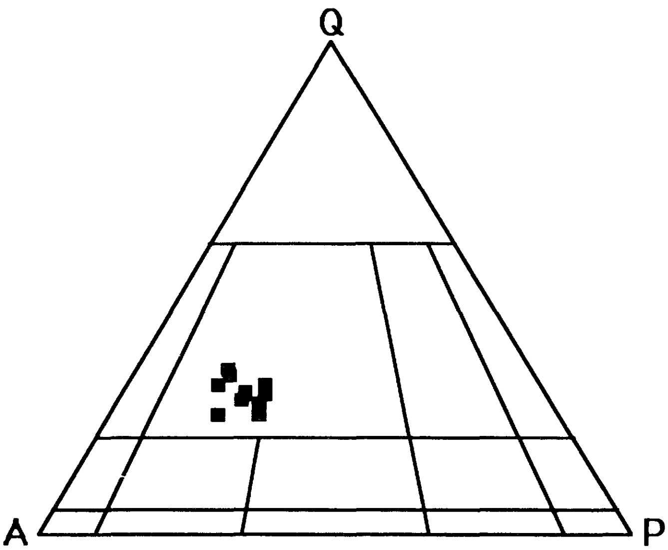

Figure 2.—Plot of modal quartz (Q), alkali feldspar (A), and plagioclase (P) for the Laurel Mills Granite. Number of analyses = 10. See figure 1 caption for field labels.

Markham. Throughout most of its area of exposure, the Laurel Mills can be readily distinguished from the other lithologic units of the Robertson River Igneous Suite based on the (1) ubiquitous coarse grain size and inequigranular texture, (2) subequal amounts of coarse-grained alkali feldspar and plagioclase, (3) prominent coarse-grained amphibole, (4) abundant, locally pale blue quartz, and (5) lack of fluorite.

In the field, the Laurel Mills is a gray, coarse-grained, inequigranular granite (fig. 2) composed of gray, alkali feldspar mesoperthite; pale green plagioclase; pale blue-gray quartz; locally prominent, dark green to black amphibole; and rare allanite. The amphibole is typically partially to entirely replaced by intergrowths of fine-grained quartz + magnetite + stilpnomelane. Many Laurel Mills outcrops display evidence of deformation along sinuous, anastomosing zones ranging from microscopic to tens of meters in scale. Throughout its area of exposure, the Laurel Mills is cut by numerous greenstone dikes; however, unlike most of the other lithologic units of the Robertson River Igneous Suite, the Laurel Mills is not intruded by finer grained dikes of similar mineralogic and geochemical composition.

The Laurel Mills is characterized in thin section by an overall coarse-grained, inequigranular texture. Major mineral phases include coarse-grained, euhedral to subhedral alkali feldspar mesoperthite; medium-grained, euhedral to subhedral plagioclase containing abundant inclusions of euhedral zoisite; medium- to coarse-grained, anhedral quartz; and medium- to coarse-grained, subhedral to anhedral amphibole (X=yellow tan, Y=pale green, Z=dark green) that is typically partially to entirely replaced by intergrowths of fine-grained quartz + magnetite + brown biotite + stilpnomelane ± titanite. The average alkali feldspar:plagioclase ratio is 3:1. Accessory phases include fine-grained zircon; apatite; ilmenite; magnetite; brown allanite (locally rimmed by pale green epidote); fine-grained, orange-brown stilpnomelane; brown biotite; and titanite. The stilpnomelane + biotite + titanite assemblage is interpreted to be a product of retrograde metamorphism. The Laurel Mills is the only widespread, amphibole-bearing unit within the Robertson River Igneous Suite with subequal amounts of primary alkali feldspar and plagioclase, as well as the only lithologic unit in the suite without fluorite.

Compositionally, the Laurel Mills is the most homogeneous of any of the units in the suite. Metaluminous in composition, this unit is characterized by major element concentrations that, with the exception of CaO, are comparable to the averages for the suite. Compared to other units of the suite, the Laurel Mills is characterized by high concentrations of Ba (average is 505 parts per million (ppm)) and Sr (83 ppm) and low values for Nb (50 ppm), Ta (2 ppm), Zr (465 ppm), and Ga (31 ppm). Furthermore, Ga/Al ratios for the Laurel Mills (average is 4.2) are typically among the lowest of the suite.

Arrington Mountain Alkali Feldspar Granite

The Arrington Mountain Alkali Feldspar Granite (Zram) is exposed discontinuously in relatively small, irregularly-shaped bodies for 23 km (14 mi) from near the Hazel River in the central portion of the Robertson River outcrop belt (E5) southward to Haywood (F3). Throughout most of this area, the Arrington Mountain is in close contact with the Hitt Mountain Alkali Feldspar Syenite, Laurel Mills Granite, and the Battle Mountain Alkali Feldspar Granite. Although the Arrington Mountain is readily distinguished from rocks of the Battle Mountain and Hitt Mountain lithologic units, differentiating between the Arrington Mountain and the surrounding Laurel Mills Granite can be complicated by the superficial similarity of these two units. However, the medium-grained, equigranular texture, low color index (average is 8.5), and extreme paucity of plagioclase (average alkali feldspar:plagioclase ratio is 19:1) of the Arrington Mountain are effective criteria for making this distinction. West and south of Castleton (E5), the Arrington Mountain is in fault contact on the west with conglomerate and coarse-grained arkose of the main outcrop belt of the Mechum River Formation (Mitra and Lukert, 1982). The presence of abundant, boulder-sized clasts of Arrington Mountain composition in the lowermost beds of the conglomerate in a small inlier located south of Castleton indicates that the Mechum River Formation is significantly younger than the Arrington Mountain and suggests that the contact in this area represents a nonconformity (Hutson, 1992).

In the field, the Arrington Mountain is a light gray, medium-grained, equigranular alkali feldspar granite (fig. 3) composed of light blue-gray quartz, perthitic alkali feldspar, and rare ferromagnesian phases. In most Arrington Mountain exposures, the primary amphibole has been replaced by irregular intergrowths of biotite ± magnetite ± quartz. Additionally, some localities contain visible allanite and fluorite. Although the majority of Arrington Mountain exposures are relatively undeformed, those located between Castleton (E5) and the Hazel River (E4) are demonstrably sheared—locally to the point of being nearly unidentifiable. Farther to the south, the intrusive relationship of the Arrington Mountain with adjacent Grenvillian(?) country rocks can be seen clearly in a shatter zone at Reference Locality 5 (F4) where the Arrington Mountain forcibly intruded foliated, biotite-bearing gneiss. A final noteworthy field characteristic of the Arrington Mountain is the local abundance of fine-grained dikes cutting this unit. Although not ubiquitous, these dikes are common throughout the Arrington Mountain outcrop area. Most of the dikes are clinopyroxene- or amphibole-bearing felsite; however, some are petrographically identical and geochemically very similar to the coarser Arrington Mountain.

In thin section, the Arrington Mountain displays a medium-grained, hypidiomorphic granular texture. Prominent phases include medium-grained, anhedral quartz showing undulatory extinction and recrystallization textures; medium-grained, subhedral microcline-microperthite; and fine-grained, anhedral amphibole (X=pale yellow-brown; Y=dark green; Z=green-blue) commonly replaced by quartz ± Fe-Ti oxides ± fine-grained, anhedral to subhedral, brown biotite. Accessory phases include fine-grained, subhedral plagioclase locally replaced by epidote ± zoisite; stilpnomelane occurring in clusters with biotite and amphibole; subhedral to euhedral, zoned, orange-brown allanite; fluorite; fine-grained, subhedral zircon with rare prismatic inclusions; discrete crystals of epidote closely associated with the ferromagnesian phases; and veinlets of muscovite developed within the alkali feldspars. Apatite, garnet, and secondary amphibole have also been identified in some Arrington Mountain samples.

Geochemically, the Arrington Mountain is characterized by a borderline metaluminous/peraluminous composition and, relative to the other units of the Robertson River Igneous Suite, displays high SiO_2 (average is 76.1 wt pct), low Al_2O_3 (12.4 wt pct), and low total alkali (average Na_2O+K_2O = 8.9 wt pct) contents. In terms of trace element concentrations and relative to the other units in the suite, the Arrington Mountain displays elevated values for Y (average is 107 ppm); average values for Th (21 ppm), Zr (495 ppm), Nb (89 ppm), and Ce (228 ppm); and low values for Zn (169 ppm). The Ga/Al ratio (average is 4.4) is somewhat low compared to the rest of the suite.

White Oak Alkali Feldspar Granite

The White Oak Alkali Feldspar Granite (Zrw) is exposed both in a narrow belt extending 13 km (7.8 mi) along the eastern edge in the southern third of the main Robertson River batholith (G3) and in a small area along the Robinson River in the central section of the outcrop belt (F3–F4). Throughout this area, the White Oak Alkali Feldspar Granite is commonly in contact with the Hitt Mountain Alkali Feldspar Syenite. Although the exposures of the White Oak along the Robinson River are unquestionably granitic in composition, in the narrow belt farther to the south the White Oak

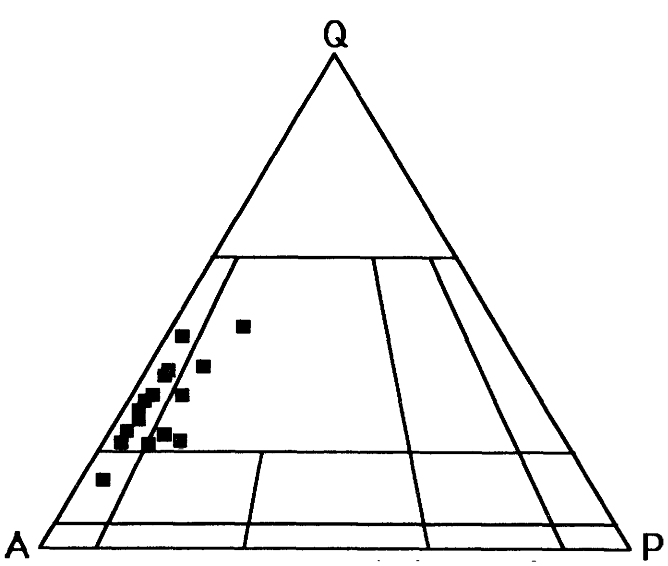

Figure 3.—Plot of modal quartz (Q), alkali feldspar (A), and plagioclase (P) for the Arrington Mountain Alkali Feldspar Granite. Number of analyses = 17. See figure 1 caption for field labels.

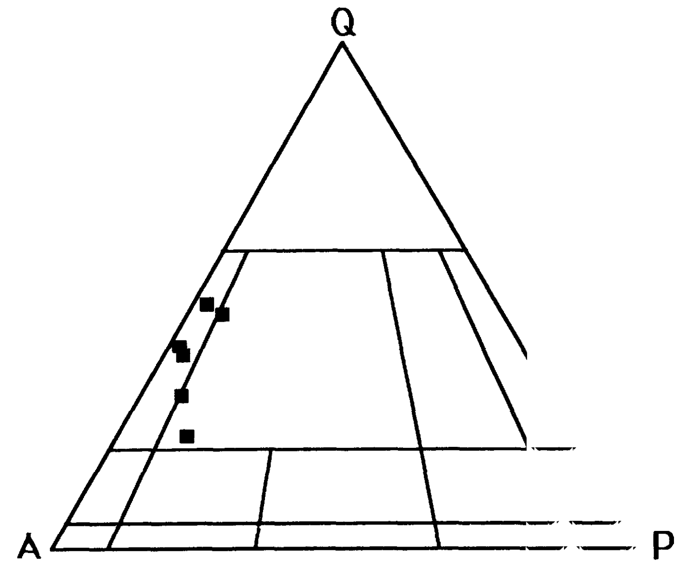

Figure 4.—Plot of modal quartz (Q), alkali feldspar (A), and plagioclase (P) for the White Oak Alkali Feldspar Granite. Number of analyses = 6. See figure 1 caption for field labels.

exhibits more of a gradational contact (marked by decreasing quartz content) with the Hitt Mountain lithologic unit, making it difficult to distinguish these two units in the field. Most exposures of the White Oak exhibit an overall glassy appearance (a possible manifestation of silicification), contain amphiboles that lack oxidized cores, and have abundant quartz, characteristics that are most effective in identifying this unit.

In the field, the White Oak is a light gray to gray, coarse-grained, inequigranular amphibole-bearing alkali feldspar granite (fig. 4) containing light gray quartz, vitreous feldspar, and irregular patches of amphibole. Most exposures of the White Oak appear to be exceedingly fresh, locally to the point that the feldspars are superficially nearly indistinguishable from the quartz. However, many exposures show evidence of hydrothermal alteration in the form of fine, prismatic, secondary amphibole occurring both throughout the rock and as concentrations along joint surfaces. Although most White Oak outcrops appear to be relatively undeformed, some exposures, especially those that are near contacts with the Grenvillian country rocks, show prominent amphibole-defined lineation and rare foliation. An important field characteristic of the White Oak is the widespread occurrence of closely associated, fine-grained, mineralogically identical alkali feldspar granite. Unlike the fine-grained dikes and enclaves of the Hitt Mountain Alkali Feldspar Syenite (described later), the fine-grained White Oak is commonly nearly indistinguishably intermixed with the coarser grained variety. However, as observed in variably defined dikes, the fine-grained variety of the White Oak locally intruded the coarse-grained, defining a relationship that is common throughout most units of the Robertson River Igneous Suite.

Petrographically, the White Oak displays a coarse-grained, hypidiomorphic, inequigranular texture similar to that of the Laurel Mills Granite. In thin section, the White Oak is characterized by medium- to coarse-grained, anhedral quartz; fine-grained, anhedral to subhedral plagioclase; medium-grained, anhedral microcline-microperthite; and medium-grained, anhedral to subhedral amphibole (X=pale yellow-green; Y=dark green; Z=green-blue). Accessory phases include subhedral, metamict allanite

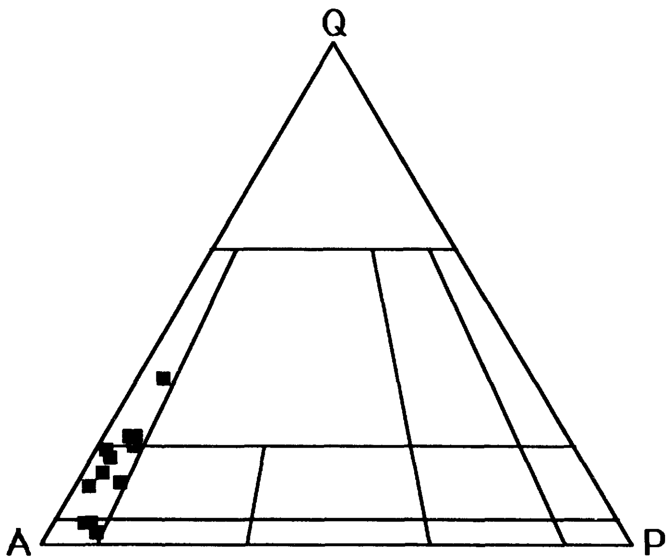

Figure 5.—Plot of modal quartz (Q), alkali feldspar (A), and plagioclase (P) for the Cobbler Mountain Alkali Feldspar Quartz Syenite. Number of analyses = 14. See figure 1 caption for field labels.

rimmed by epidote; fine-grained, anhedral fluorite; stilpnomelane occurring in clusters with ferromagnesian phases; fine-grained, subhedral to euhedral zircon; chlorite; and secondary amphibole and calcite.

Geochemically, the White Oak is characterized by a metaluminous composition with SiO_2 (average is 72.5 wt pct), Al_2O_3 (13.0 wt pct), and total alkali (9.2 wt pct) contents close to the overall average for the entire suite. In terms of trace elements, the White Oak is most notably characterized by an elevated Ce content (average is 372 ppm) relative to the other metaluminous units of the suite.

Cobbler Mountain Alkali Feldspar Quartz Syenite

The Cobbler Mountain Alkali Feldspar Quartz Syenite (Zrc) occurs as a continuous lithologic unit stretching nearly 30 km (18 mi) from the vicinity of Ashby Gap (A6) southward to the Rappahannock River (C5-C6). Near Ashby Gap, the Cobbler Mountain is apparently overlain nonconformably by phyllite of the Swift Run Formation and greenstone of the overlying Catoctin Formation. Along most of its length, the Cobbler Mountain is in contact to the west with an inlier of Grenvillian gneiss that separates the Cobbler Mountain from the Laurel Mills Granite; however, near the Rappahannock River (C5-C6), these two units are in direct contact. Dikes of Cobbler Mountain affinity intrude the gneissic inlier at several locations (for example, Reference Locality 6 (C6)). Contact relations demonstrating the intrusive nature of the Cobbler Mountain into the adjacent gneissic country rocks are exposed along Goose Creek southeast of Delaplane (Reference Locality 7 (B6)). The Cobbler Mountain can be distinguished from all other lithologic units of the Robertson River Igneous Suite by the prominent porphyritic texture defined by abundant euhedral to subhedral alkali feldspar mesoperthite grains and interstitial quartz.

In the field, the Cobbler Mountain is a light to dark gray, medium- to coarse-grained, porphyritic to seriate-inequigranular alkali feldspar quartz syenite (fig. 5) composed largely of prominent, euhedral to subhedral alkali feldspar phenocrysts; subhedral to anhedral, mostly interstitial quartz; locally prominent, dark green amphibole; fine-grained allanite; and fluorite. The feldspar phenocrysts typically exhibit abundant white string- and patch-perthite intergrowths that are best observed on weathered surfaces. The amphibole is typically replaced by intergrowths of fine-grained magnetite + quartz (Clarke, 1984). Aegirine-augite occurs in outcrops located near the summit of Big Cobbler Mountain (C6) and may have been present in the corroded cores of amphiboles from other localities (Arav, 1989). Miarolitic cavities dominated by quartz and typically measuring 1–3 cm (0.4–1.2 in.) in diameter are present throughout the Cobbler Mountain. In addition, irregularly-shaped pods of quartz syenitic pegmatite measuring up to 1 m (3.3 ft) in diameter and composed of euhedral to subhedral crystals of alkali feldspar + amphibole + quartz (with individual grains of all minerals ranging up to 15 cm (6 in.) in length) occur within gneiss at Reference Locality 8 (B6). Throughout its area of exposure, the Cobbler Mountain is cut by numerous, generally northeast-striking greenstone and fine-grained amphibolite dikes. Such dikes are especially abundant in the north where data from detailed traverses indicate that more than 25 percent of the outcrop area is composed of greenstone.

In thin section, the Cobbler Mountain is characterized by a distinctive inequigranular texture defined by prominent, medium-grained, euhedral to subhedral microcline mesoperthite; fine-grained, subhedral to anhedral plagioclase; medium- to fine-grained, subhedral to anhedral quartz; and medium- to fine-grained, euhedral to subhedral amphibole (X=pale yellow-green, Y=yellow green, Z=dark green) typically replaced by intergrowths of fine-grained quartz + green biotite + magnetite + stilpnomelane. The average alkali feldspar:plagioclase ratio is 27:1. Accessory phases include euhedral to subhedral, clear zircon; anhedral, colorless to purple fluorite; euhedral to subhedral, brown allanite rimmed by pale green epidote; and fine-grained, orange-brown stilpnomelane that typically occurs in radiating clusters. Intergrowths of fine-grained quartz + green biotite + magnetite + stilpnomelane can be observed replacing original amphibole.

The Cobbler Mountain is metaluminous in composition and, relative to the other units of the Robertson River Igneous Suite, is characterized by low SiO_2 (average is 70.6 wt pct), high Al_2O_3 (13.8 wt pct), and high total alkalies (9.9 wt pct). Relative to other metaluminous units of the Robertson River Igneous Suite, the Cobbler Mountain contains high concentrations of Zr (706 ppm) and Ga (42 ppm), and has a high Ga/Al ratio (5.8). Geochemical data further suggest that the Cobbler Mountain may include at least two compositional subunits (relatively high- and low-silica syenitoids) that cannot be distinguished on the basis of field criteria.

Hitt Mountain Alkali Feldspar Syenite

Comprising most of the southern portion of the Robertson River outcrop belt, the Hitt Mountain Alkali Feldspar Syenite (Zrh) is, together with the Cobbler Mountain Alkali Feldspar Quartz Syenite and the Laurel Mills Granite, one of the more areally widespread units in the main Robertson River batholith. The Hitt Mountain is exposed within a nearly continuous, narrow belt that is 47 km (28 mi) long, stretching from the type locality at Hitt Mountain (E4) southward to the vicinity of Charlottesville (H2). Along this area of exposure, the Hitt Mountain is in contact with four of the eight Robertson River units, but is most closely associated with the White Oak Alkali Feldspar Granite. Distinguishing between the Hitt Mountain and White Oak lithologic types can be complicated by the similarity in textures and by the locally continuous gradient in

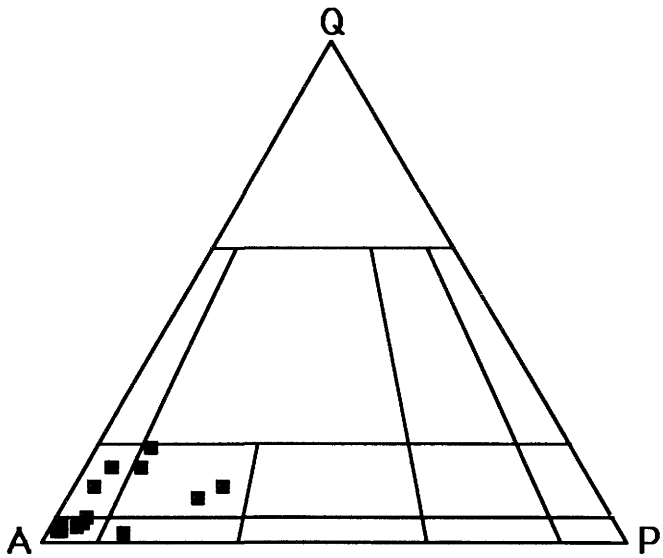

Figure 6.—Plot of modal quartz (Q), alkali feldspar (A), and plagioclase (P) for the Hitt Mountain Alkali Feldspar Syenite. Number of analyses = 14. See figure 1 caption for field labels.

quartz content that exists between these two units. However, the prominent coarse-grained, perthitic alkali feldspars, coupled with the typically much lower quartz content (average modal percentage is less than 5) and oxidized cores in the amphiboles of most Hitt Mountain exposures, serve to facilitate this distinction.

In the field, the Hitt Mountain is a light gray, coarse-grained to locally pegmatitic, inequigranular, amphibole-bearing alkali feldspar syenite to alkali feldspar quartz syenite (fig. 6). The average alkali feldpar:plagioclase ratio is 10:1. Recognition of the Hitt Mountain in the field may be complicated by the variable degree of deformation that characterizes this unit. Although most Hitt Mountain exposures are relatively undeformed, some (especially those in the southernmost part of the main batholith) are typically strongly deformed, showing features ranging from amphibole-defined lineation to localized zones of protomylonite and mylonite (Reference Localities 9 and 10 (G3 and H3, respectively)). Throughout most of its area of exposure, the Hitt Mountain is in close association with light-colored, finer-grained, mineralogically identical and geochemically comparable alkali feldspar syenite. This finer-grained variety of the Hitt Mountain contains abundant amphibole and is porphyritic with alkali feldspar phenocrysts. In most exposures, this finer-grained syenite occurs as dikes that clearly cross-cut the coarser variety. At Reference Locality 11 (E4), dark-colored, fine-grained Hitt Mountain occurs as rounded enclaves in a coarse-grained, syenitic matrix and could represent an older fine-grained syenite.

Petrographically, the Hitt Mountain displays an overall cumulate to pseudocumulate texture in which coarse-grained, subhedral to euhedral microcline-microperthite, together with coarse-grained, subhedral amphibole, form a framework in which the interstices are filled by fine-grained, anhedral, recrystallized quartz and fine-grained, anhedral to subhedral saussuritized plagioclase. The microcline-microperthite in the Hitt Mountain characteristically contains inclusions of plagioclase and stilpnomelane; whereas the amphibole (X=pale yellow-brown; Y=dark green; Z=green-blue) locally displays cores replaced by quartz. Additional mineral phases in the Hitt Mountain include fine, subhedral brown biotite; zoned, subhedral, orange-brown allanite; fibrous, reddish-orange stilpnomelane intergrown with biotite ± amphibole ± Fe-Ti oxides; fine-grained, subhedral to euhedral apatite rimmed by stilpnomelane(?); prominent subhedral to euhedral zircon; and rare garnet.

The Hitt Mountain is metaluminous in composition, and, in terms of major elements, is characterized by the lowest SiO_2 (average is 64.1 wt pct) and highest Al_2O_3 (17.2 wt pct) and total alkali (11.7 wt pct) contents of the suite. Compared to the other units of the Robertson River Igneous Suite, trace element contents of the Hitt Mountain are low for Y (average is 59 ppm), Th (6 ppm), Nb (48 ppm), and Zn (103 ppm) and average for Zr (556 ppm) and Ce (222 ppm). Ga/Al ratios (average is 4.1) are low compared to the rest of the suite.

Amissville Alkali Feldspar Granite

The Amissville Alkali Feldspar Granite (Zra) is exposed discontinuously along the eastern edge of the Robertson River outcrop belt for 16 km (10 mi) from the Rappahannock River (D5) south to the vicinity of Castleton (E5). In the northern portion of this area, the Amissville is in sharp contact with the Laurel Mills Granite and Cobbler Mountain Alkali Feldspar Quartz Syenite, both of which have been shown to be considerably older (Arav, 1989; Tollo and Aleinikoff, 1992). Dikes of the Amissville can be observed intruding the Cobbler Mountain Alkali Feldspar Quartz Syenite at Reference Locality 12 (C6). Farther to the south, the Amissville is in close contact with the geochemically similar rocks of the Battle Mountain Alkali Feldspar Granite (both granite and rhyolite) and with basement gneiss. The Amissville is in fault contact with the gneiss. Contacts between the Amissville and Battle Mountain units in this area are both intrusive and fault-bounded; however, field relationships (including dikes of Battle Mountain cutting Amissville and fine-grained chilled zones within the Battle Mountain adjacent to contacts with the Amissville) indicate that the Battle Mountain rocks are younger than the Amissville (Arav, 1989; Hawkins, 1991).

In the field, the Amissville is a light to dark gray, medium-grained, porphyritic alkali feldspar granite (fig. 7) composed of prominent (best seen on weathered surfaces) quartz phenocrysts (ubiquitous, except in the north where the texture is seriate-inequigranular), abundant alkali feldspar mesoperthite, rare plagioclase, prismatic intergrowths of riebeckite ± aegirine ± magnetite, and fluorite. Fine-grained intergrowths of riebeckite ± magnetite locally form partial to complete pseudomorphs after prismatic aegirine. In addition, rare veins and joint surface coatings composed of riebeckite + Fe-Ti oxides are locally present, further indicating that the amphibole is at least partly subsolidus in origin. In some areas, fine-grained intergrowths of magnetite + quartz form complete pseudomorphs after original aegirine and riebeckite(?). Miarolitic cavities (typically containing quartz crystals) measuring 1–3 cm (0.4–1.2 in.) in diameter and numerous fine-grained dikes of identical mineralogic composition to the Amissville occur throughout this unit. Most exposures of the Amissville are relatively undeformed except for localized, anastomozing zones (<3–4 cm in width) of leucocratic mylonite.

In thin section, the Amissville is characterized by a distinct porphyritic texture defined by prominent, medium-grained, euhedral to subhedral quartz phenocrysts. Other major phases include medium-grained, subhedral microcline mesoperthite; fine-grained, subhedral plagioclase; fine-grained, subhedral quartz (in the groundmass); fine- to medium-grained, subhedral aegirine (X=pale green, Y=yellow-green, Z=pale yellow green); fine-grained, subhedral riebeckite (X=dark blue, Y=gray-blue, Z=light

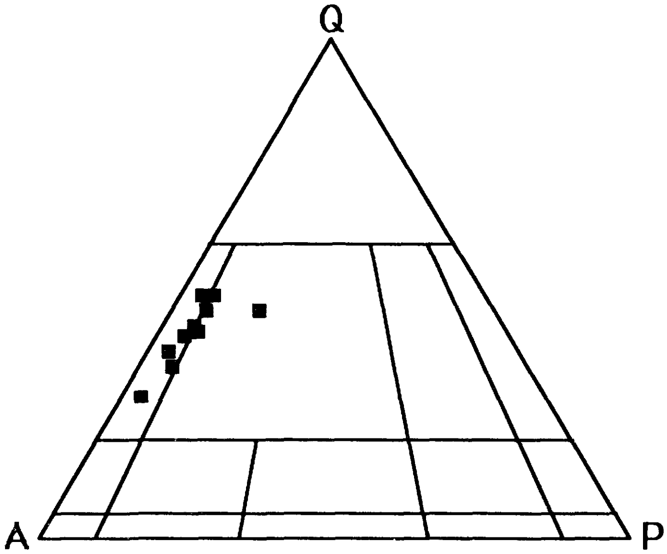

Figure 7.—Plot of modal quartz (Q), alkali feldspar (A), and plagioclase (P) for the Amissville Alkali Feldspar Granite. Number of analyses = 10. See Figure 1 caption for field labels.

brown); and fine-grained, subhedral biotite (X=light brown, Y=Z=dark greenish brown). The average alkali feldspar:plagioclase ratio is 13:1. Most riebeckite and biotite occur with quartz in fine-grained intergrowths replacing primary aegirine. Accessory phases include anhedral, turbid zircon; anhedral, colorless to purple fluorite; and fine-grained stilpnomelane that typically occurs in radiating clusters. Secondary albitic plagioclase occurs in most samples as overgrowths on primary mesoperthite grains.

Displaying an overall peralkaline bulk composition, the Amissville is characterized by high SiO_2 (average is 75.6 wt pct) and low Al_2O_3 (12.1 wt pct) relative to the other lithologic units of the Robertson River Igneous Suite. Distinctive trace element concentrations include very low Ba (14 ppm) and Sr (4 ppm), high Ga (49 ppm), and a high Ga/Al ratio (7.6). The peralkaline composition and spatial proximity of the Amissville Alkali Feldspar Granite to compositionally similar alkali feldspar granite, felsite, and rhyolite of the Battle Mountain unit suggest that the Amissville constitutes part of the shallow intrusive network of a peralkaline volcanic center.

Battle Mountain Alkali Feldspar Granite

The Battle Mountain Alkali Feldspar Granite is a composite unit that includes alkali feldspar granite (Zrbg), felsite (Zrbf), and rhyolite (Zrbr). The unit is exposed discontinuously throughout an elongate area stretching 18 km (11 mi) from near Massies Corner (D5) south to the Hazel River (E4). Along the eastern edge of this area, the Battle Mountain is in both fault and probable intrusional contact with the gneissic country rocks. On the western edge, it is in contact with the coarse-grained Laurel Mills Granite. Fine-grained dikes of Battle Mountain felsite can be seen cutting the Laurel Mills Granite at Reference Locality 2 (D5). At the northern terminus of the area of exposure and farther south near Castleton Mountain (E5), this lithologically complex unit is in contact with Amissville Alkali Feldspar Granite from which it is distinguished by the prominent quartz phenocrysts and locally abundant riebeckite of the latter. Although field relations are locally obscured by the lack of exposure, limited observations (including dikes of Battle Mountain cutting Amissville and fine-grained, chilled zones within the Battle Mountain adjacent to contacts with the Amissville) in this area suggest that the Amissville unit pre-dates the Battle Mountain Alkali Feldspar Granite (Hawkins, 1991). The Battle Mountain unit is also in contact with the Arrington Mountain Alkali Feldspar Granite in the vicinity of Castleton (E5). Felsite dikes geochemically similar to the Battle Mountain cut the Arrington Mountain unit at several localities, indicating that the Battle Mountain is younger. Battle Mountain Alkali Feldspar Granite also occurs as an elongate body located east of the main Robertson River batholith stretching 15 km (9 mi) from near Orlean (D6) southward to the vicinity of Viewtown (D5).

In the field, the Battle Mountain unit is composed of abundant, fine-grained felsite closely associated with a variety of medium-grained alkali feldspar granites (Wallace and Tollo 1986; Hawkins, 1991; Hutson and Tollo, 1991). The felsite is most abundant near the Battle Mountain type locality (south of Massies Corner (**D5**)) and in the southern portion of the Battle Mountain outcrop area between Blackwater Creek (E5) and the Hazel River (E4). In both areas, the felsite is typically a fine-grained to aphanitic, light-colored, equigranular to sparsely porphyritic rock with euhedral feldspar phenocrysts and is composed largely of quartz and alkali feldspar with minor aegirine (locally amphibole), Fe-Ti oxides, and fluorite. The alkali feldspar granites of the Battle Mountain unit (fig. 8) are typically light gray to gray, medium-grained, inequigranular, and are composed predominantly of quartz and alkali feldspar with minor biotite and fluorite. As noted originally by Lukert and Halladay (1980), the felsite and granitoids are closely associated throughout the vicinity of Battle Mountain (D5). Numerous map- and outcrop-scale dikes of felsite cutting the coarser grained granitoids occur throughout the area and demonstrate the younger nature of the felsite. However, the observed similarity in mineralogic and geochemical composition, as well as the lack of quenched margins in the felsite dikes, suggest that these subunits are probably similar in age.

Abundant field and textural evidence indicates that the Battle Mountain rocks represent the highest level of magma emplacement

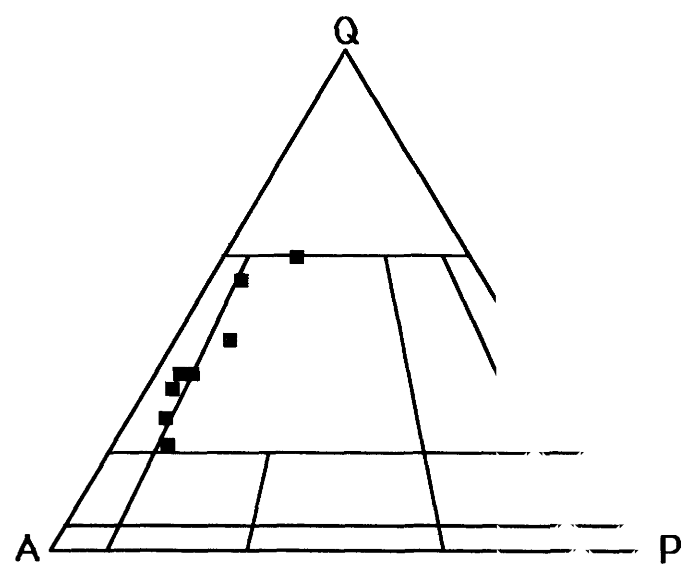

Figure 8.—Plot of modal quartz (Q), alkali feldspar (A), and plagioclase (P) for the granitoids of the Battle Mountain Alkali Feldspar Granite. Number of analyses = 8. See figure 1 caption for field labels.

in the Robertson River Igneous Suite. Miarolitic cavities (typically containing quartz) are present in both the felsite and granitoids. In addition, the felsite locally displays prominent flow banding (for example, Reference Locality 13 (D5)), indicating that magma emplacement occurred at subvolcanic to volcanic levels. Unequivocal evidence for eruptive activity within this Late Proterozoic volcanic system is preserved by light gray to white, aphanitic, geochemically similar rhyolite that is interlayered with conglomerate and phyllite correlated with the Mechum River Formation exposed nearby. This rhyolite, which includes volcaniclastic rocks, occurs within a fault-bounded graben located between Castleton Mountain and Blackwater Creek (E5) and is correlated with the Battle Mountain Alkali Feldspar Granite and felsite on the basis of similar geochemical composition. Clasts identical in composition to this rhyolite occur within intercalated conglomerate (Reference Locality 14 (E5)), thus indicating that extrusion and sedimentation were penecontemporaneous and probably episodic (Hutson, 1992).

In thin section, the Battle Mountain granitoids are alkali feldspar granite characterized by an overall medium-grained, inequigranular texture and low color index. Major mineral phases include medium-grained, euhedral to subhedral alkali feldspar mesoperthite and medium- to fine-grained, anhedral quartz. Albite is typically present as overgrowths on and as a replacement product of primary mesoperthite. Other phases include fine-grained, subhedral to anhedral aegirine (X=pale yellow, Y=yellow-green, Z=pale yellow-green) that is partially to entirely replaced by intergrowths of fine-grained quartz + magnetite + zircon ± rare earth element-bearing phases (including bastnaesite); fine-grained, green biotite; zircon; and fluorite. The felsite is typically a fine-grained to very fine-grained, allotriomorphic intergrowth of alkali feldspar and quartz with rare plagioclase ± allanite ± colorless to purple fluorite ± zircon ± magnetite ± a variety of very fine-grained, mostly unidentified, rare earth element-bearing minerals (Hawkins, 1991). The segregation of quartz and feldspar produces flow banding that can be observed on both thin section and outcrop scale. Irregular, patchy fabric locally developed within the felsite results from differences in the texture and distribution of Fe-Ti oxide phases. The rhyolite is very fine-grained to aphanitic with rare, euhedral feldspar phenocrysts.

All rocks included within the Battle Mountain unit are typically peralkaline to slightly metaluminous in composition. The alkali feldspar granites and felsites display characteristically high, although typically variable, silica values (average is 74.5 wt pct; range: 70.0–79.0 wt pct) as well as variable total alkali concentrations. A minor, mineralogically identical subset of the Battle Mountain granitoids is characterized by lower (<70 wt pct) silica values (and correspondingly higher Al_2O_3 contents) but is otherwise compositionally identical to the higher silica granitoids. The trace element composition of rocks from the Battle Mountain unit is particularly distinctive and bears directly on the complicated petrogenetic history of this complex. Relative to all other units of the Robertson River Igneous Suite, the Battle Mountain is characterized by extreme enrichments in the high field strength elements Zr (average 1,600 ppm), Hf (42 ppm), Nb (241 ppm), Ta (20 ppm), Y (129 ppm), and Ga (50 ppm). The range in Ga/Al ratios for the entire Battle Mountain unit is 6.4 to 9.0, values that exceed those for all other units of the suite except the similarly peralkaline Amissville. Some of the enrichments observed in the Battle Mountain rocks are a direct result of late-stage (possibly subsolidus) crystallization of accessory mineral phases such as basnaesite that can be seen to cross-cut the large-scale flow banding (Hawkins, 1991).

The association of hypabyssal intrusive units (Amissville and the granitoids and felsites of the Battle Mountain), compositionally correlative volcanic products (rhyolite of the Battle Mountain unit), and terrestrial clastic sedimentary deposits (correlatives of the Mechum River Formation) in the area between Poes Mountain (D5) and Boston (E4) demonstrates that these rocks represent the remnants of a former peralkaline plutonic-volcanic complex. Tollo (in press) referred to the area of abundant, multiply intrusive, subvolcanic dikes on and near Battle Mountain (D5) as the Battle Mountain volcanic center (informal name). U-Pb isotopic analyses of zircons from the felsite suggest that this high-level magmatic activity was the culminating event in the history of the Robertson River Igneous Suite (Tollo and Aleinikoff, 1992; unpub. data).

DIKES

Felsic dikes are common throughout most of the main batholith of the Robertson River Igneous Suite and in the surrounding country rocks (Arav, 1989; Lowe, 1990; Hawkins, 1991). These dikes are typically poorly exposed but are commonly recognized by their characteristic fine grain size and (where observed) sharp contacts with the enclosing rocks. The dikes, which are typically too small or too poorly exposed to be mapped in detail, are generally finer-grained petrologic equivalents of the eight formal lithologic units. A subset of very fine-grained felsite dikes display elevated concentrations of high field strength elements (notably Zr and Nb). These dikes were probably derived from the magmatic sources of the Battle Mountain volcanic center and therefore represent a relatively young population.

GEOCHEMISTRY

The lithologic units of the Robertson River Igneous Suite collectively display many of the geochemical characteristics of A-type granitoids, according to a variety of petrochemical criteria put forth in previous studies (Loiselle and Wones, 1979; Pitcher, 1983; White and Chappell, 1983; Whalen and others 1987). For major elements, these include high SiO_2 and total alkalies, high FeO_{Total}/MgO and Na+K/Al, and low CaO, relative to I-, S-, and M-type suites. Diagnostic trace element characteristics exhibited by the Robertson River Igneous Suite include high concentrations of Y, Zr, Nb, Ga, Zn, and the light rare earth elements (particularly Ce), and low Cr, Ni, V, and Cu (table 3). For most A-type suites, high Ga/Al ratios are also typical and this feature is particularly diagnostic of the Robertson River Igneous Suite (fig. 9).

Although distinctive, the chemical composition of the Robertson River granitoids is not a unique indicator of the tectonic environment in which the suite was emplaced. Bailey (1974) associated igneous rocks of alkaline composition with rift-related tectonic environments, and Loiselle and Wones (1979) suggested that A-type granitoids are indicative of anorogenic tectonic settings. However, Whalen and Currie (1990) demonstrated that the Topsails Igneous Suite of western Newfoundland, which displays numerous geochemical characteristics typical of A-type granitoids, was formed during a collisional event at an active convergent margin and concluded that gross chemical characteristics cannot be used alone to identify the tectonic environment of emplacement of such granitoids. Coleman and others (1992) reached a similar conclusion regarding the distribution of A-type granitoids in Africa

Table 3.—Major-element oxide and trace-element compositions of samples from the lithologic type localities

[n.d., not detected; A.I., agpaitic index = (Na+K)/Al; A.S.I., aluminum saturation index = molar $Al_2O_3/(Na_2O+K_2O+CaO)$]

Map unit* Sample	Zra RR–SA-6	Zram RR90-63	Zrbr RR91–12	Zrbf RR-DH-61	Zrbg RR-DH-63	Zrc RR-SA-74	Zrh RR90-60	Zrl RR-85-24	Zrr RR90-101	Zrw RR90-53
Major-element oxide composition in weight percent										
SiO_2	76.32	76.77	76.50	75.28	75.56	72.14	64.37	71.93	77.85	72.51
TiO_2	0.09	0.13	0.19	0.22	0.23	0.27	0.47	0.29	0.09	0.35
Al_2O_3	11.83	12.21	10.97	11.07	11.54	13.53	15.71	13.82	12.26	12.96
Fe_2O_3**	3.22	2.03	3.82	4.26	3.05	3.28	6.29	3.03	0.93	3.69
MnO	0.04	0.03	0.04	0.06	0.02	0.05	0.14	0.04	0.01	0.09
MgO	0.05	0.05	0.20	0.11	0.17	0.16	0.12	0.28	0.16	0.12
CaO	0.36	0.58	0.31	0.31	0.68	0.35	1.41	0.76	0.83	1.19
Na_2O	5.14	3.41	3.48	4.14	4.37	4.99	5.34	3.99	3.81	3.82
K_2O	3.77	5.21	4.02	3.89	4.02	4.84	5.73	5.39	4.51	5.42
P_2O_5	n.d.	n.d.	0.01	0.01	0.01	0.01	0.06	0.06	0.01	0.05
Total	100.82	100.42	99.54	99.35	99.65	99.62	99.64	99.59	100.46	100.20
Trace-element contents in parts per million										
Rb	142	178	263	193	177	111	84	84	211	121
Ba	n.d.	56	n.d.	7	3	64	148	415	206	257
Sr	8	14	10	6	8	9	32	74	23	96
Pb	15	26	12	16	37	3	12	15	11	70
Th	6.0	14.3	34.2	14.9	25.6	3.73	21.7	14.3	53.0	16.4
U	1.7	4.4	10.9	6.9	5.5	<1	3.5	2.2	14.2	2.0
Zr	540	243	2093	1846	860	213	1260	353	132	572
Hf	10.1	13.5	51.8	42.9	28.5	4.8	31.5	13.0	6.5	19.3
Nb	77.0	88.7	310.1	179.2	231.5	35.0	72.7	42.1	84.1	108.8
Ta	4.7	5.7	24.3	13.4	19.8	1.24	4.3	2.4	14.7	5.6
Ni	2	12	17	7	7	403	9	6	10	12
Zn	333	359	103	365	510	160	133	189	127	291
Cr	n.d.	13	n.d.	6	15	12	9	21	11	11
Ga	47	36	52	51	47	45	36	31	27	30
V	2	1	1	1	3	2	3	5	1	1
La	36	72	173	156	123	148	335	135	74	186
Ce	71	151	300	318	251	269	441	272	131	372
Nd	40.3	82.0	165.0	141.0	127.0	106.0	264.0	124.0	38.4	187.0
Sm	10.8	25.6	41.9	33.3	33.8	17.7	45.1	27.2	10.2	42.0
Eu	0.20	0.41	0.79	0.71	0.77	0.47	3.20	1.63	0.24	1.98
Tb	1.66	4.90	6.80	4.66	5.63	1.19	4.17	3.38	1.97	4.89
Yb	5.29	15.44	20.80	12.90	13.80	2.77	10.60	7.27	10.80	11.00
Lu	0.77	1.92	2.61	1.73	1.67	0.46	1.59	0.94	1.36	1.48
Y	62	152	239	155	140	19	91	83	78	111
Selected ratios										
La(n)/Yb(n)	4.5	3.1	5.6	8.1	6.0	36.0	21.3	12.5	4.6	11.4
10,000 × Ga/Al	7.54	5.58	9.01	8.77	7.76	6.23	4.38	4.29	4.09	4.37
A.I.	1.06	0.92	0.92	1.00	1.00	0.99	0.95	0.90	0.91	0.94
A.S.I.	0.90	0.99	1.03	0.96	0.90	0.96	0.90	1.00	0.97	0.91

*See map for description of map units

**Total iron expressed as Fe_2O_3

and Arabia. Nevertheless, a variety of geologic data support the original proposal of Rankin (1975, 1976) that the Robertson River Igneous Suite was emplaced within an anorogenic, actively rifting continental setting. Data supporting this interpretation include: (1) the lack of evidence for any major orogenic event in the central and southern Appalachian orogen during the Late Proterozoic, (2) the temporal and spatial association of the Robertson River Igneous Suite with sedimentary deposits of terrestrial clastic origin correlated with the rift-related Mechum River Formation (Hutson and Tollo, 1991), (3) the occurrence of large-scale faults that may be similar in age to the Robertson River Igneous Suite and which have been related to regional extension (Simpson and Kalaghan, 1989), (4) the association of the Robertson River Igneous Suite with bimodal volcanic sequences and dike swarms of Late Proterozoic age, and (5) the inclusion of the Robertson River Igneous Suite within a larger province of geochemically similar plutonic bodies that occur throughout the Laurentian terranes from New York to North Carolina (Rankin and others, 1983; Bartholomew and Lewis, 1984) and which, in North Carolina and southern Virginia, have been shown to be consanguineous with rift-related volcanic rocks (Rankin, 1975; 1976).

Like many other A-type suites, such as the Topsails Igneous Suite (Newfoundland), the Malani Igneous Suite (India), the White Mountains Plutonic-Volcanic Suite (New Hampshire), and Saudi Arabian granites (Eby, 1990; Whalen and Currie, 1990), the Robertson River Igneous Suite includes both metaluminous and

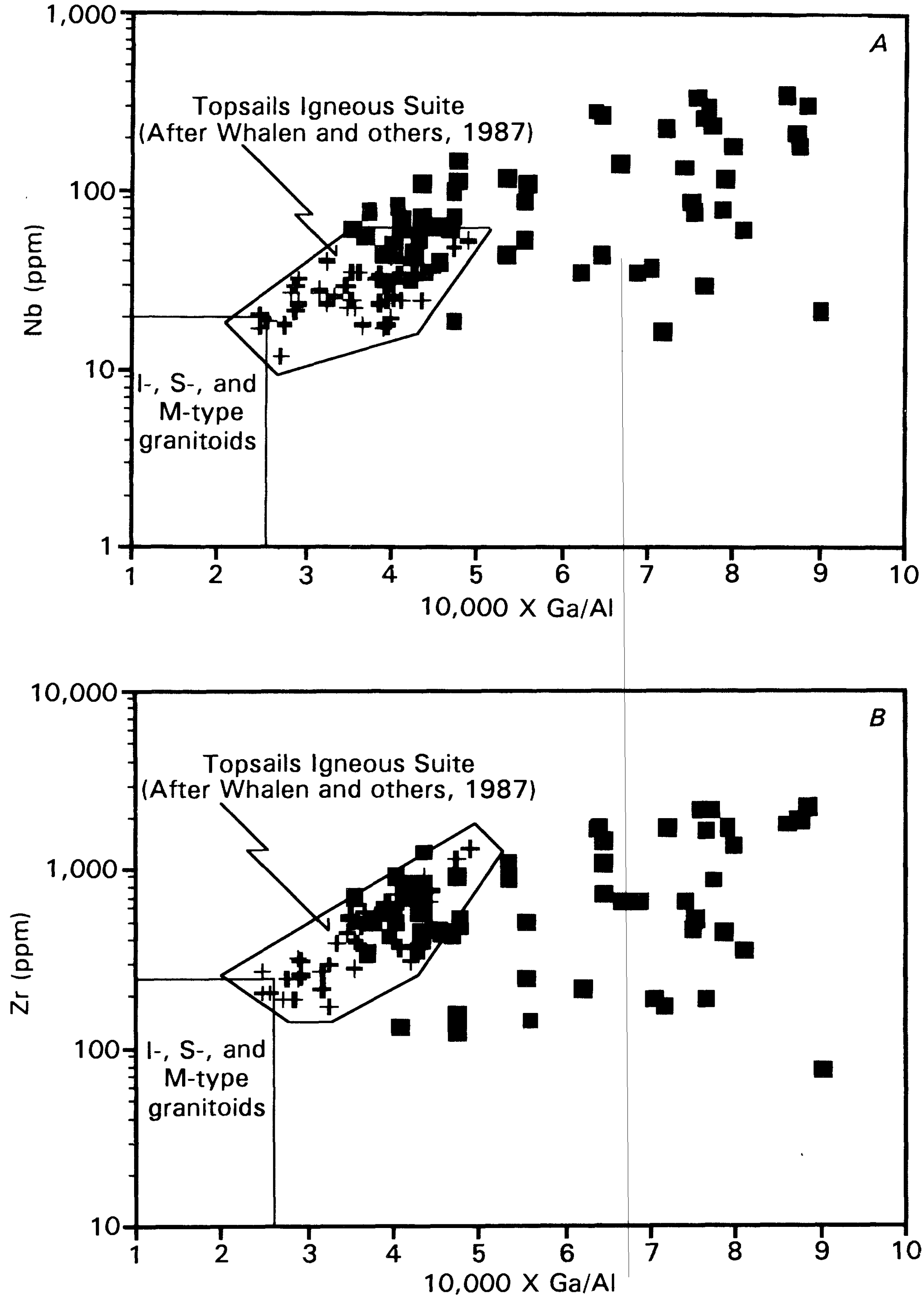

Figure 9.—Plots of Ga/Al vs. Nb(*A*) and Zr (*B*) for the Robertson River Igneous Suite (squares) and the Topsails Igneous Suite (pluses) relative to I-, S-, and M-type granitoids (Whalen and others, 1987).

peralkaline compositional groups. For the Robertson River, these groups can be distinguished in the field and petrographically by the following characteristic ferromagnesian mineral assemblages: the peralkaline units (Battle Mountain and Amissville Alkali Feldspar Granites) contain aegirine ± blue (sodic) amphibole, such as riebeckite, whereas the metaluminous group (all other units) contain green (calcic) amphibole (typically containing a significant hastingsitic component) ± biotite. Overlapping silica contents, the effects of weathering, and the post-magmatic redistribution of alkalies by metasomatic fluids make distinction using major elements difficult. However, the two groups can be defined using selected trace elements.

The most effective discriminating geochemical characteristic between the peralkaline and metaluminous groups is Ga/Al ratio (typically expressed as 10,000 × Ga/Al). Whalen and others (1987) successfully used this geochemical parameter to distinguish A-type granitoids from I-, S-, and M-type suites. Ga/Al ratios for the entire Robertson River Igneous Suite are generally high relative to the Topsails Igneous Suite (Whalen and others, 1987). Within the Robertson River, however, the peralkaline units are characterized by higher Ga/Al ratios (average = 7.7) than the metaluminous units (4.7). The high Ga/Al ratio of the Robertson River (Tollo and Arav, 1992) and other similar suites (see references given above) has been attributed to the fractionation of plagioclase, which has a low distribution coefficient for Ga (Goodman, 1972) and/or ionic complexing in the melt (Collins and others, 1982). For the Robertson River, the enrichment in Ga may also be a result of alkali feldspar accumulation according to evidence preserved at Reference Locality 15 (F3) by rocks of the metaluminous Hitt Mountain Alkali Feldspar Syenite. The alkali feldspar-rich rocks at this locality exhibit cumulate texture (Lowe, 1990) and are characterized by a "peralkaline" Ga/Al ratio (7.2).

Other trace element data have limited usefulness for distinguishing between the peralkaline and metaluminous groups. For example, in general, the peralkaline group displays higher Rb concentrations and lower Ba and Sr concentrations relative to the metaluminous group. However, overlap in the concentrations of these elements between the two groups reduces their effectiveness as distinguishing criteria. Eby (1990) demonstrated that the Y/Nb ratio may be relatively constant for any particular A-type suite provided that there has been no late-stage metasomatic redistribution of these elements. For the Robertson River Igneous Suite, Hawkins (1991) determined that variable Y/Nb ratios in rocks of the Battle Mountain Alkali Feldspar Granite resulted from local enrichment and depletion by post- or late-magmatic fluid activity. Such element migration has important implications for petrologic and geochemical modelling. Nevertheless, the consistency of the Y/Nb ratio and other sensitive trace element ratios, including Yb/Ta and Ce/Nb, in the peralkaline Amissville Alkali Feldspar Granite suggests that this unit did not experience such elemental mobilization. Comparison of Y/Nb ratios throughout the Robertson River Igneous Suite, exclusive of those rocks affected by remobilization in the Battle Mountain Granite, indicates that the peralkaline units are characterized by overall lower (<0.6) ratios than the metaluminous units (>0.6).

Eby (1990, 1992) has further suggested that the trace element ratios Y/Nb, Yb/Ta, and Ce/Nb are indicative of the source area characteristics of A-type granitoids. Compilation of these data for the Robertson River Igneous Suite shows that the peralkaline units consistently plot at lower values relative to the metaluminous units. By comparison with the synthesis of Eby (1990, 1992), these data suggest that the metaluminous units were derived from geochemically evolved continental crust source materials possibly similar to exposed Grenville-age gneisses of the Blue Ridge basement, whereas the peralkaline units were derived from more chemically primitive sources similar to those of oceanic island basalts.

METAMORPHISM AND DEFORMATION

Rocks of the Robertson River Igneous Suite, in contrast to rocks of the surrounding basement units, are not characterized by well-developed, pervasive metamorphic fabrics (Clarke, 1984; Lukert and Banks, 1984). Nevertheless, most lithologic units of the Robertson River Igneous Suite exhibit considerable evidence of post-emplacement recrystallization and deformation. Within the peralkaline (Amissville Alkali Feldspar Granite and various intrusive phases of the Battle Mountain unit) and some borderline metaluminous/peralkaline (Cobbler Mountain Alkali Feldspar Quartz Syenite) units, evidence for late- to post-magmatic recrystallization includes auto-metamorphic(?) development of riebeckite after aegirine, albite after mesoperthite, and (in the Battle Mountain rocks) locally abundant REE-bearing phases that form bands which cross-cut the primary flow banding (Arav, 1989, Hawkins, 1991).

Evidence for Paleozoic(?) metamorphism is present throughout the suite. Stilpnomelane of possible metamorphic origin occurs as radiating clusters in rocks of the Amissville Alkali Feldspar Granite (Rankin, 1975; Arav, 1989); however, stilpnomelane is more common in the metaluminous units where it typically occurs intergrown with biotite ± quartz forming pseudomorphs after original amphibole (for example, in the Laurel Mills Granite, Arrington Mountain Alkali Feldspar Granite, and Hitt Mountain Alkali Feldspar Syenite - see discussion above). Chlorite is relatively uncommon, but occurs locally in some units (for example, the White Oak Alkali Feldspar Granite) intergrown with biotite. Primary plagioclase in the Laurel Mills Granite exhibits evidence of metamorphic reaction in the form of abundant inclusions of euhedral zoisite. The mineral assemblages (for example, stilpnomelane + chlorite + biotite + zoisite) described above are indicative of metamorphic recrystallization under greenschist facies conditions (Turner, 1981). This is consistent with the level of regional metamorphism indicated by mineral assemblages observed in the cross-cutting greenstone dikes and in the nearby Catoctin and Mechum River Formations (Reed, 1955; Badger, 1989; Hutson, 1992). However, some units of the Robertson River Igneous Suite (such as the Arrington Mountain Alkali Feldspar Granite and the Hitt Mountain Alkali Feldspar Syenite) contain garnet of possible metamorphic origin (Lowe, 1990). The presence of garnet in these units and the mineral assemblages in cross-cutting amphibolite dikes in the southern portion of the Robertson River outcrop belt (where the garnet occurs) indicate that the Paleozoic(?) metamorphic grade was higher in this area than in the north.

Most units of the Robertson River Igneous Suite are cut by locally abundant, sinuous, anastomosing deformation zones that range in size from microscopic to map-scale and in mode of origin from ductile to brittle. These zones typically display sharp strain gradients and exhibit no consistent orientation(s) throughout the area of exposure. A detailed study of such deformation zones in rocks of the Robertson River Igneous Suite and surrounding basement units by Mitra (1979) indicated that such features may be a result of dominantly ductile, compressional deformation of late Paleozoic(?) age. Microscopic evidence of fine-scale ductile deformation is abundant throughout most lithologic units of the Robertson River Igneous Suite. Quartz commonly preserves evidence of deformation and recrystallization, including the development of equigranular, recrystallized subgrains and elongate, sinuous shear bands. Deformation in feldspars is typically limited to brittle fractures. Considered together, these features suggest that deformation occurred under greenschist facies conditions (Simpson, 1986). Results from other studies concerned with sense-of-motion indicators of comparable features in similar anorogenic granites in the southern Blue Ridge further suggest that much of this type of deformation may be a consequence of Late Proterozoic crustal extension (Simpson and Kalaghan, 1989; Bailey and Simpson, 1991).

GEOLOGIC EVOLUTION OF THE ROBERTSON RIVER IGNEOUS SUITE

The Robertson River Igneous Suite was emplaced into deformed and metamorphosed Grenville-age rocks of the Blue Ridge basement during the interval 735 to 700 Ma (Tollo and Aleinikoff, 1992; unpub. data). The presence of xenoliths and cross-cutting relations indicate that, at least locally, the Robertson River magmas forcibly intruded both (1) a variety of coarse-grained gneisses which constitute part of the Blue Ridge basement and (2) medium-grained, biotite-rich granofels that have no obvious counterpart at the present level of exposure (Reference Localities 5 and 16 (F4 and D5, respectively)). In all cases, the Robertson River magmas reacted with and partially assimilated variably-sized blocks of pre-existing rocks, as demonstrated by the presence of xenocrystic zircons in many Robertson River units (Tollo and Aleinikoff, unpub. data).

The nearly 20:1 aspect (length-to-width) ratio of the Robertson River Igneous Suite, elongate nature of individual intrusive units, and subparallel alignment of internal and external contacts, some inliers, and xenolith zones indicate that the Robertson River is a large-scale dike-like fracture filling emplaced episodically during a period of active crustal extension. Bartholomew (1992) noted similar N. 25° E. (present directions) orientations for the Robertson River Igneous Suite and both felsic and mafic-greenstone dikes of possible Late Proterozoic age in northern Virginia. He suggested that all of this igneous activity occurred during ongoing extension accompanying rifting leading to development of the Iapetan seaway.

Most of the Robertson River lithologic units exhibit evidence of emplacement at relatively high structural levels; this is particularly true for the felsite of the Battle Mountain unit (see description). Although evidence bearing on the intrusive *versus* extrusive nature of some of the rocks in the immediate vicinity of Battle Mountain is largely inconclusive, the recognition of chemically similar rhyolites interlayered with conglomerates of probable Mechum River affinity south of Castleton Mountain (Reference Locality 14 (E5)) indicates that volcanic deposits were produced during the waning stages of Robertson River magmatic activity (Hutson and Tollo, 1991; Hutson, 1992). The spatial proximity and peralkaline composition of these volcanic products further suggest that the rocks of the Battle Mountain area, together with the adjacent Amissville Alkali Feldspar Granite, represent the subvolcanic infrastructure of a peralkaline plutonic-volcanic complex.

The association of peralkaline volcanic rocks and conglomerates of fluvial and debris-fan origin (Hutson, 1992) indicates that the latter stages of Robertson River magmatic activity coincided with active crustal rifting. The timing of this rifting is fixed by the age of specific Robertson River lithologic units. The intercalated nature of rhyolites chemically related to the Battle Mountain Alkali Feldspar Granite with metaconglomerates and phyllites correlated with the Mechum River Formation indicates that such rifting was ongoing at 702 Ma, the age of the Battle Mountain felsite as determined by U-Pb analysis of zircons (Tollo and Aleinikoff, 1992). Furthermore, the recognition of a nonconformable stratigraphic contact in which meta-arkoses and metaconglomerates representing the local base of the rift-related Mechum River Formation overlie the Arrington Mountain Alkali Feldspar Granite and contain cobbles and boulders of this Robertson River lithologic unit (Hutson and Tollo, 1991; Hutson, 1992) indicates that the onset of rifting (as represented locally by the lowermost beds of the Mechum River Formation) is significantly younger than the age of Arrington Mountain which was one of the earliest metaluminous units emplaced.

The Robertson River Igneous Suite is one of at least ten bodies of anorogenic granitoid exposed within the Blue Ridge terrane north of Galax, Virginia (Shenandoah massif of Rankin and others, 1989). These bodies include rock types ranging from syenite to alkali feldspar granite to granite and are typically metaluminous to weakly peralkaline in composition with high Ga/Al ratios (Bartholomew and Lewis, 1984; Tollo and others, unpub. data). The occurrence of numerous bodies throughout the Shenandoah massif and the presence of volcanic rocks near Battle Mountain argue strongly that such magmatic activity was not restricted to the vicinity of major Appalachian salients located near South Mountain, Pennsylvania and Mount Rogers, Virginia, as proposed in the pioneering studies of Rankin (1975, 1976). Instead, rift-related magmatism was widespread throughout the region, forming elongate, dike-like plutonic bodies of varying size and was marked by an additional site of volcanism located nearly 60 km (100 mi) south of South Mountain.

ACKNOWLEDGMENTS

This work was supported by funding from the U.S. Geological Survey (USGS), Virginia Division of Mineral Resources, National Science Foundation grant #EAR89–16048 (to Tollo), grants from the George Washington University (GWU) Committee on Research (to Tollo), and a grant from the Sigma Xi Society (to Lowe). We would like to thank Peter T. Lyttle and Robert C. McDowell for helping to make this map possible and acknowledge the comments and assistance during the review and production process of Lyttle, Douglas W. Rankin, Arthur E. Nelson, Elizabeth D. Koozmin, David A. Emery, Gisela B. Harris, and Dewey L. Wood (all USGS). Many GWU students contributed to various aspects of this project through technical assistance and theses. These include Stanley F. Flagel, Paul J. Wallace, Sara Arav, David P. Hawkins, Nancy J. Byrd, Karen J. Gray, Angela V. Bee, Kathleen E. Ashton, James M. Colbert, Frederick E. Hutson, Steven J. Semick, and Giorgia Dario-Paolucci. Finally, the senior author would like to express his gratitude to Stacie J. Kreitman for her support throughout all phases of this long project.

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