Middle and Upper Paleozoic Granitic Rocks in the Piedmont Near Fredericksburg, Virginia: Geochronology

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By LOUIS PAVLIDES, THOMAS W. STERN, JOSEPH G. ARTH, KATHLEEN G. MUTH, *and* MARCIA F. NEWELL

CONTRIBUTIONS TO THE GEOLOGY OF THE VIRGINIA PIEDMONT

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CONTENTS

ILLUSTRATIONS

TABLES

MIDDLE AND UPPER PALEOZOIC GRANITIC ROCKS IN THE PIEDMONT NEAR FREDERICKSBURG, VIRGINIA: GEOCHRONOLOGY

By LOUIS PAVLIDES, THOMAS W. STERN, JOSEPH G. ARTH, KATHLEEN G. MUTH, and MARCIA F. NEWELL

ABSTRACT

Several suites of plutonic rocks have been identified by geologic mapping in the polydeformed and metamorphosed (amphibolite-grade) Piedmont near Fredericksburg, Va. Two of these suites were dated by U/Pb (zircons) and Rb/Sr (whole-rock) methods. The oldest suite is the Falls Run Granite Gneiss, a coarse-grained, strongly foliated, and highly metamorphosed rock that ranges in composition from granite to monzonite. The chief mass of Falls Run Granite Gneiss (formerly called the Berea pluton) is intrusive into the Holly Corner Gneiss of Early Cambrian(?) age. Both these gneisses are allochthonous remnants of the inverted limb of a recumbent fold; subsequent deformation formed a type-2 interference fold. U/Pb and Rb/Sr studies indicate that the Falls Run is 410 million years old and has an initial $^{87}Sr/^{86}Sr$ of 0.7070.

Younger granitoid plutons, dikes, and sills, assigned to the Falmouth Intrusive Suite, are widespread in the area. These plutons are abundant in the eastern part of the area but are rare west of the Quantico Formation. Rocks of the Falmouth consist of strongly to weakly foliated: A, biotite adamellite and granodiorite having Rb/Sr less than 0.2, and B, muscovite-biotite adamellite and granite having Rb/Sr greater than 0.4. Concordant zircon ages and two whole-rock isochrons indicate that both groups are 300-325 million years old. The initial $^{87}Sr/^{86}Sr$ of group A is 0.704, which suggests a lower crust or mantle source, whereas that of group B is 0.7088, similar to the 0.7070 for the Falls Run, and suggests crustal involvement in the magma generation. Recently reported ages from North and South Carolina are similar to those of the Falmouth. Thus, an extensive belt of 300-325 million-year-old plutons is present in the eastern Piedmont.

INTRODUCTION

The Piedmont terrane of northern Virginia is of particular interest to Appalachian geology because it bridges the area between the extensively studied Piedmont of Pennsylvania and Maryland and the Piedmont of the Southeastern United States. Some of the best fresh bedrock exposures in the northern Virginia Piedmont are found along the Rappahannock River near Fredericksburg. Geologic mapping (Pavlides, 1976, 1980) shows that this area is composed mainly of metasedimentary and metavolcanic rocks, but also includes several suites of intrusive granitoid rocks. The age of these suites can be used to place limits on the age of some deformational and metamorphic events which affected the terrane. This report summarizes the geochronology of two of these granitoid suites: Falls Run Granite Gneiss and the Falmouth Intrusive Suite. The petrography and modal composition of these rocks have been described elsewhere (Pavlides, 1980), and, therefore, they will be only briefly summarized in this paper.

ACKNOWLEDGMENTS

We wish to thank John Mangum for zircon separations, A. R. Bobyarchick for preparing the whole-rock splits, and S. Linda Cranford for numerous modal analyses. We are grateful to M. W. Higgins and J. F. Sutter for reviewing the manuscript.

GEOLOGIC SETTING

The Fredericksburg area (fig. 1) consists primarily of Proterozoic Z(?) and Paleozoic metasedimentary and meta-igneous rocks in the amphibolite facies of metamorphism that have been polydeformed (Pavlides, 1976). The oldest rocks are the Po River Metamorphic Suite of Proterozoic Z(?) and (or) early Paleozoic age. The others are of Paleozoic age and include the

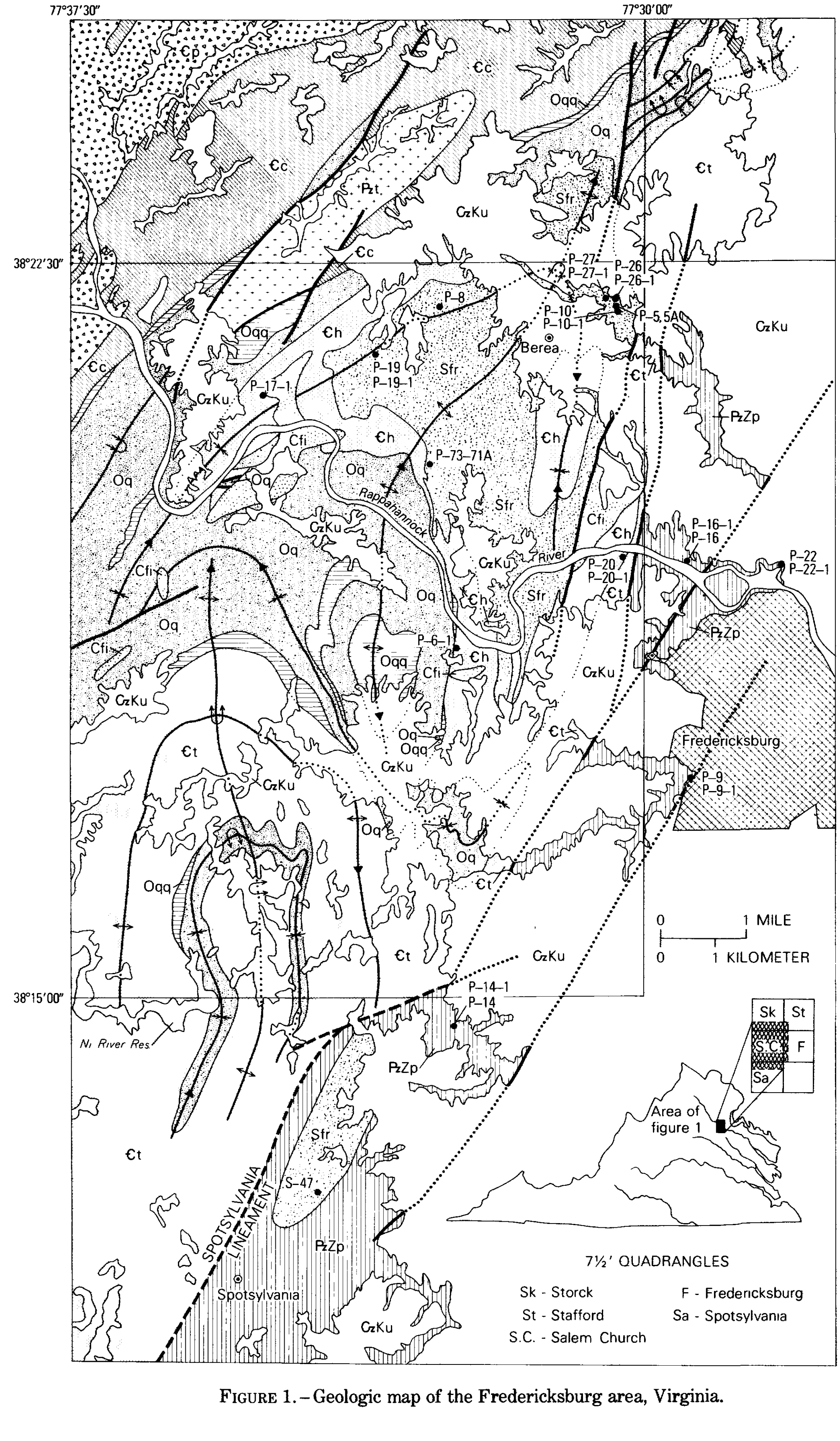

FIGURE 1.—Geologic map of the Fredericksburg area, Virginia.

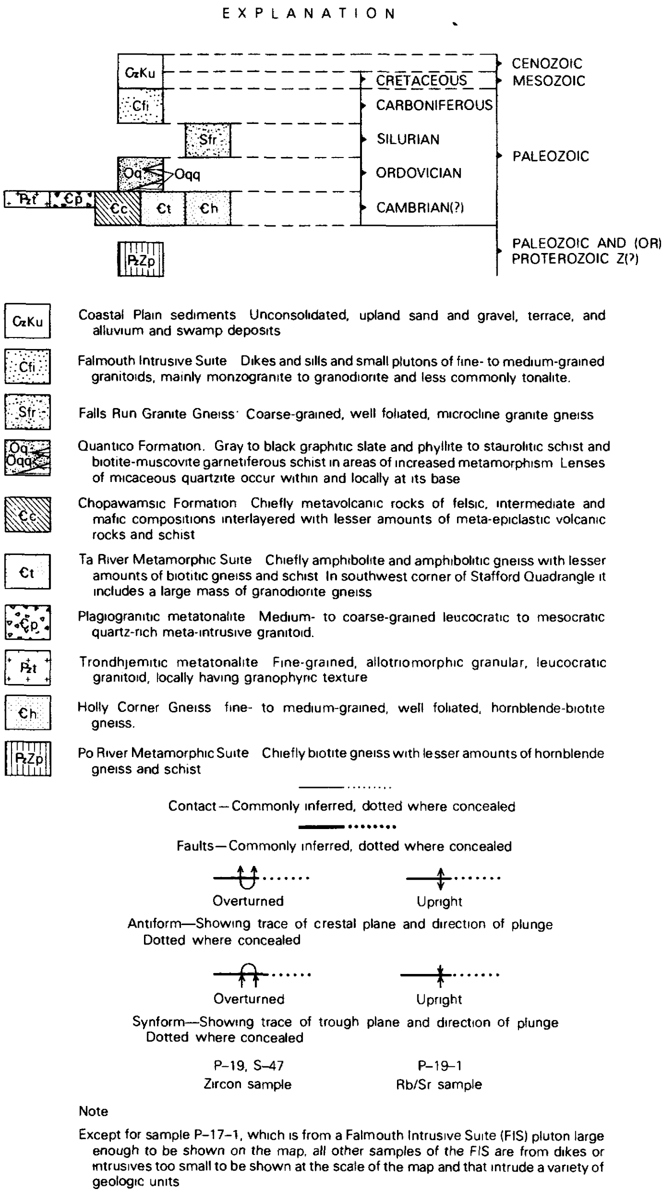

FIGURE 1.—Geologic map of the Fredericksburg area, Virginia—Continued.

metavolcanic Chopawamsic Formation and its eastern, more mafic facies, the Ta River Metamorphic Suite (amphibolites with granitoid intrusions), both of Early Cambrian(?) age. The Holly Corner Gneiss (biotite-hornblende gneiss) is also considered to be an eastern facies of the Chopawamsic. Schists of the Quantico Formation of Late Ordovician age lie unconformably above the Chopawamsic. The Chopawamsic Formation is intruded by tonalite plutons of Cambrian to pre-Late Ordovician age. The Falls Run Granite Gneiss was intruded into the Holly Corner Gneiss, probably after the Quantico was deposited but before the major deformation that affected the region.

Regional deformation consisted of a pre-Quantico local deformation (F_1) followed by a phase of upright folding (F_2) that locally produced recumbent folds. During this episode of recumbent folding, the Holly Corner Gneiss and its sill-like mass of Falls Run Granite Gneiss were transported westward during the forming of a recumbent fold or nappe and now are allochthonous remnants of the inverted limb of the fold. Subsequent deformation (F_3) produced the type-2 interference fold within which the gneisses are found; earlier folds (F_2) in the Ta River terrane were also refolded by this late (F_3) episode. Metamorphism proceeded with the polydeformation of the area.

The granitoids of the Falmouth Intrusive Suite were emplaced during and at the close of Hercynian deformation. They represent the last Paleozoic plutonic event now recognized in the Fredericksburg region.

DESCRIPTION OF GRANITIC INTRUSIVE ROCKS

FALLS RUN GRANITE GNEISS

The Falls Run Granite Gneiss occupies about 25 km²; it crops out primarily in the type-2 interference fold (fig. 1) near Berea but also forms a small pluton within the Po River Metamorphic Suite near Spotsylvania. The Falls Run is a pale-pink to nearly white, coarse-grained, strongly foliated hornblende and biotite granite gneiss ranging in composition from monzonite to granite, as classified by the IUGS (Streckeisen, 1973). Microcline forms elongate generally poikiloblastic grains as much as several centimeters long that are oriented within the plane of foliation defined by biotite. The habit of microcline, biotite, and hornblende demonstrate the recrystallized nature of the Falls Run. Myrmekite, which is also present, is thought to be of metamorphic origin; it is found in plagioclase that is in contact with potassium feldspar. Accessory minerals include apatite, epidote, sphene, and opaque minerals.

FALMOUTH INTRUSIVE SUITE

The Falmouth Intrusive Suite consists of fine-grained and pegmatitic granite, fine-grained adamellite, granodiorite, and tonalite (less common) that intrude the Fredericksburg terrane from the western edge of the Coastal Plain to the eastern margin of the Chopawamsic Formation (fig. 1). Both fine- and coarse-grained rocks occur as small plutons, tabular bodies concordant to the host-rock foliation, or cross-cutting dikes and are generally too small to be shown on the geologic map. Cross-cutting relationships suggest that pegmatites are the youngest of several generations of these intrusive rocks. Some of the dikes are folded and in turn are cut by nonfolded dikes. Foliation, generally defined by dimensionally alined biotite, is slightly to well formed and is commonly at an angle to wall-rock contacts of dikes. Locally the foliation is highly folded, as in the pluton at the northeast edge of the Salem Church Quadrangle (fig. 1). These relationsips indicate that the Falmouth rocks were emplaced during deformation (folded granitoids), as well as near the end of or after deformation (nonfolded and (or) poorly foliated granitoids).

ANALYTICAL METHODS

U-Th-Pb METHOD

Uranium, thorium, and lead were determined on zircon separates by isotope-dilution mass spectrometry using a partly automated 12-inch 90°-sector NBS-type mass spectrometer. Zircons were separated from samples weighing about 70 kg by concentrating by means of a Wilfley table,[1] heavy liquids, and a magnetic separator. The zircon separates were washed with hot HNO_3 and HCL to remove surface contamination, and 20 to 50 mg were digested with HF in teflon bombs. One aliquot was spiked for concentration measurement of uranium, thorium, and lead with a combined ^{235}U-^{230}Th-^{208}Pb-enriched solution prepared by Mitsunobu Tatsumoto of the U.S. Geological Survey. A second aliquot for lead-isotope composition was not spiked. Lead was separated from uranium and thorium in a 5-cc column using Dowex 1 anion-exchange resin and was then electrode deposited. Uranium and thorium were further purified on a 2-cc column using Dowex 50 anion-exchange resin. Lead blanks ranged from 0.3 to 1.9 ng (nanograms). Isotopic measurements of lead were made by the silica-gel technique. Fractionation resulting in depletion of heavy isotopes by less than 0.05 percent was measured by using NBS SRM 982. No correction is applied. Accuracy of the concentration determinations is estimated at 1.0 percent at the 67 percent confidence level.

The analytical data for lead, uranium, and thorium, as well as the calculated ages, are given in table 1. The ^{238}U-^{206}Pb ages are the most dependable because ^{238}U constitutes more than 99 percent of natural uranium and the age has a laboratory analytical error of 2 percent at the 95 percent confidence level. The necessity of correcting for common lead causes a larger uncertainty in the ^{235}U-^{207}Pb, ^{207}Pb-^{206}Pb, and ^{232}Th-^{208}Pb ages. Graphical solutions developed by Wetherill (1956) and Tilton (1960) are of limited use for samples of Paleozoic age because the concordia curve is nearly linear in that age range and intersections to the curve by chords defined by data points cannot be accurately determined, particularly when the zircons have undergone several thermal events after initial crystallization. Several of the Falmouth Intrusive Suite zircons have ^{207}Pb/^{206}Pb ages that are much older than the ages determined by the lead-uranium method. These older ages may be the result of the presence of xenocrystic zircon, which would also increase the lead-uranium ages.

[1] Any trade names are used for descriptive purposes only and do not constitute endorsement by the U.S. Geological Survey.

Rb-Sr ISOCHRON METHOD

Strontium, rubidium, and ^{87}Sr/^{86}Sr were determined on whole-rock splits by isotope-dilution mass spectrometry using a partly automated 6-inch 60°-sector NBS-type mass spectrometer. Sample powders were produced from unweathered 3,000- to 5,000-g rock samples by crushing, grinding, mixing, and splitting to 200-mesh size. Rubidium and strontium spikes (99.9 percent ^{84}Sr and 98.0 percent ^{87}Rb) were added to a 300 to 500 mg split of each sample. The samples were dissolved in HF in teflon beakers. Rubidium and strontium were completely separated using 3*N* HCL and Dowex 50WX8, 100/200 mesh, cation-exchange resin on a 26 by 1 cm quartz column. Rubidium and strontium were loaded as chlorides onto a triple rhenium-filament assembly for mass analysis. No corrections for ^{87}Rb were required in the strontium-isotope measurement. Strontium-isotope ratios were corrected for fractionation on the basis of an ^{86}Sr/^{88}Sr ratio of 0.11940. Blank determinations were less than 2 ng for strontium and 0.2 ng for rubidium.

Accuracy of the strontium-isotope measurements is based on 14 analyses of NBS SRM 987, which give a mean ^{87}Sr/^{86}Sr value of ~~0.7106~~ ± 0.00003 (67 percent confidence level) compared with 0.71015 ± 0.00003 obtained at the National Bureau of Standards (I. Lynus Barnes, oral commun.). Precision of individual rock determinations, based on eight complete replicate whole-rock determinations, is 0.011 percent for ^{87}Sr/^{86}Sr, 0.6 percent for rubidium, and 1.0 percent for strontium at the 67 percent confidence level.

The analytical data for rubidium and strontium are given in table 2 and plotted on isochron diagrams in figures 2 and 3. The size of individual data points reflects the 95 percent confidence level. The regression and uncertainty calculation method of York (1969) was used to determine ages and their uncertainty at the 67 percent confidence level.

TABLE 1. – *U-Th-Pb analytical data on zircons from the Falls Run Granite Gneiss and the Falmouth Intrusive Suite, of the Fredericksburg area, Virginia*

[n.d., no data]

Sample No.	Concentration in ppm			Atom percent				Millions of years			
	Pb	U	Th	^{204}Pb	^{206}Pb	^{207}Pb	^{208}Pb	$^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$	$^{208}Pb/^{232}Th$
Falls Run Granite Gneiss											
P-5	83.9	1,481.0	1,185.0	0.0319	84.54	5.01	10.42	347	349	360	147
P-5A	88.3	1,473.4	1,134.0	.0380	84.53	4.94	10.48	366	355	280	159
P-8	53.1	885.6	583.6	.0244	81.76	4.92	13.29	356	368	450	255
P-19	83.8	1,205.0	687	.0114	81.60	4.62	13.77	411	409	400	366
P-26	95.2	1,468.0	1,202.0	.0568	82.38	5.15	12.41	384	372	300	183
P-27	79.7	1,282.0	n.d.	.1318	79.86	5.53	14.48	351	302	n.d.	n.d.
S-47	91.2	1,398.0	2,163.0	.1167	79.38	6.14	14.36	367	378	450	94
Falmouth Intrusive Suite											
P-10	55.9	1,205.0	438.6	0.1693	78.72	6.70	14.42	258	268	360	227
P-14	34.3	533.4	646.7	.0740	67.90	5.26	26.77	313	359	660	286
P-16	21.6	372.1	197.5	.2068	76.58	7.06	16.14	309	310	310	204
P-20	9.8	164.0	187.2	.0617	70.15	4.42	25.37	302	291	200	272
P-22	63.0	557.7	360.9	.6926	50.16	12.95	36.19	307	331	500	370

Description of specimens

Falls Run Granite Gneiss:

P-5 and P-5A: Coarse-grained, foliated granite gneiss. Dark-colored streaks of biotite define foliation along which large dimensionally oriented microcline (34 percent) is also alined. Microcline is locally perthitic; coarse-grained quartz (30 percent) is also abundant. Twinned and untwinned plagioclase (32 percent) commonly is myrmekitic where in contact with or partly enclosed by microcline. Coarse-grained green biotite encloses well-formed sphene and forms clot-like aggregates with epidote and opaque minerals. Symplectic intergrowths of vermicular quartz with epidote and biotite are locally present. Salem Church Quadrangle, Va., at lat 38°22′03″ N. and long 77°30′22″ W.

P-8: Coarse-grained, foliated granite gneiss. Streaky foliation defined by biotite along which large dimensionally oriented pink microcline is alined. Salem Church Quadrangle, Va., at lat 38°22′03″ N. and long 77°30′24″ W.

P-19 and P-19-1: Coarse-grained, weakly foliated granite gneiss. Green biotite (1 percent) is crudely dimensionally alined and imparts weak foliation to the rock. Quartz (30 percent), plagioclase, both twinned and untwinned (32 percent), and microcline, locally perthitic (32 percent), have allotriomorphic granular texture. Myrmekite (5 percent) occurs in plagioclase that is in contact with or partially enclosed by microcline. Salem Church Quadrangle, Va., at lat 38°21′34″ N. and long 77°33′32″ W.

P-26 and P-26-1: Coarse-grained, allotriomorphic-granular granite gneiss. Major constituents are quartz (39 percent), microcline (30 percent), and plagioclase (26 percent). Microcline is locally composed of thread and interpenetrant perthite. Large microcline grains are poikiloblastic and enclose smaller grains of microcline, quartz, and epidote. Myrmekite (2 percent) typically occurs along plagioclase that is in direct contact with microcline. Green biotite (2 percent) forms irregular clots and streaks that are crudely alined and that impart foliation to the rock. Green hornblende is a minor accessory (0.5 percent), as are epidote and opaque minerals that together make up about 1 percent of the rock. Salem Church Quadrangle, Va., at lat 38°22′06″ N. and long 77°30′25″ W.

P-27 and P-27-1: Coarse-grained, foliated granite gneiss. Major constituents in allotriomorphic granular texture are microcline (35 percent), quartz (30 percent), and plagioclase (25 percent). Microcline is locally perthitic (band and thread) and, in places, poikiloblastic. Plagioclase, in contact with microcline, has formed rim and lobate myrmekite (5 percent). Green biotite (3 percent) in local dimensional alinement imparts foliation to the rock. Locally it encloses sphene (rare). Other minor minerals are muscovite, epidote, and opaque minerals. Salem Church Quadrangle, Va., at lat 38°22′07″ N. and long 77°30′24″ W.

P-73-71A: Coarse-grained, foliated granite gneiss. Major constituents are microcline and orthoclase (37 percent), plagioclase (29 percent), and quartz (23 percent). Salem Church Quadrangle, Va., at lat 38°20′22″ N. and long 77°32′52″ W.

S-47: Coarse-grained, foliated granite gneiss. Streaky foliation is defined by biotite and elongate microcline grains. Spotsylvania Quadrangle, Va., at lat 38°13′04″ N. and long 77°34′14″ W.

Falmouth Intrusive Suite:

P-10 and P-10-1: Medium-grained granite in dike intruded into Falls Run Granite Gneiss. Fine-grained, allotriomorphic-granular rock composed mostly of microcline (32 percent), plagioclase (31 percent), and quartz (30 percent). Myrmekite (3 percent) forms in plagioclase bounded by and in contact with microcline. Greenish-brown biotite (3 percent) alinement imparts crude foliation to the rock. Other sparse minerals include muscovite, opaque minerals, and zircon. Salem Church Quadrangle, Va., at lat 38°22′03″ N. and long 77°30′24″ W.

P-14 and P-14-1: Foliated adamellite in small pluton intruded into Po River Metamorphic Suite. Major constituents are quartz (36 percent), plagioclase (29 percent), and microcline (24 percent), which have a general dimensional alinement in the foliation plane of the rock. Foliation is defined by fine-grained, reddish-brown biotite (7 percent). Muscovite (2 percent) is locally coarse grained and poikiloblastic. Minor assessory minerals include apatite, epidote, opaque minerals, chlorite, and myrmekite. Spotsylvania Quadrangle, Va., at lat 38°14′42″ N. and long 77°32′29″ W.

P-16 and P-16-1: Weakly foliated, fine-grained granodiorite in small pluton intruded into gneisses of the Po River Metamorphic Suite. Major constituents in allotriomorphic-granular texture are plagioclase (46 percent), quartz (30 percent), and microcline (14 percent). The plagioclase is both twinned and untwinned and clouded with fine-grained alteration. Microcline is locally poikilitic. Myrmekite (2 percent) formed within plagioclase that is in contact with microcline. Greenish-brown fine-grained biotite (5 percent) along with muscovite (2 percent) imparts a crude foliation to the rock. Other minor minerals are apatite and epidote. Fredericksburg Quadrangle, Va., at lat 38°19′28″ N. and long 77°29′24″ W.

P-20 and P-20-1: Fine-grained biotite granodiorite in a dike cutting granitic gneiss of the Po River Metamorphic Suite. Generally massive and allotriomorphic-granular rock composed mostly of plagioclase (51 percent), quartz (23 percent), and microcline (14 percent). Plagioclase is locally clouded with fine-grained sericitic alteration. Greenish-brown biotite (10 percent) and muscovite (1 percent) are chief accessory minerals. Minor minerals include myrmekite, epidote, and apatite. Salem Church Quadrangle, Va., at lat 38°19′31″ N. and long 77°30′16″ W.

P-22 and P-22-1: Strongly foliated biotite granodiorite in dike intruded into granite gneisses of the Po River Metamorphic Suite. Major constituents include plagioclase (41 percent), quartz (29 percent), and microcline (19 percent). Reddish-brown biotite (10 percent) in strongly alined habit defines the foliation of the rock. Leucocratic grains are dimensionally alined and also define the foliation. Accessory minerals include myrmekite, muscovite, apatite, zircon, epidote, and opaque minerals. Fredericksburg Quadrangle, Va., at lat 38°19′25″ N. and long 77°28′10″ W.

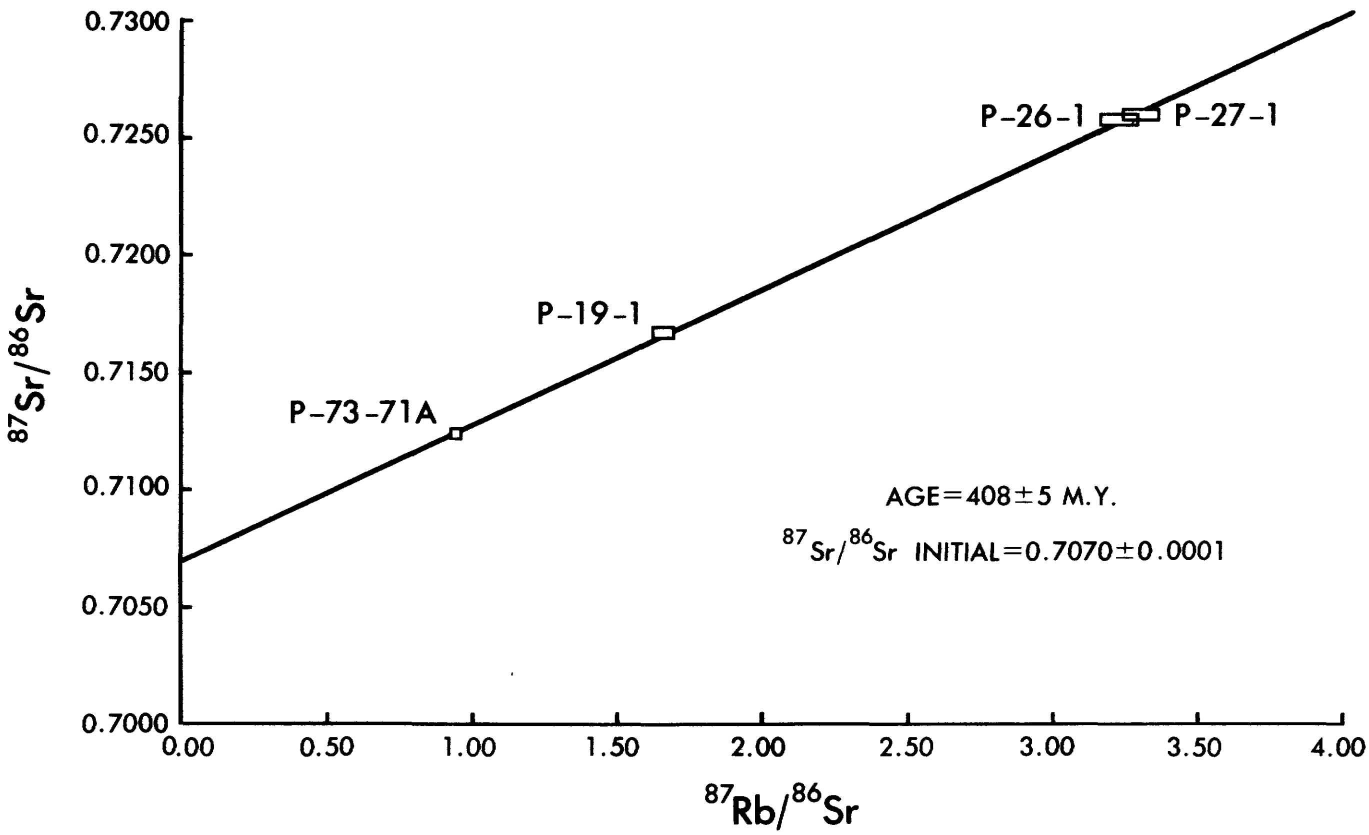

FIGURE 2. – Rb-Sr isochron diagram for the Falls Run Granite Gneiss. For analytical data on samples, see table 2.

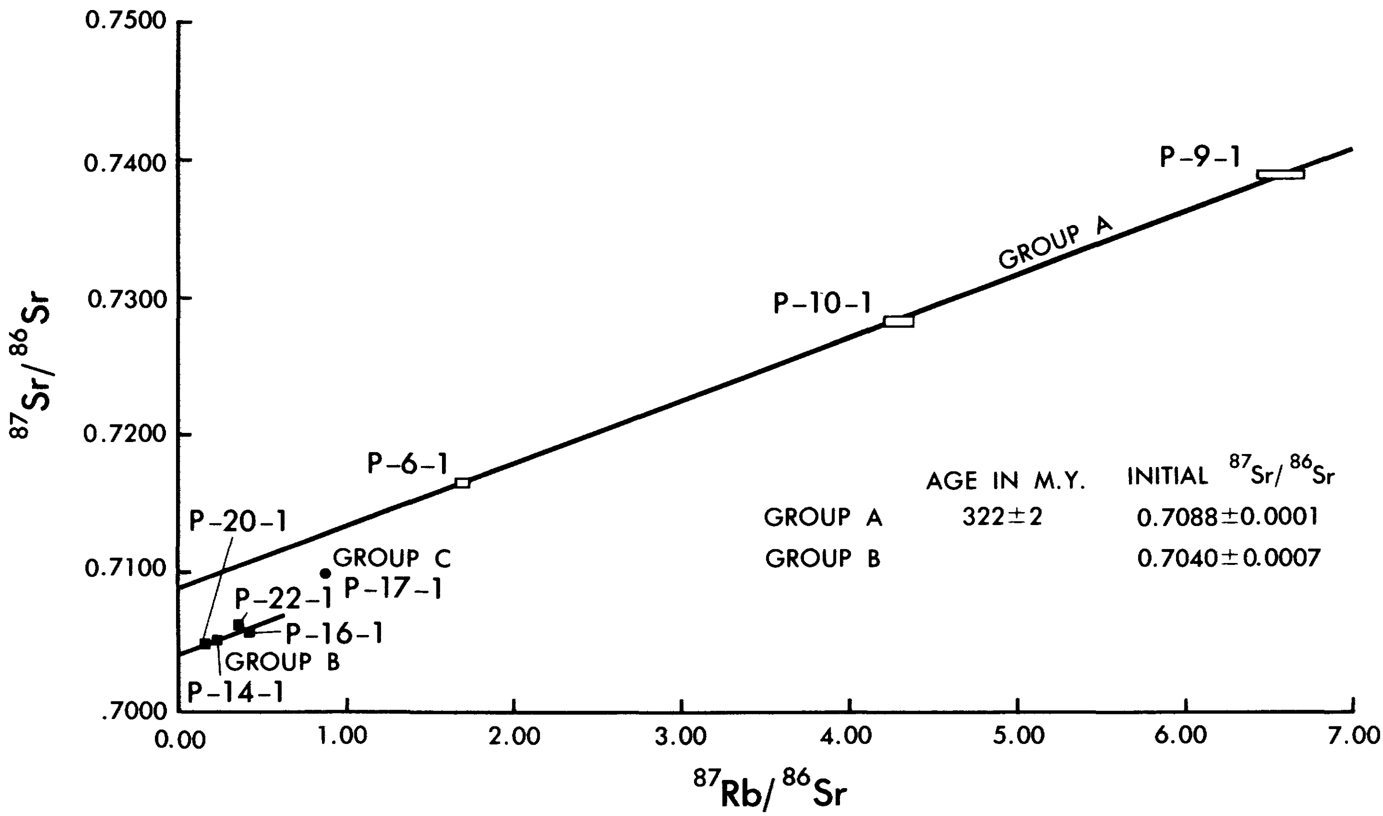

FIGURE 3. – Rb-Sr isochron diagram for the Falmouth Intrusive Suite. For analytical data on samples, see table 2.

TABLE 2.—*Rb-Sr analytical data for the Falls Run Granite Gneiss and Falmouth Intrusive Suite of the Fredericksburg area, Virginia*

Sample No.	Concentration in ppm Rb	Sr	Rb/Sr	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$
Falls Run Granite Gneiss					
P-19-1	178	310	0.57	1.662	0.71673
P-26-1	263	236	1.11	3.233	.72584
P-27-1	250	219	1.14	3.307	.72602
P-73-71A	167	514	.32	.9427	.71241
Falmouth Intrusive Suite					
Group A					
P-6-1	127	216	0.59	1.701	0.71657
P-9-1	210	92.6	2.27	6.567	.73896
P-10-1	242	164	1.48	4.295	.72838
Group B					
P-14-1	64.9	800	0.08	0.2347	0.70500
P-16-1	93.2	624	.15	.4322	.70567
P-20-1	53.9	957	.06	.1631	.70477
P-22-1	99.2	779	.13	.3685	.70625
Group C					
P-17-1	133	438	0.30	0.8759	0.70989

Description of Specimens

Falls Run Granite Gneiss:
P-19-1: See table 1.
P-6-1: See table 1.
P-27-1: See table 1.
P-73-71A: See table 1.
Falmouth Intrusive Suite:
P-6-1: Coarse-grained granite in a folded dike intruded into Holly Corner Gneiss. Major constituents are plagioclase (37 percent), quartz (27 percent), and microcline (21 percent) in allotriomorphic granular texture. Brown biotite (6 percent) has crude dimensional orientation. Chlorite (rare) locally replaces biotite. Other minor constituents include muscovite and epidote. Salem Church Quadrangle, Va., at lat 38°18′37″ N. and long 77°32′27″ W.
P-9-1: Crudely foliated, fine-grained granite in small intrusion emplaced in gneisses of the Po River Metamorphic Suite. Major constituents having allotriomorphic-granular texture are plagioclase (30 percent), microcline (30 percent), and quartz (29 percent). Muscovite (8 percent) in coarse grains is dimensionally oriented and defines the rock foliation. Reddish-brown biotite (1 percent) is a minor, finer grained mica. Plagioclase is locally clouded by "dusty" alteration, and microcline is locally poikilitic. Myrmekite (2 percent) has formed in plagioclase where it is in contact with microcline. Fredericksburg Quadrangle, Va., at lat 38°17′17″ N. and long 77°29′23″ W.
P-10-1: See table 1.
P-14-1: See table 1.
P-16-1: See table 1.
P-17-1: Fine-grained, massive, allotriomorphic-granular adamellite from west margin of pluton. Major constituents include plagioclase (45 percent), quartz (26 percent), and microcline (21 percent). Plagioclase is generally clouded with sericitic alterations; microcline is locally poikilitic. Green biotite (5 percent) and muscovite (2 percent) are chief accessory minerals. Minor minerals include myrmekite, apatite, epidote, and opaque minerals. Salem Church Quadrangle, Va., at lat 38°21′10″ N. and long 77°35′01″ W.
P-20-1: See table 1.
P-22-1: See table 1.

DECAY CONSTANTS

The isotopic and decay constants used are those recommended by the IUGS Subcommission on Geochronology (Steiger and Jager, 1977). Ages quoted from the literature are recalculated to these constants.

AGE OF INTRUSIVE GRANITES

FALLS RUN GRANITE GNEISS

The ^{238}U-^{206}Pb ages for zircons from six samples of the Falls Run Granite Gneiss (table 1) range from 411 to 347 m.y. (million years). For two samples, the ^{238}U-^{206}Pb ages and ^{235}U-^{207}Pb ages are concordant (agree) within the analytical uncertainty. Sample P–19 is concordant at 410 m.y., and sample P–5 is concordant at 348 m.y. The remaining 5 samples are discordant.

Rb-Sr whole-rock data for four samples of Falls Run are plotted on an isochron diagram in figure 2. All samples plot on the regression line within analytical uncertainty and indicate an age of 408± m.y. (uncertainty stated is the 67 percent confidence level). The initial $^{87}Sr/^{86}Sr$ is 0.7070±0.0001.

The whole-rock isochron age of 408± m.y. is, within analytical uncertainty, the same as the oldest and concordant zircon age of 410 m.y. (P–19, table 1). This age is thought to represent the time of magmatic crystallization of the Falls Run. The younger ages of five of the zircon samples may represent partial resetting of the zircon clocks by a younger event or events. A concordant age for sample P–5 (table 1) is probably fortuitous because of the large analytical uncertainty of ^{207}Pb-^{235}U ages. Another sample from the same locality, P–5A, is discordant.

FALMOUTH INTRUSIVE SUITE

Rocks of the Falmouth Intrusive Suite can be divided into at least three groups on the basis of petrographic and chemical criteria. Figure 4 is a plot of rubidium against strontium for the Falmouth. Samples of fine to medium-grained muscovite-bearing granites having high rubidium content, low strontium content, and Rb/Sr greater than 0.5 are designated as group A. Samples of fine-grained biotite granodiorite to granite having high strontium content, low rubidium content, and Rb/Sr less than 0.2 are designated as group B. A single sample of intermediate texture and composition represents a group designated as C.

For group A rocks, three samples are plotted on the whole-rock isochron diagram of figure 3. The samples plot on the regression line within analytical uncertainty and indicate an age of 322± m.y. The initial ratio is 0.7088±0.0001. Zircon sample P–10 of group A is discordant and has a ^{238}U-^{206}Pb age of 258 m.y. (table 1). This zircon contains more uranium plus thorium than do the other zircons of the Falmouth Intrusive Suite. It may have been more metamict and, therefore, more susceptible to loss of radiogenic lead than were the other zircons at the time of any younger events or during prolonged heating due to burial.

For group B rocks, ^{238}U-^{206}Pb ages for zircons range from 313 to 302 m.y. and have a mean of 309 m.y. (table 1, P–14, P–16, P–20, P–22). One sample (P–16) gives a concordant age of 309 m.y. The same four samples of group B show a range of whole-rock $^{87}Rb/^{86}Sr$ ratios (fig. 3) that is too limited to provide a precise linear regression, but a 309-m.y. age is not in conflict with the data. Because the points are close to the intercept, the initial $^{87}Sr/^{86}Sr$ ratio is determined with reasonable certainty as 0.7040±0.0007 if a 309-m.y. age is assigned.

A single whole-rock sample was analyzed from group C. It has an isotopic composition intermediate between those of the other two groups (fig. 3).

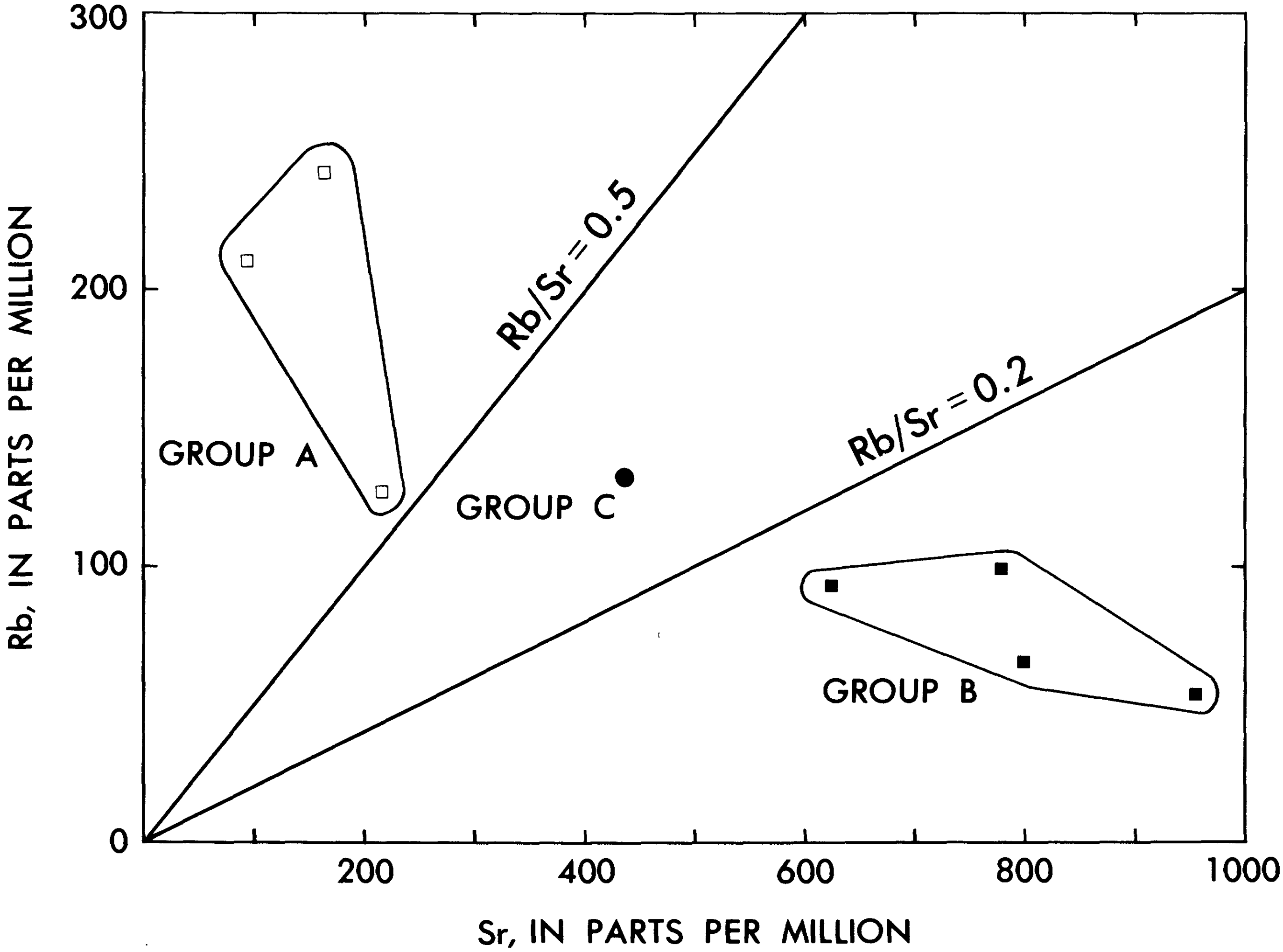

FIGURE 4. – Rb-Sr plot for the Falmouth Intrusive Suite, indicating the separation of these rocks into groups A, B, and C.

The ages of crystallization of the Falmouth Intrusive Suite are in the range 300–325 m.y. before present. The time of magmatic crystallization of group B rocks is probably best represented by the zircon ages of 309± m.y. (table 1, P–16). The time of magmatic crystallization of group A rocks is probably best represented by the whole-rock isochron age of 322±2 m.y. The younger zircon age for one sample (table 1, P–10) may reflect the influence of a later event of Permian or younger age or may indicate slow cooling and uplift following intrusion.

TIMING OF METAMORPHISM

The deformation that caused recumbent folding, described earlier, was accompanied by metamorphism that produced sillimanite and kyanite in some of the metasedimentary rocks within the area (Pavlides, 1976). This deformation and metamorphism occurred after intrusion of the Falls Run Granite Gneiss at about 410 m.y. ago and before the intrusion of the oldest Falmouth rocks at about 322 m.y. ago.

COMPARISON WITH OTHER PIEDMONT TERRANES

Paleozoic ages in the Piedmont north and south of the Fredericksburg area are similar to the ages reported here. In North Carolina and South Carolina, granitic plutons in the age range 410–380 m.y. constitute one of the major episodes recognized by Fullagar (1971). Well-determined isochrons like those for the Salisbury pluton, North Carolina (402±4 m.y., Fullagar and others, 1971), and Lowrys pluton, South Carolina (398±4 m.y., Fullagar, 1971), show them to be very similar in age to the Falls Run Granite Gneiss (408±5 m.y.) of this report. In Maryland, swarms of large pegmatite dikes were dated by Wetherill and others (1966) as 416±20 m.y. Thus, on the basis of the time scale in use by the U.S. Geological Survey in 1980 there is an apparent continuity of igneous activity along the length of the Piedmont, albeit in different tectonic belts, in Silurian to Early Devonian time. Pavlides (1976, p. 16) had considered the Falls Run Granite Gneiss (the Berea pluton of former usage) to be correlative with the Petersburg Granite of Virginia on the basis of lithologic similarity and possible age equivalence. The data summarized in this report for the Falls Run and the age indicated for the Petersburg Granite by Wright and others (1975), invalidate a correlation between these rocks.

The small plutons and dikes of the Falmouth Intrusive Suite are probably part of the extensive group of plutons 325–265 m.y. old recognized to the south in Georgia and the Carolinas by Fullagar and Butler (1979) that possibly also includes the Petersburg Granite (Wright and others, 1975). To the north in Maryland, no plutons of this age are yet known, but Wetherill and others (1966) suggested that a thermal event may have occurred from 325 to 275 m.y. ago on the basis of presumed reset Rb-Sr biotite ages and K-Ar ages in older rocks. Thus, a Pennsylvanian to Permian event or events is also suggested through much of the eastern Piedmont.

Determination of the extent and nature of events between about 410 and 325 m.y. is more subtle. We infer that the deformation that produced nappe structures in the Fredericksburg area began after about 410 m.y. and culminated before about 325 m.y. ago. To the south, Acadian deformation is evidenced in shearing, which is thought to have ended in the Charlotte belt by about 368 m.y. ago (Butler and Fullagar, 1978). To the north, lamprophyre dikes were emplaced near Great Falls on the Potomac River about 360 m.y. ago (Reed and others, 1970). In Maryland, small pegmatites intruded the Guilford quartz monzonite and Ellicott City granodiorite about 340 m.y. ago (Wetherill and others, 1966). Thus, tectonothermal events are reported throughout the Piedmont in the interval 370–340 m.y. ago, but the timing and nature of the activity were quite diverse.

CONCLUSIONS

The ages of two episodes of igneous intrusion and one deformation have been clarified in the Fredericksburg area by Rb-Sr and U-Pb age determinations. The Falls Run Granite Gneiss was intruded about 410 m.y. ago and then deformed to become part of a nappe before about 325 m.y. ago. The Falmouth Intrusive Suite was emplaced between 325 and 300 m.y. ago syntectonically and late tectonically during the Hercynian deformation. Both the 410–and the 325–300-m.y. intrusive events in the Fredericksburg area were part of similar granitic activity occurring throughout the Piedmont at those times. The initial $^{87}Sr/^{86}Sr$ of group B of the Falmouth Intrusive Suite suggests a lower crust or mantle source. However, the initial $^{87}Sr/^{86}Sr$ of group A of the Falmouth Intrusive Suite is 0.709, similar to the 0.707 of the Falls Run, and suggests crustal involvement in the magma generation of these rocks.

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