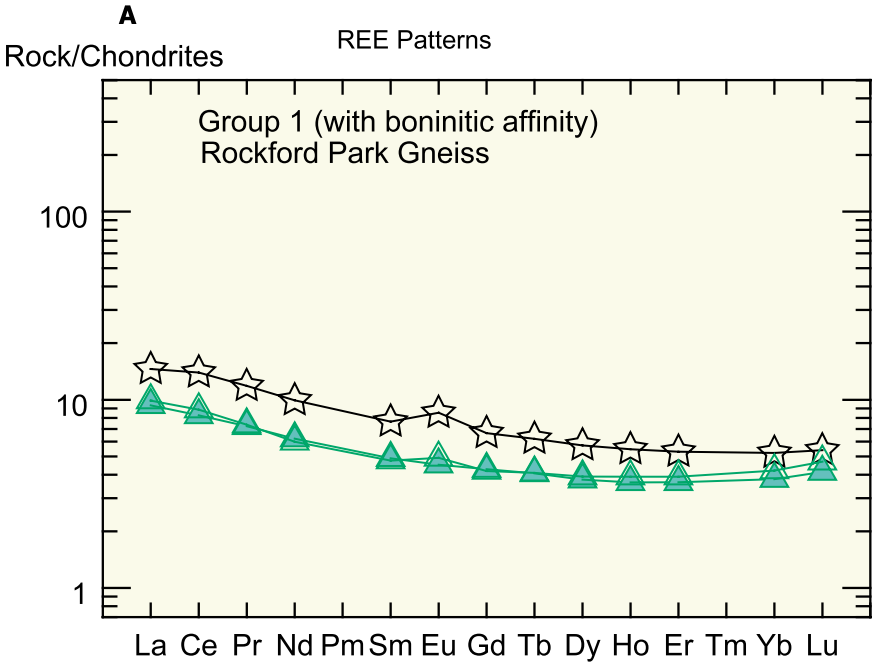
State of Delaware
DELAWARE GEOLOGICAL SURVEY
Robert R. Jordan, State Geologist

REPORT OF INVESTIGATIONS NO. 60

GEOCHEMISTRY OF THE MAFIC ROCKS, DELAWARE PIEDMONT AND ADJACENT PENNSYLVANIA AND MARYLAND: CONFIRMATION OF ARC AFFINITY

By: Margaret O. Plank[1], LeeAnn Srogi[2], William S. Schenck[1], Terry A. Plank[3]



University of Delaware
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2001

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CONTENTS

TABLES

ILLUSTRATIONS

Figure | Page

APPENDICES

Appendices | Page

GEOCHEMISTRY OF THE MAFIC ROCKS, DELAWARE PIEDMONT AND ADJACENT PENNSYLVANIA AND MARYLAND: CONFIRMATION OF ARC AFFINITY

Margaret O. Plank[1], LeeAnn Srogi[2], William S. Schenck[1], Terry A. Plank[3]

ABSTRACT

Geochemical data from Ordovician and Silurian mafic rocks in the Wilmington Complex in Delaware, the James Run Formation in Cecil County, Maryland, and the Wissahickon Formation in Delaware and Pennsylvania were collected in conjunction with preparation of a new geologic map of the Delaware-Pennsylvania Piedmont. Although concentrations of most elements may have been disrupted by metamorphism, the more stable high field strength elements, including the rare earth elements (REE), are consistent within mapped lithodemic units and are compared to modern basaltic magmas from relatively well known tectonomagmatic environments.

Analyzed mafic rocks of the Wilmington Complex are separated into six geochemical groups based on REE patterns and mantle-normalized spider diagrams. Group I rocks have boninitic affinities: They plot as boninites on discrimination diagrams, have concave-upward REE patterns, overall REE depletion, and very low Ti. Group II rocks have concave-downward REE patterns and light rare earth element (LREE) enrichments similar to arc tholeiites. Although penetrative deformation and granulite facies metamorphism have obscured igneous fabrics and contact relationships, groups I and II can be distinguished in the field. Group I rocks are mafic/felsic gneisses interlayered on a scale of inches, whereas group II rocks are thin discontinuous layers within massive felsic gneiss.

Groups III, IV, and V plus mafic samples from the James Run Formation in Cecil County are all amphibolites. Some Group III amphibolites contain quartz and possibly have a volcanic origin. The concave-downward REE patterns, LREE enrichment, and negative Nb and Ta anomalies suggest an arc affinity. Group IV amphibolites are thinly interlayered with felsic gneisses, have flat REE patterns, and negative Nb and Ta anomalies characteristic of island arc tholeiites. In the field both Groups III and IV are also interlayered and interfingered with pelitic and psammitic gneisses and quartzites of probable sedimentary origin. Samples of pillow lavas from the Gilpins Falls Member of the James Run Formation in Cecil County have flat REE patterns and negative Nb and Ta anomalies that are similar to Group IV. Group V amphibolites are gabbroic cumulates.

Group VI mafic rocks are apparently younger because igneous fabrics are preserved. REE patterns are similar to mid-ocean ridge basalts (MORB) or backarc basin basalts (BABB). Mingling of the mafic magmas with coeval granitic magmas and intrusion into felsic gneisses of Group II preclude an origin as MORB, and suggest these rocks are BABBs associated with late extension within the arc.

Chemical analysis has identified two types of amphibolites in the Wissahickon Formation: type 1 Kennett Square amphibolite with flat REE patterns similar to ocean floor basalts, and type 2 White Clay Creek amphibolite with high Fe, moderate to high Ti, and trace element patterns that suggest within plate basalts. A marginal basin, possibly a forearc setting, is proposed for the Wissahickon Formation.

Our results are similar to those for other Appalachian mafic rocks and suggest a suprasubduction zone tectonic setting for the Wilmington Complex and the James Run Formation in Cecil County, Maryland. Thus, the rocks of the Wilmington Complex plus the James Run Formation in Cecil County may be stages in a continuum that records the temporal magmatic evolution of an arc complex.

INTRODUCTION

This report presents new geochemical data from mafic rocks in the Delaware Piedmont, data from other geologists who have worked in the area, and our detailed interpretation of the analyses. It supplements Delaware Geological Survey Report of Investigations No. 59 and Geologic Map No.10 (Plank et al., 2000; Schenck et al., 2000, respectively).

Mapping in the Delaware Piedmont confronted the problems normally associated with mapping in highly metamorphosed and intensely deformed rocks with complex relationships in a densely populated area. Not only are rock exposures restricted to streambeds, artificial cuts, and rock cores, but it is often difficult to distinguish mafic, felsic, and pelitic gneisses in the field. During high grade metamorphism the major elements, with the exception of Ti, are normally mobile and cannot be reliably used to identify units; however, trace elements are more stable, particularly the incompatible high field strength elements (HFSE), including the rare earth elements (REE). Thus, the trace elements in the mafic rocks were used to geochemically group the rocks of the Wilmington Complex. By comparing the geochemical groups with their field and petrographic characteristics we found a quantitative basis for identifying map units. In addition, REE patterns, trace element spider diagrams, and various discrimination diagrams were used to interpret tectonic settings.

We sampled 16 mafic rocks in the Wilmington Complex and two in the Wissahickon Formation, and analyzed them for abundances of major and trace elements. R. C. Smith and J. H. Barnes of the Pennsylvania Geological Survey provided us with data from 31 samples: three from the Wilmington Complex, five from the James Run Formation in Cecil County, Maryland, and 23 from the

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Wissahickon Formation in Delaware and Pennsylvania. Mafic rocks rather than felsic rocks were sampled because they are more stable during high-grade metamorphism, melt at higher temperatures, are more directly derived from a mantle source, and can be used to interpret their tectono-magmatic environment.

Regional Geology

In order to understand the geological context of the rock chemistry, we provide a brief summary of the rock units and age information described in more detail in Plank et al. (2000).

The Wilmington Complex (Figure 1) was originally defined by Ward (1959) to include the igneous and metamorphic rocks across northern Delaware from Cecil County, Maryland, to Chester, Pennsylvania. Based on detailed mapping by the authors, new U-Pb zircon ages (John N. Aleinikoff, U. S. Geological Survey, personal communication, 2000), and the new geochemical data described in this report, the rock units within the Wilmington Complex have been subdivided and redefined (Plank et al., 2000; Schenck et al., 2000).

Two rock units now comprise Ward's (1959) banded gneiss. The Rockford Park Gneiss (Figure 1) is an interlayered mafic and felsic orthogneiss interpreted to be of volcanic origin. The Brandywine Blue Gneiss (Figure 1) is predominantly a felsic orthogneiss with thin discontinuous mafic layers, possibly of plutonic origin. Units mapped by Ward (1959) as amphibolite are now defined as the Faulkland Gneiss, Montchanin and Mill Creek Metagabbros, and Windy Hills Gneiss (Figure 1). The Faulkland Gneiss, predominantly massive amphibolite that interfingers with metasedimentary gneiss, and the Windy Hills Gneiss, interlayered felsic gneiss, amphibolite, and minor metasedimentary gneiss, are interpreted to be of volcanic origin. The Barley Mill Gneiss is a tonalitic pluton that intrudes the Faulkland Gneiss, and the Christianstead Gneiss is a granodioritic pluton that intrudes the Windy Hills Gneiss and the James Run Formation in Cecil County, Maryland (Figure 1). Ward (1959) originally correlated the granodioritic pluton with the Port Deposit granodiorite in Maryland; however, because the Port Deposit and the Christianstead granodiorites have intruded different units and are separated geographically by most of Cecil County, Schenck et al. (2000) mapped and named the granodiorite in Delaware as a separate body. Felsic rocks within all of these units have similar U-Pb zircon ages interpreted as the time of igneous crystallization in the Ordovician, ranging from 488±8 Ma for the Christianstead Gneiss to 470±9 for the Barley Mill Gneiss (John N. Aleinikoff, U. S. Geological Survey, personal communication, 2000).

Granitic rocks in the composite Arden Plutonic Supersuite that intrude the Brandywine Blue Gneiss are significantly younger, around 434±4 Ma (John N. Aleinikoff, U. S. Geological Survey, personal communication, 2000), consistent with their less deformed and less recrystallized character. Relatively undeformed gabbroic rocks from the Arden, Bringhurst, and Iron Hill plutons (Figure 1), and in

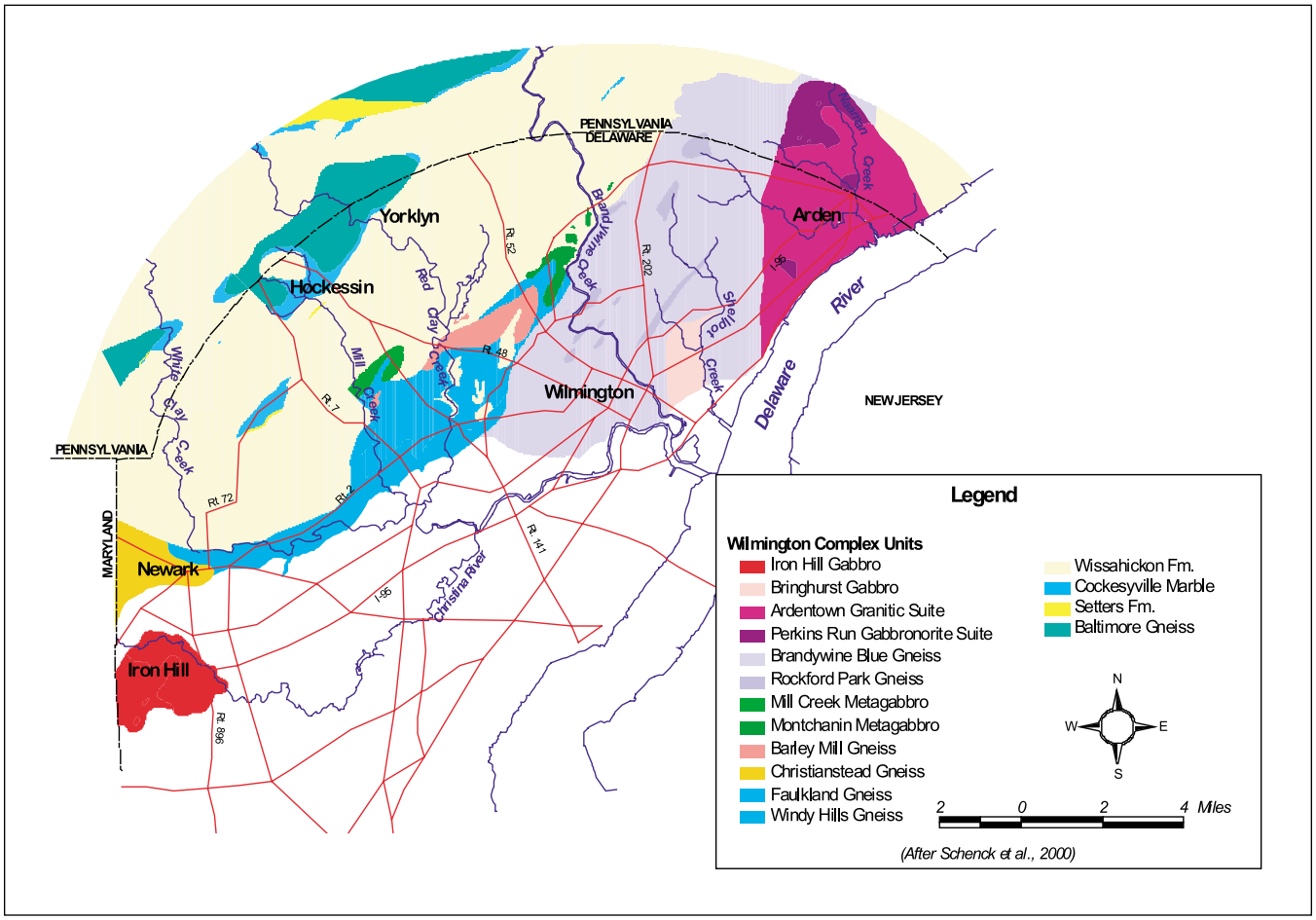

Figure 1. Generalized geologic map of the study area adapted from Schenck et al. 2000.

numerous stocks and dikes too small to map, are presumed to be of similar age. The igneous crystallization age of the Arden granitic rocks is essentially identical to the age of zircons grown during partial melting accompanying granulite facies metamorphism of the Rockford Park and Brandywine Blue Gneiss, dated at 432±6 and 428±8 Ma, respectively (John N. Aleinikoff, U. S. Geological Survey, personal communication, 2000). This suggests that magmatism accompanied regional-scale metamorphism of the Wilmington Complex in the Silurian, albeit with waning deformation. Following Ward (1959), Woodruff and Thompson (1972, 1975), and subsequent workers, we include the Silurian plutonic rocks with the Ordovician units in the Wilmington Complex.

The Wissahickon Formation, first named and studied by Bascom (1902) and Bascom and Stose (1932), is an extensive sequence of pelitic and psammitic gneiss interlayered with amphibolite that borders the Wilmington Complex to the west, north, and east (Figure 1). For a detailed summary of the history of the Wissahickon Formation in Maryland and Delaware see Schenck (1997). The relationship between the Wilmington Complex and the Wissahickon Formation has been controversial; our new data demonstrate that these units shared a common history at least during the Ordovician and Silurian. Metavolcanic rocks of the Faulkland and Windy Hills Gneiss (482±4 and 481±4 Ma, respectively; John N. Aleinikoff, U. S. Geological Survey, personal communication, 2000) are interlayered and interfingered with metasedimentary rocks of the Wissahickon Formation. Plutonic rocks of the Brandywine Blue Gneiss and the Barley Mill Gneiss (476±6 and 470±9 Ma, respectively, John N. Aleinikoff, U. S. Geological Survey, personal communication, 2000) contain xenoliths of pelitic gneiss that were most likely derived from the Wissahickon Formation. In Pennsylvania north of the map area of Figure 1, a mafic dike essentially identical in composition to the mafic layers of the Rockford Park Gneiss crosscuts an outcrop of both the Wissahickon Formation and Brandywine Blue Gneiss (Bosbyshell et al., 1999). The Silurian Arden pluton intrudes both the Brandywine Blue Gneiss and the Wissahickon Formation (Figure 1). Metamorphic grade in the Wissahickon Formation decreases with distance from the Wilmington Complex, suggesting its metamorphism is coeval with the granulite facies metamorphism in the Wilmington Complex. On the basis of these field relationships, we conclude that the emplacement of the Wissahickon Formation is either coeval with or older than the Wilmington Complex.

Many workers have suggested correlations between the Wilmington Complex and the James Run Formation in Maryland. Southwick and Fisher (1967) originally defined the James Run Gneiss as the interlayered quartz amphibolite and biotite-quartz plagioclase gneiss exposed along James Run in Harford County, Maryland. Subsequently, Higgins (1971, 1972) formally defined the James Run Formation to include all the metavolcanic and metavolcaniclastic rocks that crop out in the northeastern Maryland Piedmont, and he considered the layered rocks of the Wilmington Complex to be correlative with the James Run Formation. Portions of Ward's (1959) Wilmington Complex amphibolite units were placed in the James Run Formation by Pickett (1976), Hager (1976), and Thompson (1979). Higgins (1990) traced the Big Elk Member of the James Run Formation for over one half mile into Delaware. However, the U-Pb zircon ages of the Windy Hills Gneiss and Faulkland Gneiss (481±4 and 482±4) are significantly older than the ages for the type section of the James Run Formation in Baltimore, Maryland (454±5 to 464±5, Horton et al., 1998). Further, the Christianstead Gneiss obscures the relationships between the Windy Hills Gneiss in Delaware and the Big Elk Member in Maryland (Figure 1). Schenck et al. (2000), therefore, assigned the Christianstead, Windy Hills, and Faulkland gneisses to the Wilmington Complex. In this report, we compare the geochemistry of mafic units mapped as James Run Formation in Cecil County, Maryland, with units in the Wilmington Complex to evaluate a possible correlation.

Samples and Analytical Methods

Of the 16 mafic samples collected from the Wilmington Complex, 8 are from the unit shown on older geologic maps of the Delaware Piedmont as the banded gneiss and 8 are from the unit described as amphibolite (Ward, 1959; Woodruff and Thompson, 1972, 1975). Within the granulite-grade banded gneiss we sampled the mafic gneiss interlayered on a centimeter scale with felsic gneiss, the very thin bands of mafic rocks in the massive felsic gneiss, and the massive coarse-grained amphibolite that occurs along the contact between the banded gneiss and the amphibolite.

Data from R. C. Smith and J. H. Barnes were received from personal communication and from a series of unpublished reports entitled "Wilmington Complex metabasalts, Pennsylvania and Delaware 1993;" "James Run Formation Metabasalts, Cecil County, Maryland, 1993;" "White Clay Creek Amphibolites, Pennsylvania and Delaware, 1994 and 2001;" and "Kennett Square Amphibolites, Pennsylvania and Delaware, 1994." Smith and Barnes (1994) published some of these data in a field guide.

The geochemical data for all samples are listed in Table 1. An electronic version of the data in Table 1 is available in the DGS Data Repository[1]. Sample locations are shown on a generalized regional geologic map (Figure 2) and are described in Appendix II.

The choice of samples for this study was partly controlled by availability of fresh samples. Rock cores and rocks blasted during construction and were preferred over weathered samples from natural exposures. After collection, the samples were trimmed of weathered material, crushed, ground, and pulverized. To minimize contamination, the samples were powdered in a ceramic mortar and pestle. The powders were analyzed by T. A. Plank at the University of Kansas Plasma Analytical Laboratory for whole-rock major elements and selected trace elements. All trace elements were determined by Inductively Coupled Plasma-Mass Spectrometry (ICP-MS) following HF:HNO_3 digestions. The analyses were calibrated using standard reference materials W2, and in-house mid-ocean ridge basalt (MORB) (MAR) and Kilauea (K1919) standards digested using the same procedure. Major elements were determined on the same solutions using an Inductively Coupled Plasma-Atomic Emission Spectrometer. Further analytical details may be found in Johnson and Plank (1999). Adsorbed water and loss on ignition (LOI) were determined gravimetically by Micro-Analysis, Inc., Wilmington, Delaware, following heating to 120˚C overnight and 900˚C for 30 minutes respectively.

[1]Geochemistry data are in the form of an Excel spreadsheet called RI60 and are accessible through the DGS Data Repository located under Publications on the DGS web site at http://www.udel.edu/dgs.

Table 1. Geochemical data for Wilmington Complex, Wissahickon Formation, and James Run Formation samples used in this report and previously unpublished.

Wilmington Complex Sample Geochemical Data

Sample	Group	DGS No.	DGS Sampe No.	SiO[2]	TiO[2]	Al[2]O[3]	Fe[2]O[3]	FeO	MgO	MnO	CaO	Na[2]O	Cr	Sm	Th
NATURAL	I	Bd22-a	43900	50.96	0.35	17.90	10.01	9.00	6.83	0.17	10.16	2.86	35.89	1.17	0.07
RAMP	I	Bd43-a	43901	51.12	0.28	13.69	10.33	9.30	10.35	0.23	10.67	2.64	533.32	0.75	0.25
ROCKFORD	I	Bd41-b	43428	49.40	0.33	17.05	10.78	9.70	7.52	0.17	11.55	2.53	248.93	0.73	0.32
NEWPORT	II	Cc34-41	24860	52.20	1.16	17.07	8.34	7.50	6.89	0.16	9.87	3.12	42.60	5.15	1.29
TOWN	II	Bd13-d	43902	56.26	0.46	16.43	9.87	8.88	5.39	0.18	8.77	2.36	18.15	3.93	0.17
ZOO	II	Bd52-a	43746	52.05	0.32	13.68	10.99	9.89	9.30	0.24	10.90	2.13	452.49	2.04	0.12
PACKARD	III	Bc53-a	42352	59.12	0.99	15.77	8.95	8.05	3.18	0.16	7.92	3.15	5.75	3.93	4.64
BSP	III	Cc12-a	43478	53.34	0.42	13.33	9.18	8.26	11.37	0.23	10.66	0.76	599.49	2.09	1.77
HYDE	III	Bc52-j	43380-b	53.02	0.56	14.30	8.94	8.04	9.61	0.17	9.92	2.71	470.99	1.77	1.05
HAGLEY	III	Bd31-d	43545	56.08	0.37	14.55	7.58	6.82	8.51	0.12	9.97	2.46	481.91	1.88	0.42
HAVEG	IV	Cc22-c	41923	50.88	0.84	16.55	9.82	8.84	7.57	0.21	11.55	1.43	347.43	2.04	1.70
WINDY	IV	Cb42-c	43425	49.33	0.77	15.84	9.98	8.98	8.27	0.19	11.45	2.70	315.79	1.85	0.39
JRBEWH (S&B)*	IV	JRBEWH		48.89	0.76	15.98	8.43	8.98	8.32	0.20	11.66	2.60	391.00	1.90	0.80
GREEN	IV	Cb34-d	43517-b	50.67	0.65	16.56	8.89	8.00	7.72	0.15	11.38	2.84	342.24	1.54	0.42
MILLCREEK	V	Bb55-b	43475	41.64	1.58	16.27	20.12	18.10	6.68	0.22	12.23	0.59	8.23	0.86	0.09
BCSP	V	Bd21-a	41931	47.81	0.49	16.94	9.64	8.68	0.19	10.31	12.82	0.93	206.28	1.33	0.09
WC3	VI	WC3		49.28	2.75	15.71	12.85	11.56	6.42	0.20	9.67	3.20	30.00	4.50	0.10
BRING (S&B)*	VI	BRING		48.87	2.00	15.74	12.71	11.44	7.55	0.24	10.34	2.47	140.00	5.40	0.30
HERCWEST	Not Assigned	Bc52-f	42168	50.81	1.64	14.93	13.45	12.10	6.06	0.22	11.12	0.99	134.21	4.12	0.36

*Reference S&B Smith and Barnes, Unpublished report, Pennsylvania Geological Survey, 1993

Sample	Group	DGS No.	DGS Sampe No.	K[2]O	P[2]O[5]	H2O -(120C)	LOI	Sr	Rb	Nb	Cs	Ba	Sc	V
NATURAL	I	Bd22-a	43900	0.39	0.03	0.04	0.30	148.75	2.21	1.55	0.03	63.00	39.60	226.87
RAMP	I	Bd43-a	43901	0.19	0.03	0.06	0.40	89.10	0.80	0.87	0.04	23.50	42.34	214.63
ROCKFORD	I	Bd41-b	43428	0.40	0.02	0.07	0.17	92.40	2.82	1.42	0.06	78.00	41.60	308.71
NEWPORT	II	Cc34-41	24860	0.53	0.14	0.09	0.43	228.18	4.72	6.34	0.08	105.80	29.13	154.72
TOWN	II	Bd13-d	43902	0.22	0.06	0.19	0.12+	128.66	0.98	4.10	0.05	82.00	34.76	225.74
ZOO	II	Bd52-a	43746	0.12	0.04	0.05	0.20	116.67	1.20	1.81	0.02	51.80	43.50	213.00
PACKARD	III	Bc53-a	42352	0.49	0.12	0.04	0.13	222.11	4.11	7.67	0.05	101.14	28.22	190.70
BSP	III	Cc12-a	43478	0.26	0.07	0.06	0.32	108.99	5.02	1.73	0.11	3.95	36.59	197.55
HYDE	III	Bc52-j	43380-b	0.26	0.09	0.08	0.34	157.38	2.17	2.11	0.02	22.38	33.06	225.79
HAGLEY	III	Bd31-d	43545	0.33	0.05	0.39	0.04+	131.56	1.90	2.26	0.05	90.00	26.67	152.19
HAVEG	IV	Cc22-c	41923	0.32	0.07	0.10	0.66	161.91	3.12	2.22	0.04	48.44	36.51	234.92
WINDY	IV	Cb42-c	43425	0.98	0.06	0.04	0.40	131.08	20.17	1.96	0.52	90.51	38.56	251.31
JRBEWH	IV	JRBEWH		0.86	0.06	0.03	0.29	127.00	23.00	2.10	0.40	96.00	38.00	233.00
GREEN	IV	Cb34-d	43517-b	0.78	0.04	0.03	0.29	116.83	10.01	1.46	0.05	154.05	34.37	237.82
MILLCREEK	V	Bb55-b	43475	0.06	0.36	0.26	142.00	0.84	0.85	0.02	12.03	58.01	845.90	
BCSP	V	Bd21-a	41931	0.16	0.03	0.04	0.65	141.59	2.33	0.77	0.03	14.30	44.05	194.09
WC3	VI	WC3		0.18	0.22			260.00	9.50	11.00		90.00	34.00	284.00
BRING	VI	BRING		0.24	0.34			308.00	9.50	6.00		118.00	33.00	373.00
HERCWEST	Not Assigned	Bc52-f	42168	0.34	0.19	0.09	0.17	132.93	1.65	5.79	0.01	8.36	40.23	314.21

Table 1. Geochemical data for Wilmington Complex, Wissahickon Formation, and James Run Formation samples used in this report and previously unpublished. *Continued*

Wilmington Complex Sample Geochemical Data

Sample	Group	DGS No.	DGS Sampe No.	Co	Ni	Cu	Y	Zr	Ga	Zn	La	Ce	Pr	Nd
NATURAL	I	Bd22-a	43900	37.69	32.91	0.26	8.31		14.23	87.15	3.45	8.55	1.13	4.64
RAMP	I	Bd43-a	43901	43.26	107.63	0.73	5.45		10.65	154.35	2.22	5.06	0.69	2.90
ROCKFORD	I	Bd41-b	43428	39.80	56.87	5.35	6.23		14.27	79.00	2.35	5.43	0.70	2.80
NEWPORT	II	Cc34-41	24860	34.11	70.49	54.97	31.94		15.41	60.94	11.81	30.92	4.49	19.96
TOWN	II	Bd13-d	43902	28.52	17.19	7.30	24.02		16.61	91.43	8.91	24.66	3.78	16.79
ZOO	II	Bd52-a	43746	42.24	83.11	2.96	12.18		11.67	105.63	4.68	12.89	1.92	8.35
PACKARD	III	Bc53-a	42352	22.12	1.79	5.41	24.35		17.82	85.47	14.73	33.57	4.28	17.01
BSP	III	Cc12-a	43478	41.84	158.25	4.38	10.81		14.04	221.92	7.95	17.59	2.28	9.35
HYDE	III	Bc52-j	43380-b	41.34	198.36	8.22	13.06		14.70	73.91	5.00	11.50	1.55	6.75
HAGLEY	III	Bd31-d	43545	34.28	152.85	0.49	13.33		11.79	44.85	7.98	18.54	2.27	8.61
HAVEG	IV	Cc22-c	41923	39.75	108.25	88.08	20.10		14.83	75.14	3.24	8.17	1.28	6.29
WINDY	IV	Cb42-c	43425	40.92	79.42	5.52	16.50		15.10	79.44	3.98	8.80	1.36	6.26
JRBEWH	IV	JRBEWH		42.00	82.00	7.00	21.00	42.00	15.00	70.00	4.80	9.60	1.40	6.50
GREEN	IV	Cb34-d	43517-b	38.78	98.41	37.13	14.15		14.83	75.49	3.07	7.18	1.07	4.94
MILLCREEK	V	Bb55-b	43475	57.63	8.53	69.91	5.14		19.58	124.11	1.15	3.16	0.53	2.68
BCSP	V	Bd21-a	41931	48.15	105.25	106.32	9.05		14.54	78.00	2.26	5.68	0.88	4.35
WC3	VI	WC3			40.00	50.00	36.00	120.00	0.00	78.44	7.50	21.00		15.00
BRING	VI	BRING			58.00	19.00	34.00	127.00	0.00	105.00	11.70	32.00		21.00
HERCWEST	Not Assigned	Bc52-f	42168	45.87	51.21	95.07	36.20		17.41	207.33	6.27	17.99	2.83	13.64

Sample	Group	DGS No.	DGS Sampe No.	U	La/Sm	Yb/Sm	La/Lu	La/Lu ratio	La conc.	La/Nb	Ti	Mg#	AltIndex
NATURAL	I	Bd22-a	43900	0.01	2.95	0.76	25.21	2.6	11.11	2.23	2086	57.49	35.68
RAMP	I	Bd43-a	43901	0.08	2.96	0.86	21.1	2.2	7.12	2.55	1672	66.48	44.19
ROCKFORD	I	Bd41-b	43428	0.07	3.23	0.98	19.72	2	7.55	1.65	1966	58.00	35.99
NEWPORT	II	Cc34-41	24860	0.33	2.29	0.55	27.91	2.9	37.96	1.86	6960	62.38	36.33
TOWN	II	Bd13-d	43902	0.03	2.27	0.65	22.33	2.3	28.65	2.17	2740	52.18	33.50
ZOO	II	Bd52-a	43746	0.02	2.29	0.64	22.37	2.3	15.03	2.58	1894	62.64	41.96
PACKARD	III	Bc53-a	42352	0.90	3.75		38.97	4	47.36	1.92	5911	38.64	24.90
BSP	III	Cc12-a	43478	0.26	3.8	0.51	48.48	5	25.56	4.59	2494	71.03	50.46
HYDE	III	Bc52-j	43380-b	0.32	2.83	0.76	24.04	2.5	16.08	2.37	3363	68.00	43.87
HAGLEY	III	Bd31-d	43545	0.08	4.24	0.78	34.25	3.5	25.66	3.54	2206	68.96	41.56
HAVEG	IV	Cc22-c	41923	0.76	1.59	0.98	10.38	1.1	10.42	1.46	5047	60.45	37.82
WINDY	IV	Cb42-c	43425	0.18	2.16	0.88	15.55	1.6	12.80	2.04	4610	62.12	39.52
JRBEWH	IV	JRBEWH		0.20							4616		
GREEN	IV	Cb34-d	43517-b	0.08	1.99	0.89	14.21	1.5	9.87	2.1	3879	63.36	37.41
MILLCREEK	V	Bb55-b	43475	0.03	1.35	0.64	14.02	1.4	3.70	1.37	9466	39.71	34.44
BCSP	V	Bd21-a	41931	0.03	1.7	0.69	15.81	1.6	7.27	0.97	2907	65.12	41.62
WC3	VI	WC3		0.20	1.67	0.78	15.63	1.6	24.12	0.79	16486	49.60	33.90
BRING	VI	BRING		0.10	2.17	0.66	21.67	2.2	37.62	1.23	11990	54.05	37.82
HERCWEST	Not Assigned	Bc52-f	42168	0.12	1.52	0.85	11.67	1.2	20.22	1.08	9338	47.09	34.56

Wilmington Complex Sample Geochemical Data

Sample	Group	DGS No.	DGS Sampe No.	Eu	Gd	Tb	Dy	Ho	Er	Yb	Lu	Hf	Ta	Pb
NATURAL	I	Bd22-a	43900	0.50	1.37	0.23	1.45	0.31	0.88	0.89	0.14		0.08	2.71
RAMP	I	Bd43-a	43901	0.26	0.88	0.15	0.96	0.21	0.60	0.64	0.11		0.06	2.80
ROCKFORD	I	Bd41-b	43428	0.29	0.86	0.15	0.99	0.22	0.65	0.72	0.12		0.07	3.24
NEWPORT	II	Cc34-41	24860	1.45	5.59	0.94	5.58	1.14	3.12	2.83	0.42		0.35	3.65
TOWN	II	Bd13-d	43902	1.07	3.88	0.64	3.92	0.83	2.43	2.55	0.40		0.15	3.48
ZOO	II	Bd52-a	43746	0.59	2.14	0.35	2.14	0.45	1.29	1.31	0.21		0.10	1.88
PACKARD	III	Bc53-a	42352	1.24	4.26	0.70	4.26	0.89	2.50	2.43	0.38		0.58	5.38
BSP	III	Cc12-a	43478	0.76	2.08	0.33	1.96	0.40	1.12	1.06	0.16		0.11	3.70
HYDE	III	Bc52-j	43380-b	0.65	2.10	0.36	2.25	0.48	1.38	1.34	0.21		0.12	2.01
HAGLEY	III	Bd31-d	43545	0.67	2.09	0.36	2.27	0.49	1.41	1.47	0.23		0.17	7.82
HAVEG	IV	Cc22-c	41923	0.75	2.82	0.50	3.29	0.72	2.05	2.00	0.31		0.19	3.24
WINDY	IV	Cb42-c	43425	0.72	2.42	0.42	2.70	0.59	1.66	1.62	0.26		0.30	2.79
JRBEWH	IV	JRBEWH		0.80	2.40	0.50	3.00	0.60	1.90	1.80	0.28	1.00	0.30	
GREEN	IV	Cb34-d	43517-b	0.61	2.09	0.38	2.40	0.51	1.43	1.37	0.22		0.11	4.01
MILLCREEK	V	Bb55-b	43475	0.48	1.00	0.17	1.06	0.22	0.58	0.54	0.08		0.05	0.62
BCSP	V	Bd21-a	41931	0.59	1.58	0.27	1.69	0.36	0.97	0.92	0.14		0.05	1.71
WC3	VI	WC3		1.63		1.10				3.49	0.48		0.50	
BRING	VI	BRING		1.93		1.00				3.58	0.54	3.30	0.30	
HERCWEST	Not Assigned	Bc52-f	42168	1.41	5.33	0.94	5.94	1.30	3.65	3.50	0.54		0.40	4.60

Wissahickon Formation Sample Geochemical Data

Sample No	Type	Type Name	DGS Sampe No.	SiO[2]	TiO[2]	Al[2]O[3]	Fe[2]O[3]	MgO	MnO	CaO	Na[2]O	K[2]O	P[2]O[5]	LOI	Total
LUCK (S&B)*	1	Kennett Sq.		47.93	1.29	14.08	11.92	8.4	0.2	11.52	2.59	0.5	0.08	0.6	99.1
KS (S&B)*	1	Kennett Sq.		48.99	1.25	15.18	11.07	7.62	0.17	9.46	4.42	0.32	0.12	0.38	99.0
WICK (S&B)*	1	Kennett Sq.		43.89	1.25	15.54	12	7.14	0.16	14.57	2.03	0.38	0.18	0.59	97.7
ROSE (S&B)*	1	Kennett Sq.		46.8	0.94	14.09	10.73	6.71	0.24	18.65	1.72	0.6	0.2	0.05	100.7
BRNTML (S&B)*	1	Kennett Sq.		46.65	0.87	15.55	10.51	8.47	0.18	12.65	2.72	0.62	0.12	0.7	99.1
CHFD (S&B)*	1	Kennett Sq.		46.24	0.85	14.26	10.64	7.61	0.17	15.32	1.85	0.2	0.2	0.76	98.1
BRANDY2 (S&B)*	1	Kennett Sq.		47.03	0.78	14.75	11.12	8.12	0.19	14.43	2.41	0.5	0.04	0.68	100.1
WCCMBIV (S&B)*	2	White Clay		45.79	4.75	13.7	16.83	4.91	0.2	7.95	2.77	0.63	0.38	0.49	98.4
YRKLYN (S&B)*	2	White Clay		47.13	4.64	11.86	18.14	5	0.26	9.33	2.36	0.78	0.48	0.35	100.3
LANS (S&B)*	2	White Clay		46.64	4.5	12.13	17.67	4.51	0.24	8.59	1.95	0.58	0.42	0.37	97.6
WCCW (S&B)*	2	White Clay		43.88	3.44	12.74	19.04	6.52	0.2	10.4	1.82	0.48	0.28	0.5	99.3
LANM (S&B)*	2	White Clay		47.67	3.04	11.62	15.44	6.54	0.19	10.93	2	0.44	0.22	0.75	98.9
WCCMBI (S&B)*	2	White Clay		47.02	2.88	13.48	18.36	5.52	0.24	9.72	1.5	0.76	0.28	0.52	100.3
GREENLAWN2 (S&B)*	2	White Clay		46.86	2.86	12.95	18.66	5.18	0.22	9.14	1.59	0.45	0.24	1.72	99.9
WCCMBIII (S&B)*	2	White Clay		48.24	2.64	14.7	14.64	5.8	0.18	9.7	2.6	0.56	0.4	0.68	100.1
WCCMC (S&B)*	2	White Clay		51.21	2.5	14.07	13.17	6.26	0.17	8.91	2.33	0.49	0.27	0.45	99.8
WCCN2 (S&B)*	2	White Clay		48.54	2.38	13.82	16.84	6	0.22	9.6	1.3	0.68	0.28	0.58	100.2
WCCMBII (S&B)*	2	White Clay		47.23	2.36	16.92	13.01	5.88	0.19	10.5	2.22	0.58	0.25	0.47	99.6
MP5 (S&B)*	2	White Clay		48.39	2.04	14.71	12.59	7.19	0.17	11.01	2.35	0.32	0.24	0.58	99.6
WCCMBI 10-20cm (S&B)*	2	White Clay		49.64	1.98	13.78	14.31	6.25	0.2	9.66	2.13	0.65	0.28	0.75	99.6
WCCW+W (S&B)*	2	White Clay		49.78	1.97	14.54	13.88	6	0.21	10.28	1.74	0.5	0.17	0.047	99.5
LANN (S&B)*	2	White Clay		48.14	1.94	14.08	11.81	7.37	0.17	11.32	2.36	0.4	0.24	0.82	98.6
WCC (S&B)*	2	White Clay		49.53	1.66	14.49	13.31	6.42	0.19	9.9	2.27	0.5	0.2	0.65	99.1
HERCRR (Plank)*	2	White Clay	42295	52.43	2.06	13.08	14.07	6.27	0.271	9.69	1.37	0.56	0.19		
WOODDALE (Plank)*	2	White Clay		49.28	3.9	12.32	18.49	5.28	0.226	8.64	1.27	0.57	0.40	0.11	100.4
SADDLE (McEwen)*	1	Kennett Sq.	43507	48.58	0.18	16.15	7.11	12.15	0.14	14.06	0.62	0.11	0	0.71	99.92
COTSWOLD (McEwen)*	1	Kennett Sq.	43506	46.19	0.98	15.15	12.79	8.89	0.2	11.85	2.22	0.76	0.12	0.42	99.54

***Reference**	S&B	Smith and Barnes, Unpublished report, Pennsylvania Geological Survey, 1994
	Plank	Data this study
	McEwen	McEwen, 1997

Table 1. Geochemical data for Wilmington Complex, Wissahickon Formation, and James Run Formation samples used in this report and previously unpublished. *Continued*

Wissahickon Formation Sample Geochemical Data

Sample No	Type	Type Name	DGS Sampe No.	Rb	Nb	Ce	Ba	Sc	V	Cr	Co	Ni	Cu	Y	Zr	Ga	Zn
LUCK	1	Kennett Sq.		10	6	11	190	50	282	330	51	90	160	24	60		
KS	1	Kennett Sq.		23	7	11	160	38	266	240	49	90	440	24	70		110
WICK	1	Kennett Sq.		<10	5	17	38	34	269	280	53	171	1	22	86		91
ROSE	1	Kennett Sq.		11	6	14	502	32	256	320	42	129	86	30	78		71
BRNTML	1	Kennett Sq.		<10	3	11	90	38	234	340	46	126	23	20	62		71
CHFD	1	Kennett Sq.		<10	2	5	41	45	290	330	41	80	110	26	56		50
BRANDY2	1	Kennett Sq.		<10	2	4	68	45	280	310	48	90	250	20	49		45
WCCMBIV	2	White Clay		<10	28	43	118	36	284	80	54	41	30	41	261		120
YRKLYN	2	White Clay		20	19	55	237	33	442	70	52	25	90	50	264		222
LANS	2	White Clay		<10	27	49	230	30	450	1.9	45	20	280	50	280		150
WCCW	2	White Clay		16	13	40	126	44	635	70	77	131	246	22	131		134
LANM	2	White Clay		14	18	37	160	46	444	4.8	53	80	245	38	160		130
WCCMBI	2	White Clay		<10	14	39	72	51	525	85	65	54	131	28	125		123
GREENLAWN2	2	White Clay		10	11	30	154	51	713	110	56	56	127	33	130	19	129
WCCMBIII	2	White Clay		<10	17	50	46	39	283	200	51	69	26	30	164		102
WCCMC	2	White Clay		3	14	39	105	29	307	159	48.1	110	26	36	180	19	162
WCCN2	2	White Clay		12	14	36	224	52	423	180	67	66	152	23	122		124
WCCMBII	2	White Clay		14	18	37	88	28	234	170	45	111	28	24	156		101
MP5	2	White Clay		<10	11	27	95	27	245	240	49	209	149	28	124		101
WCCMBI 10-20cm	2	White Clay		5	12	29	124	38	324	121	49.2	57	37	31	126	19	167
WCCW+W	2	White Clay		3	12	33	149	47	372	171	50.3	44	99	29	124	23	80
LANN	2	White Clay		11	9	20	130	28	290	240	41	130	120	26	110		85
WCC	2	White Clay		<10	10	26	188	34	273	140	50	85	99	24	108		102
HERCRR	2	White Clay	42295	4.9	11.1	32	75	37.15	353	141	46.6	78.8	46	30.4		18.6	128.4
WOODDALE	2	White Clay		3	22.24	52	124	36.3	516	21		59.6	131	45.8	268		121.3
SADDLE	1	Kennett Sq.	43507	5	2	2	12					115	298	27	39	14	95
COTSWOLD	1	Kennett Sq.	43506														

Sample No	Type	Type Name	DGS Sampe No.	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Yb	Lu	Hf	Ta
LUCK	1	Kennett Sq.		11		8	2.3	0.87		0.6				2.31	0.36	1.4	0.2
KS	1	Kennett Sq.		11		7	2.2	0.88		0.6				2.43	0.33	1.6	0.4
WICK	1	Kennett Sq.		17		11	3.1	1.06		0.6				2.38	0.36	1.9	0.7
ROSE	1	Kennett Sq.		14		8	2.3	0.87		0.5				2.2	0.34	1.6	0.4
BRNTML	1	Kennett Sq.		11		8	2.4	0.83		0.6				2.12	0.33	1.3	0.6
CHFD	1	Kennett Sq.		5		5	1.8	0.7		0.5				2.57	0.4	1.2	0.1
BRANDY2	1	Kennett Sq.		4		4	1.5	0.55		0.4				2.4	0.38	1	0.4
WCCMBIV	2	White Clay		43		30	8.1	2.64		1.5				4.35	0.58	6.7	1.2
YRKLYN	2	White Clay		55		37	9.7	2.74		1.7				4.14	0.6	7.1	1.6
LANS	2	White Clay		49		32	7.8	2.75		1.4				3.64	0.52	6.6	1.1
WCCW	2	White Clay		40		26	6.2	2.03		1.3				2.82	0.4	4.7	0.6
LANM	2	White Clay		37		25	6.2	2.2		1.2				3.19	0.44	4.3	0.9
WCCMBI	2	White Clay		39		23	5.6	1.82		1.1				3.45	0.51	3.9	0.7
GREENLAWN2	2	White Clay		30	4.27	21	5.3	1.85	6	1	5.9	1.2	3.4	2.97	0.43	3	0.8
WCCMBIII	2	White Clay		50		34	8	2.73		1.4				3.55	0.5	5.2	0.9
WCCMC	2	White Clay		39	5.66	27	6.7	2.18	6.75	1.2	6.51	1.26	3.62	3.12	0.41	4.8	1.2
WCCN2	2	White Clay		36		25	5.7	1.87		1.2				3.32	0.47	4.1	1.2
WCCMBII	2	White Clay		37		23	5.5	1.93		1				2.46	0.35	3.7	0.4
MP5	2	White Clay		27		17	4.8	1.58		1				2.11	0.31	3	1
WCCMBI 10-20cm	2	White Clay		29	4.38	20	5.1	1.72	5.33	1	5.55	1.1	3.3	3.09	0.43	3.2	1
WCCW+W	2	White Clay		33	4.41	20	5.1	1.85	5.57	1	5.6	1.1	3.2	2.96	0.42	3.6	0.8
LANN	2	White Clay		20		12	3.3	1.14		0.7				1.62	0.23	2.7	0.3
WCC	2	White Clay		26		17	4.3	1.41		0.8				2.37	0.38	2.8	0.7
HERCRR	2	White Clay	42295	32	4.52	19.93	5.1	1.69	5.69	0.94	5.56	1.12	3.02	2.67	0.4		0.76
WOODDALEQUARRY	2	White Clay		51.77	7.27	33.42	8.6	2.68	9.42	1.61	8.47	1.66	4.25	3.56	0.53		2.04
SADDLE	1	Kennett Sq.	43507	2													
COTSWOLD	1	Kennett Sq.	43506														

Wissahickon Formation Sample Geochemical Data

Sample No	Type	Type Name	DGS Sampe No.	Th	U	Ti	La/Lu
LUCK	1	Kennett Sq.		0.3	<0.2	7734	11.4
KS	1	Kennett Sq.		0.3	<0.1	7493	13.3
WICK	1	Kennett Sq.		0.6	<0.1	7493	18.9
ROSE	1	Kennett Sq.		0.4	<0.1	5635	16.5
BRNTML	1	Kennett Sq.		0.4	<0.1	5215	12.4
CHFD	1	Kennett Sq.		0.1	<0.1	5095	3
BRANDY2	1	Kennett Sq.		0.1	<0.1	4676	2.9
WCCMBIV	2	White Clay		1.9	<0.1	28476	26.4
YRKLYN	2	White Clay		1.8	0.6	27816	35.8
LANS	2	White Clay		1.5	<0.5	26977	42.3
WCCW	2	White Clay		1.4	0.8	20622	37.3
LANM	2	White Clay		1.1	0.7	18225	39.3
WCCMBI	2	White Clay		1.8	1.4	17266	30
GREENLAWN2	2	White Clay		1.4	0.5	17145	31.6
WCCMBIII	2	White Clay		1.8	0.8	15827	36.8
WCCMC	2	White Clay		3.5	0.7	14987	41
WCCN2	2	White Clay		1.6	<0.1	14268	27.2
WCCMBII	2	White Clay		1.1	0.3	14148	44
MP5	2	White Clay		0.8	<0.1	12230	34.2
WCCMBI 10-20cm	2	White Clay		2.3	0.6	11870	30.5
WCCW+W	2	White Clay		1.4	0.4	11810	31.7
LANN	2	White Clay		0.7	<0.5	11630	37
WCC	2	White Clay		1.2	<0.1	9952	41.1
HERCRR	2	White Clay	42295	1.23	0.4	12350	33.3
WOODDALE	2	White Clay		1.803	0.3	23381	36.8
SADDLE	1	Kennett Sq.	43507	1		1079	
COTSWOLD	1	Kennett Sq.	43506			5875	

James Run Formation, Cecil County, Maryland

Sample No.	Unit	SiO[2]	Al[2]O[3	Fe[2]O[3]	MgO	MnO	CaO	Na[2]O	K[2]O	P[2]O[5]	LOI%	Total %
JRFMC (S&B)*	Frenchtown Member	53.27	13.02	16.45	3.29	0.28	7.22	3.25	0.42	0.62	0.90	100.88
JRGFAS (S&B)*	Gilpins Falls Member	60.21	14.56	9.96	2.38	0.17	5.44	5.25	0.16	0.30	0.41	100.32
JRGFA (S&B)*	Gilpins Falls Member	58.95	12.89	11.64	2.41	0.22	6.43	3.48	0.34	0.34	0.58	98.75
JRFMV (S&B)*	Frenchtown Member	66.24	13.56	5.48	2.26	0.08	3.54	5.42	0.52	0.24	0.86	99.42
JRS (S&B)*	dike	56.84	15.64	11.70	3.54	0.20	4.86	4.98	0.72	0.08	1.34	100.78

Sample No.	Unit	Sr	Nb	Cs	Ba	Sc	V	Cr	Co	Ni	Cu	Y
JRFMC	Frenchtown Member	140.0	6.0	<0.2	70.0	33.0	76.0	3.4	15.0	<10	50.0	52.0
JRGFAS	Gilpins Falls Member	208.0	11.0	0.4	46.0	21.0	117.0	4.0	14.0	10.0	14.0	56.0
JRGFA	Gilpins Falls Member	160.0	8.0	<0.2	90.0	21.0	110.0	3.0	17.0	<10	15.0	48.0
JRFMV	Frenchtown Member	140.0	10.0	0.3	160.0	19.0	120.0	0.7	9.1	<20	<10	40.0
JRS	dike	80.0	5.0	0.3	220.0	30.0	288.0	2.7	26.0	<20	10.0	24.0

Sample No.	Unit	Zr	Zn	La	Ce	Nd	Sm	Eu	Tb	Yb	Lu	Hf
JRFMC	Frenchtown Member	97.00	35.00	6.50	18.00	14.00	4.60	1.60	1.20	4.18	0.66	2.4
JRGFAS	Gilpins Falls Member	246.00	120.00	24.30	55.00	29.00	7.10	1.88	1.40	5.86	0.88	5.9
JRGFA	Gilpins Falls Member	180.00	90.00	14.00	34.00	19.00	4.90	1.47	1.20	4.30	0.68	4.4
JRFMV	Frenchtown Member	166.00	<10	17.00	37.00	18.00	4.40	1.18	1.00	3.60	0.58	4
JRS	dike	59.00	60.00	3.00	6.00	4.00	1.50	0.54	0.40	1.76	0.28	1.3

Sample No.	Unit	Ta	Th	U	Ti	La/Lu
JRFMC	Frenchtown Member	0.20	0.60	<0.5	12949	1.03
JRGFAS	Gilpins Falls Member	0.70	6.00	1.30	8872	2.88
JRGFA	Gilpins Falls Member	0.50	3.60	0.80	8692	2.14
JRFMV	Frenchtown Member	0.50	3.90	1.20	7194	3.05
JRS	dike	<0.1	1.10	<0.5	5035	1.12

*Reference S&B Smith and Barnes, Unpublished report, Pennsylvania Geological Survey, 1993

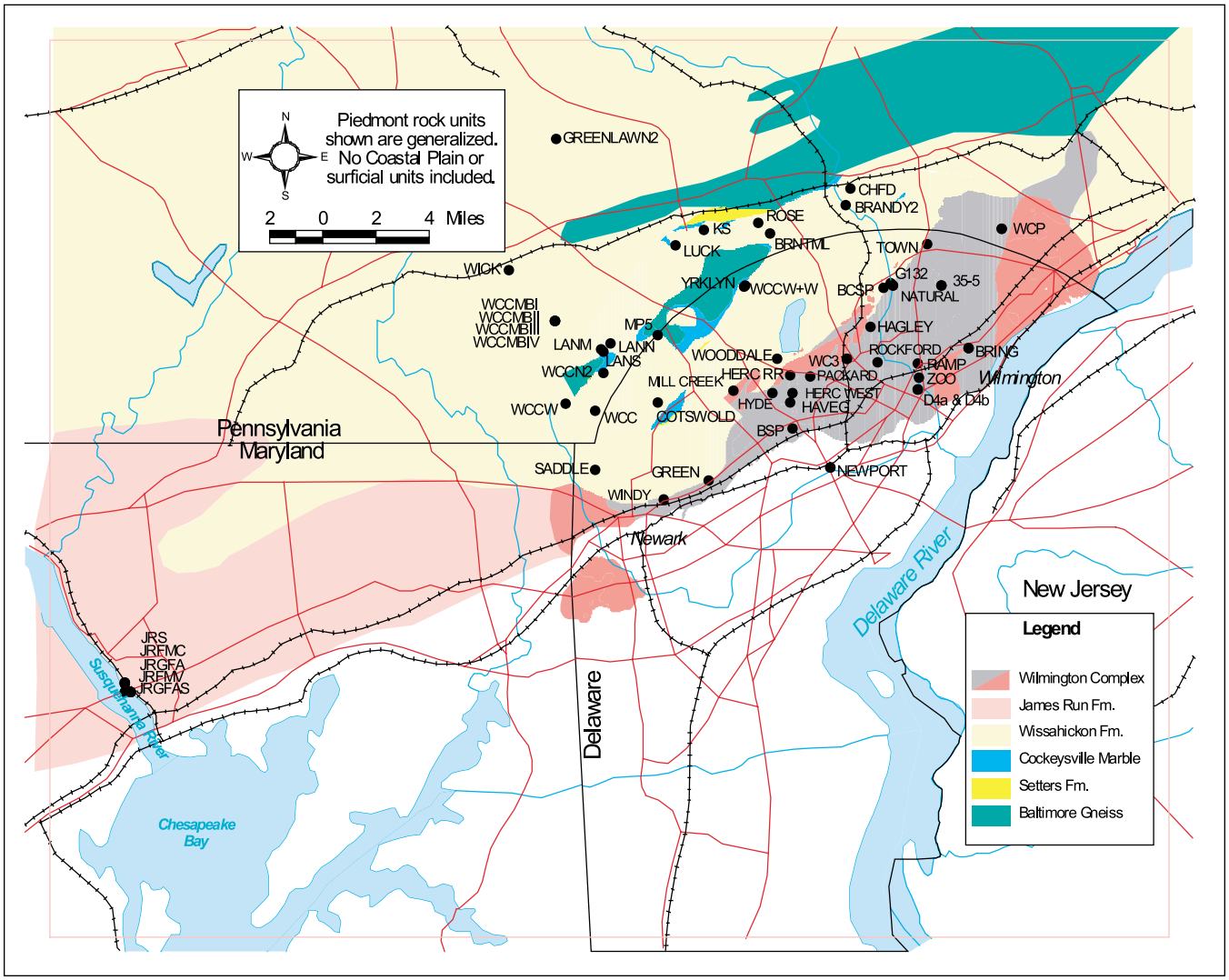

Figure 2. Generalized regional geologic map showing locations of samples from Appendix II identified by sample name.

Precision, based on replicates in each run, is typically <2 percent relative standard deviation. Accuracy can be assessed by comparing our analysis of standard reference material JB-3 with the accepted values from Govindaraju (1994) given in Appendix I. Accuracy is typically about 5 percent, but the ICP-MS values may be better determined than the "accepted" values for some elements; however, our method of analysis has a few drawbacks. The samples were dissolved in HF, thus volatilizing the Si. SiO_2 was determined by difference from 100 percent with accuracy of about 5 percent relative. Zircon was not dissolved in the samples; therefore the Zr and Hf numbers are not reported. Aside from Zr and Hf, the other elements affected by the zircon dissolution problem are U and heavy rare earth elements (HREE). Based on the amount of zircon in these samples (calculated to be <0.02 wt percent, by comparing x-ray fluorescence [XRF] and ICP-MS Zr data for the same samples) and published partition coefficients for U and Yb, the maximum errors for U and HREE are estimated at 10 percent.

Comparison of the results for our sample WINDY with sample JRBEWH collected and analyzed from the same outcrop by R. C. Smith, shows disparity in two trace elements. Th values for our sample are lower than the Smith sample and Ta values are higher (Table 1).

Smith and Barnes samples were analyzed for Nb and Zr by XRF. Cu, Pb, Zn, Ag, Ni, Cd, Bi, V, and Be were analyzed by acid total digestion and induction coupled plasma (ICP). Si, Al, Fe, Mn, Mg, Ca, Na, K, Ti, P, Ba, Sr, and Y were done by fusion ICP. These data for Y were low by a variable amount and had to be rerun on the whole rock XRF pellet. Au, As, Br, Co, Cr, Cs, Hf, Rb, Sb, Cs, Se, Sr, Ta, Th, U, W, La, Ce, Nb, Sm, Eu, Tb, Yb, and Lu were analyzed by the Instrument Neutron Activation Analysis technique by Eric L. Hoffman at Activation Laboratories, Ltd. Estimate of sampling error plus analytical error suggests that precision is typically within 10 percent. Accuracy was determined by running BCR-1 as an unknown. Precision was determined by preparing and analyzing a separate slab from a block of the Fishing Creek Member (Pennsylvania) of the Sams Creek Formation (Maryland) with each batch. This approach estimates the worst case sum of sampling error plus analytical precision.

Acknowledgments

We express our appreciation to Robert C. Smith and John H. Barnes of the Pennsylvania Geological Survey who graciously allowed us to present their unpublished geochemical data in this report. The report was critically reviewed by

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RESULTS

Wilmington Complex

Major Element Chemistry

The rocks of the Delaware Piedmont have been metamorphosed to the upper amphibolite and lower granulite facies and have been subsequently altered by weathering and/or interaction with hydrothermal fluids. Consequently, it is reasonable to look for possible effects of these processes on the rock geochemistry. The major elements K_2O, Na_2O, CaO, and SiO_2 are reported to be mobile at all grades of metamorphism, whereas, FeO, MgO, MnO, and Al_2O_3 are stable at lower metamorphic grades and may also be stable at high metamorphic grades depending on the fluid content of the rock (Badger, 1993; Rollinson, 1993).

A number of schemes have been proposed to determine the extent of the alteration by hydrothermal fluids. For ore deposits which are generally more hydrothermally altered than the Wilmington Complex rocks, Hashiguchi et al. (1983) proposed an alteration index (AI) calculated using the formula:

$$AI=100(MgO+K_2O)/MgO+K_2O+CaO+Na_2O).$$

Indices of <36±8 represent relatively unaltered rocks. Of the 16 Wilmington Complex samples analyzed by T. A. Plank, plus 3 from Smith and Barnes (unpublished report, 1993), only two from the Faulkland Gneiss fall outside the acceptable range for major elements (Table 1). This does not mean that an individual sample has gained or lost some components, only that the majority of samples have major element chemistries like unaltered igneous rocks.

We also note that retrograde hydration in all rocks must be low because the rocks contain <1 percent H_2O, as determined by LOI (Table 1). Altered rocks typically have higher LOIs.

We first consider some aspects of the major element chemistry, using the Wilmington Complex data determined for this study plus that from Smith and Barnes (unpublished reports, Pennsylvania Geological Survey, 1993 and 1994) and McEwen (1997) (Table 1).) Also included are data from Ward (1959), Srogi (1988), and Higgins (1990). On the total alkalis vs. silica diagram (LeBas et al., 1986), it is noteworthy that rock compositions from the Wilmington Complex span the complete range of silica content, from 45 to 76 weight percent SiO_2, and have total alkali contents typical of subalkaline basalts, andesites, dacites, and rhyolites (Figure 3). (Although this diagram was designed for volcanic rocks, we have probably plotted both volcanic and plutonic samples because it is difficult to determine the origin of the high-grade metamorphic rocks in the Delaware Piedmont). The compositions are consistent with those reported from magmatic arcs formed at convergent margins. On the diagram of K_2O vs. SiO_2 for arc magmatic series (Peccerillo and Taylor, 1976), the same samples plot in the low-K tholeiite series, with a few samples falling in the calc-alkaline series (Figure 4). This is consistent with the petrography which shows that, in general, K-bearing minerals are sparse (Table 2; see also Ward, 1959, and Schenck and Plank, 1995). The same

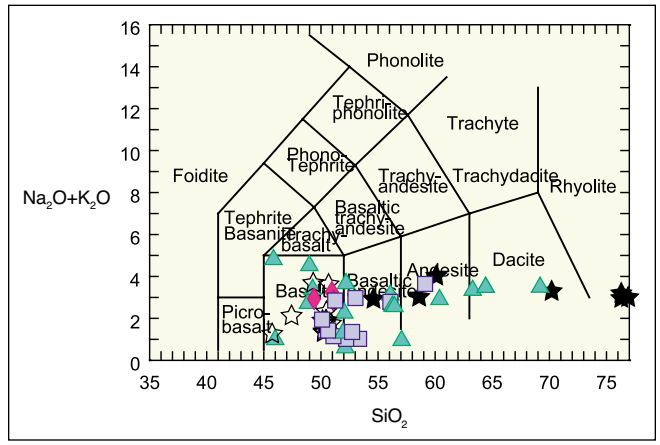

Figure 3. Total weight percent alkali (Na_2O+K_2O) vs. SiO_2 plot of Wilmington Complex samples and the classification scheme for volcanic rocks from LeBas et al. (1986). Data are from this study plus those of Ward (1959), Srogi (1988), Higgins (1990), Smith and Barnes (1994; unpublished report 1993), Chace (1995), and McEwen (1997).
Symbols: closed triangle, Brandywine Blue Gneiss; closed diamond, Rockford Park Gneiss; closed box, Faulkland Gneiss; open star, Windy Hills Gneiss; closed star, James Run Formation, Cecil County, Maryland.

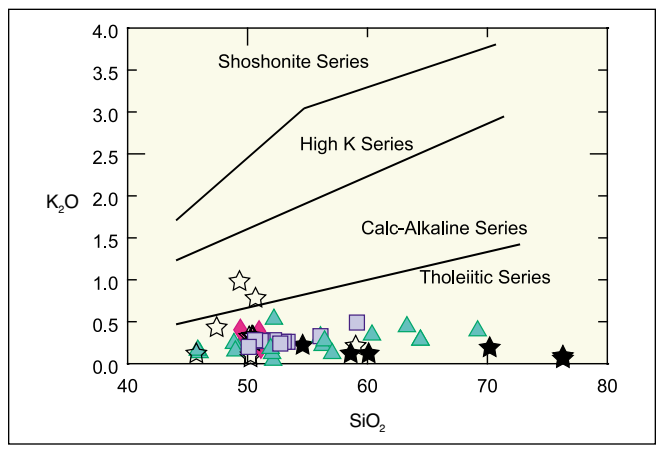

Figure 4. Weight percent K_2O vs. SiO_2 plot for Wilmington Complex samples. Series boundaries are after Peccerillo and Taylor (1976). Data and symbols same as Figure 3.

Wilmington Complex samples also indicate a predominantly tholeiitic trend on the AFM diagram of Figure 5 (alkalis, Fe oxides, and MgO). This diagram is commonly used to distinguish between tholeiitic and calc-alkaline differentiation trends in a magma series (Irvine and Barager, 1971). Harker diagrams plotted for the Wilmington Complex rocks (not shown) show significant scatter, probably due to the mobility of many of the major elements and to different crystallization histories for different samples. Although these data should be viewed with caution, as alkalies are mobile during metamorphism, they are consistent with the interpretation that the mafic rocks of the Wilmington Complex originated as low-K tholeiites at a converging margin.

Table 2. Modal analyses of Wilmington Complex samples. Samples Bd41-b Rockford, Bd43-a Ramp, Bd22-a Natural, Bd13-d Town, and Bd52-a Zoo are mafic layers. All other samples are amphibolites.

	Rockford Park Gneiss			Brandywine Blue Gneiss			Gabbroic Plutons	
DGS Number	Bd41-b	Bd43-a	Bd22-a	Bd13-d	Bd52-a	Cc34-41	Bb55-b	Bd21-a
Sample Number	43428	43901	43900	43902	43746	24860	43475	41931
Local Identification	Rockford	Ramp	Natural	Town	Zoo	Newport	MillCreek	BCSP
Mineral, wt.%								
Quartz	x	x	x	8		3		x
Plagioclase	43	37	50	60	45	46	39	35
Biotite					x	1		
Hornblende	22	26	23	7	43	47	61	63
Cummingtonite								
Orthopyroxene		4	15		7	3		
Clinopyroxene	35	32	11	21				2
Opaque Minerals	1	1	1	4	5	x	x	x
Magnetite								
Points Counted	800	500	500	500	500	500	500	500
	Faulkland Gneiss					Windy Hills Gneiss		
DGS Number	Bc53-a	Bd31-d	Cc12-a	Bc52-j	Bc52-f	Cc22-c	Cb34-d	Cb42-c
Sample Number	42352	43545	43478	43380-b	42168	41923	43517-b	43425
Local Identification	Packard	Hagley	BSP	Hyde	Hercwest	Haveg	Green	Windy
Mineral, wt.%								
Quartz	19	< 1	2	22	33	15	2	1
Plagioclase	49	33	28	16	15	30	36	31
Biotite			3			4		5
Hornblende	30	33		56		51	54	62
Cummingtonite			52					
Orthopyroxene		7	15		45			
Clinopyroxene		27					2	
Opaque Minerals	2	< 1	<1	6			6	
Clinozoisite					7			1
Points Counted	500	500	Chace	Chace	Chace	Chace	500	800

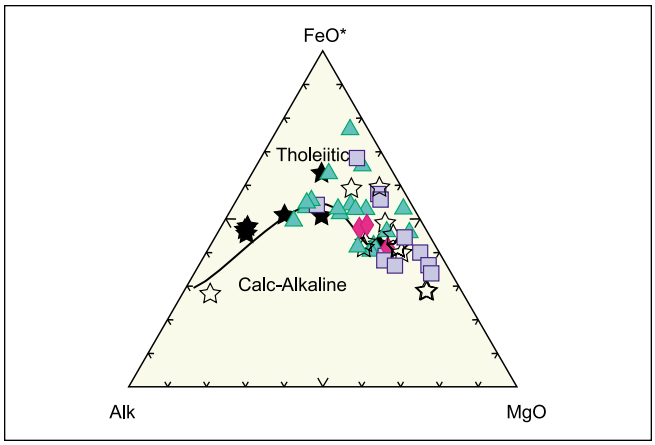

Figure 5. AFM diagram illustrating tholeiitic trends in rocks of Wilmington Complex. Data and symbols same as Figure 3. Total iron is reported as FeO*.

Trace Element Chemistry

In highly metamorphosed areas where the major elements may have been mobilized, selected trace elements are often used to group rocks with similar chemistry and to provide insight into petrogenetic processes (Pearce and Cann, 1973; Pearce, 1982; Rollinson 1993). Among the trace elements, the incompatible high field strength elements (HFSE) including the REE, are the most immobile. One of the best ways to compare the trace element compositions is by plotting REE patterns and extended REE patterns called normalized multi-element diagrams or spider diagrams (Rollinson, 1993). The REE patterns used in this report were normalized to the chondrite values of Sun and McDonough (1989) and were prepared using Igpet 32 for Win95/NT (Carr, 1998). Two types of spider diagrams are plotted, one to compare rock chemistry with a mantle source (the chondrite-normalized form of diagram proposed by Thompson, 1982), and one to compare rock chemistry with the most abundant volcanic rocks, mid-ocean ridge basalts (the MORB-normalized form proposed by Pearce, 1983).

REE patterns and spider diagrams when combined with field observations allow us to divide the mafic samples from the Wilmington Complex into six groups. All groups, except group VI, have a geochemical signature characteristic of rocks formed during plate convergence. This includes enrichment of light rare earth elements (LREE) relative to the HREEs, enrichment in large ion lithophile elements (LILE) such as Rb, K, Ba, and Th, and depletion in HFSEs, such as Nb, Ta, Ti, Sc, and Y (Gill, 1981; Rollinson, 1993; Bloomer et al., 1995; Plank, 1996).

When comparing REE patterns, the critical aspects are the abundance of REE relative to chondrites and the degree

of LREE enrichment relative to HREEs. These aspects are reflected in the La concentration and La/Lu ratios, respectively, with lower values of both parameters indicating a more depleted source for the magma (Rollinson, 1993; Shervais et al., 1996). The TiO_2 content also provides a qualitative index of the degree of source depletion, with lower TiO_2 indicting greater depletion (Gill, 1981; Philpotts 1990; Ragland, 1989; Rollinson, 1993).

Groups I and II

Two geochemical groups, I and II, were identified within the granulite facies rock unit previously mapped as the banded gneiss of Ward (1959) and as a hypersthene-quartz-andesine gneiss by Woodruff and Thompson (1975), allowing us to subdivide the unit. Group I samples are from a unit typified by interlayered mafic and felsic gneiss, now mapped as the Rockford Park Gneiss (Schenck et al., 2000). The three mafic samples from group I, ROCKFORD, RAMP, and NATURAL, plot as basalts on the LeBas diagram (Figure 3) and as low-K tholeiites on the K_2O vs. SiO_2 plot and AFM diagram (Figures 4 and 5). Group II samples were collected from a unit that is predominantly intermediate to silicic with thin discontinuous mafic layers. It is mapped as the Brandywine Blue Gneiss (Schenck et al., 2000). Samples from the thin mafic layers, TOWN, ZOO, and NEWPORT plot as basaltic andesites on the LeBas diagram and as low-K tholeiites on the AFM diagram and K_2O vs. SiO_2 plot.

Table 3. Ratios and adundances, Wilmington Complex and James Run Formation samples.
* Samples published in Higgins (1990).

Ratios and Abundances, Wilmington Complex samples

Sample	La/Lu ratio	La Concentration	TiO_2
Group I	xchondrite	xchondrite	wt.%
NATURAL	2.6	11.10	0.35
RAMP	2.2	7.12	0.28
ROCKFORD	2.0	7.54	0.33
Group II			
NEWPORT	2.9	37.95	1.16
TOWN	2.3	28.64	0.46
ZOO	2.3	15.03	0.32
Group III			
PACKARD	4.0	47.34	0.99
BSP	5.0	25.55	0.42
HYDE	2.5	16.07	0.56
HAGLEY	3.5	25.65	0.37
Not Assigned			
HERCWEST	1.2	20.15	1.64
Group IV			
HAVEG	1.1	10.41	0.84
WINDY	1.6	12.79	0.77
GREEN	1.5	9.87	0.65
Group V			
MILLCREEK	1.4	3.70	1.58
BCSP	1.6	7.27	0.49
Group VI			
WC3	1.6	12.12	2.75
BRING	2.2	37.60	2.00

Ratios and Abundances, James Run Formation, Maryland

Sample	La/Lu ratio	La Concentration	TiO_2
Gilpins Falls	xchondrite	xchondrite	wt. %
P-1,c*	1.72	12.9	0.64
P-1,v*	2.06	16.1	0.64
Pb-2,c*	2.2	19.4	0.56
Pb-2,r*	1.93	14.2	0.64
JRGFA	2.14	45.0	1.45
JRGFAS	2.88	78.1	1.48
Frenchtown			
JRFMC	1.03	20.89	2.16
JRFMV	3.05	54.64	1.2
Dike			
JRS	1.12	9.64	0.84

Group I samples have very low abundances of LREE (La concentrations 7x to 11x chondrite), moderate La/Lu ratios (2x to 2.6x chondrite), and concave up REE patterns with slight positive europium anomalies (Table 3 and Figure 6A). Group II samples have higher abundances (La concentration 15x to 38 x chondrite), La/Lu ratios similar to group I (2.3x to 2.9x chondrite), and REE patterns with slight negative europium anomalies (Table 3 and Figure 6B). The REE patterns for groups I and II are typical of magmas from an arc environment with sloping LREE patterns, slightly concave to flat HREE patterns, and moderate LREE enrichment relative to HREE.

The Pearce (1983) and Thompson (1982) spider diagrams plot the LILEs on the left and the HFSEs on the right. In typical magmatic arcs, the abundance of the LILEs is controlled by the fluid phase and consequently shows variable enrichment. The HFSEs are a function of the chemistry of the source and crystal/melt processes and are normally depleted relative to the LILEs (Rollinson, 1993). The spider diagrams for the group I and II samples (Figures 7 and 8) show many features typical of arc basalts, including negative Ta and Nb anomalies, and enrichment of LILEs relative to HFSEs (Gill, 1981; Pearce, 1982; Plank, 1996). The incoherent "spikey" appearance of the LILEs is probably due to metasomatism. The lack of a positive Th anomaly is atypical and may reflect Th retained in undissolved zircons.

Group I samples show extreme depletion of HFSEs relative to both the LILE and the MORB line on the Pearce diagram and have very low TiO_2 contents, <0.35 wt. percent (Table 3). These features suggest a possible boninitic affinity for the group I rocks. Boninites are distinctive igneous rocks found in the forearc regions of modern western Pacific island arcs (Hickey and Frey, 1982; Stern et al., 1991; Bloomer et al., 1995). Distinctive chemical features include Mg#>70 [where Mg# = Mg/(Mg+Fe)], high SiO_2 (>55 percent), extremely low TiO_2 (<0.5 percent), CaO/Al_2O_3 between 0.5 and 0.75, low abundance of high field strength cations including the REEs, concave upward HREE patterns, and strong LILE enrichment relative to MORB (Crawford et al., 1989). Our group I samples have the very low TiO_2, low abundance of REEs, concave upward HREE patterns, and LILE enrichment relative to HFSE depletion typical of boninitic rocks (Tables 1 and 3; Figures 6, 7, and 8). CaO/Al_2O_3 values are within the range reported for boninitic rocks. Sc values for our samples are also within the range of 41±3 reported as characteristic of low-Ca type 3 and high-Ca boninites (Crawford et al., 1989).

The Mg# and SiO_2 contents of group I samples are lower than those reported for modern boninites; however, SiO_2, Al_2O_3, MgO, and FeO are normally mobile during metamorphism and may not be useful parameters for comparing modern and metamorphosed boninites (Coish, 1989; Kim and Jacobi, 1996). Cr and Ni content are low, but values

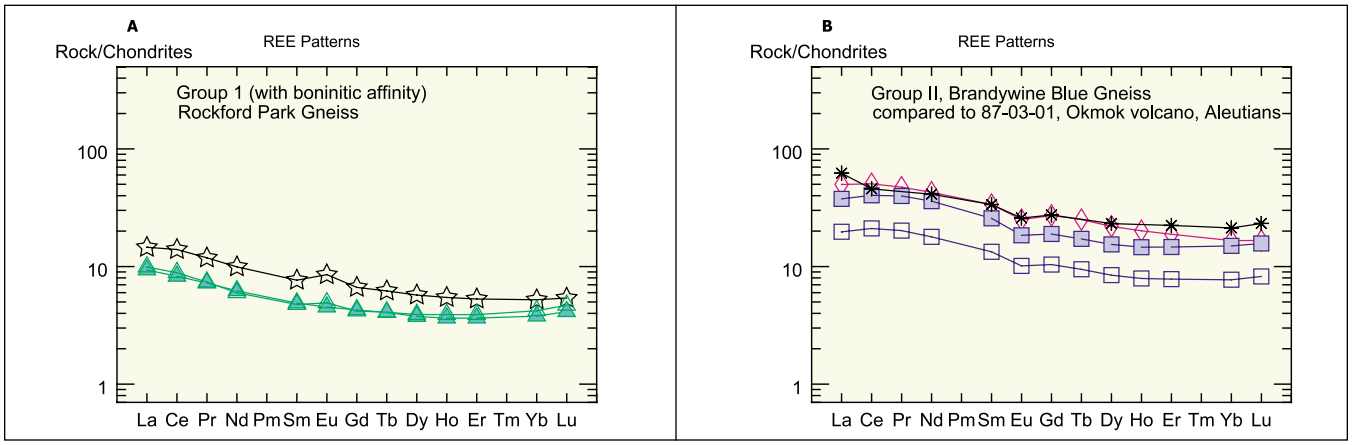

Figure 6. REE patterns for Wilmington Complex groups I and II. Chondrite values proposed by Sun and McDonough (1989). A. Group I samples are from mafic layers in the Rockford Park Gneiss. B. Group II samples are from thin mafic layers and stringers in the Brandywine Blue Gneiss. Symbols group I: open star, NATURAL; open triangle, ROCKFORD; closed triangle, RAMP. Symbols group II: open diamond, NEWPORT; open square, ZOO; closed square, TOWN, asterisk, Okmok volcano, Aleutian Arc (Miller et al., 1992)

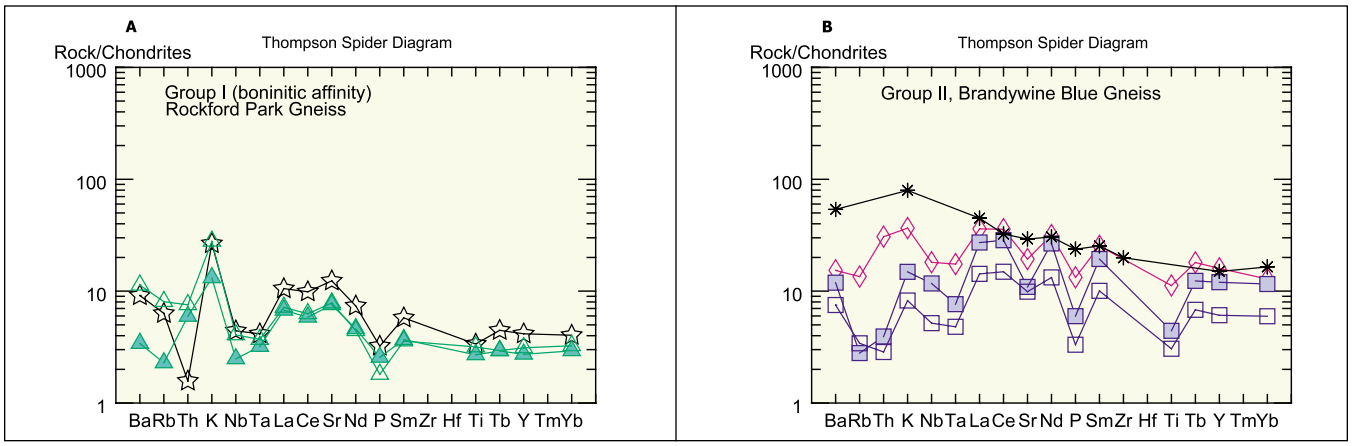

Figure 7. Spider diagrams for groups I and II, Wilmington Complex samples. Element order and normalizing values based on chondrites proposed by Thompson (1982). A. Group I; B. Group II. Symbols are same as in Figure 6.

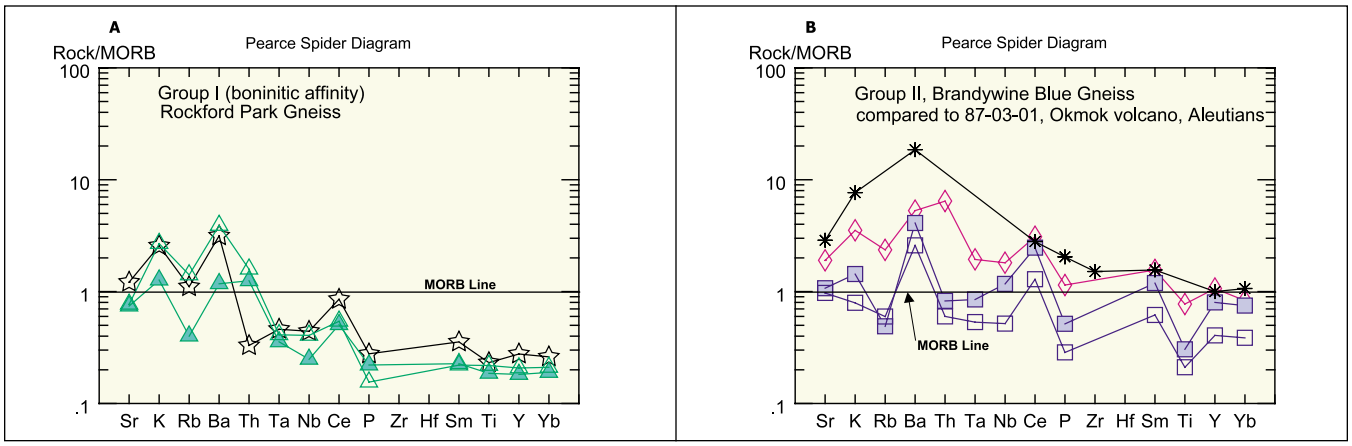

Figure 8. Spider diagrams for group I and II, Wilmington Complex samples. Element order and normalizing values based on MORB proposed by Pearce, 1983. A. Group I; B. Group II. Symbols are same as in Figure 6.

for two samples, RAMP and ROCKFORD, are consistent with Cr and Ni reported for boninitic rocks from the Thetford Mines Ophiolite, Quebec, Canada (Coish, 1989). The Cr and Ni contents of the NATURAL sample are unusually low.

Because it is possible for some cumulate gabbroic rocks to have trace element characteristics similar to boninitic rocks, it is important to evaluate a cumulate origin for the group I rocks. The lack of a strong positive Eu anomaly and normal concentrations of Sr suggest the rocks are not cumulates (Gill, 1981). In addition, there is no petrographic or field evidence to suggest an origin as cumulate or melanosome.

Interpretation. In recent years, metabasalts with boninitic affinities have been recognized in Ordovician volcanic sequences from the northern Appalachians (Coish, 1989; Kim and Jacobi, 1996; MacLachian and Dunning, 1998). Figure 9 shows the REE patterns for group I samples are similar to Eocene boninites from the modern Marianas forearc (Stern et al., 1991) and Ordovician boninitic rocks from the northern Appalachians; the Hawley Formation of northwestern Massachusetts (Kim and Jacobi, 1996), the Exploits Subzone, Newfoundland, Canada (MacLachian and Dunning, 1998), and the Thetford Mines Ophiolite, Quebec, Canada (Coish, 1989). Boninitic metabasalts have been recognized in the Pennsylvania Piedmont and are also associated with an ophiolite complex, in this case, the Baltimore Mafic Complex (Smith and Barnes, 1994).

From the many recent studies of boninites, there is now a consensus that boninite melts form from severely depleted mantle (harzbergite), whose bulk chemistry has been altered by the introduction of LREE-rich, Ti-poor fluids. These fluids may be derived by dehydration of subducted basaltic crust or re-equilibration of fluids released from the dehydrating slab with the overlying mantle wedge. Melting results from the combined effects of this fluid and an unusually steep geotherm. Consequently, boninite magmas generally form at convergent margins during relatively short-lived events that are not in thermal equilibrium (Hickey and Frey, 1982; Coish, 1989; Stern et al., 1991; Stern and Bloomer, 1992; Pearce et al., 1992; Bloomer et al., 1995). The models proposed for the origin of boninites include the "infant arc" model of Stern and Bloomer (1992), forearc spreading model (Hickey and Frey, 1982; Hawkins et al., 1984), and early-stage backarc spreading model (Crawford et al., 1989).

The boninitic rocks in Delaware are interlayered with felsic rocks having compositions of metatonalites, metatrondhjemites, or metadacites. The rapid rate of crust formation proposed for subduction zone infancy (Stern and Bloomer, 1992) provides an explanation for the formation of tonalites (and rhyolites) within several million years of the depleted mafic sequence by melting of the depleted rocks at the base of the thickened arc crust. Unfortunately, deformation and metamorphism obscure the original thickness and the relationship between the boninitic rocks and the felsic

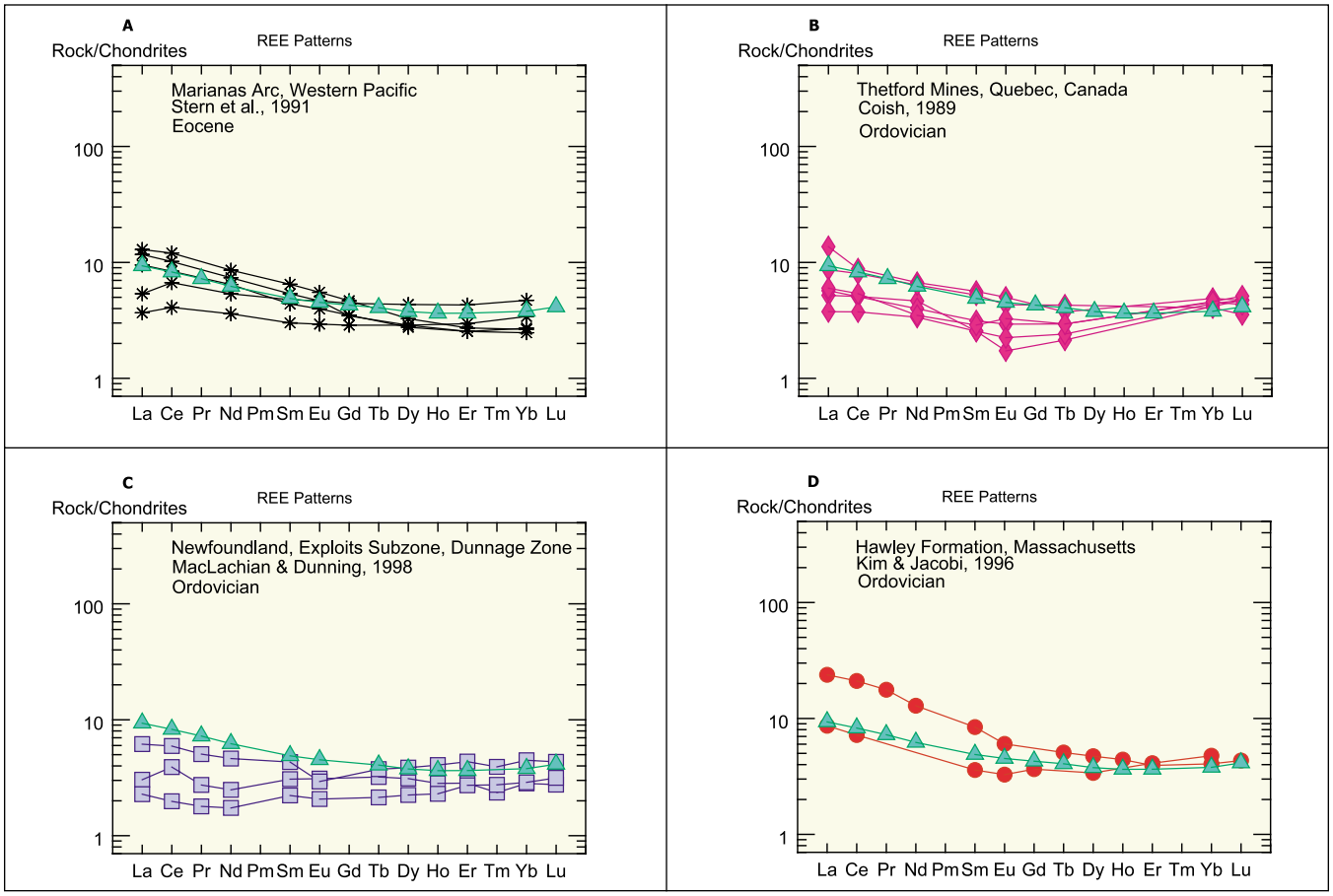

Figure 9. A, B, C, and D are REE patterns for boninitic rocks from modern and ancient environments compared to the patterns for Wilmington Complex, group I sample, RAMP.
Symbols: closed triangle, RAMP; asterisk, Marianas Arc, Western Pacific; closed diamond, Thetford Ophiolite, Quebec Canada; closed box, Dunnage Zone, Newfoundland; closed circle Hawley Formation, Massachusetts.

rocks in the Rockford Park Gneiss, and prevent us from proposing a more comprehensive model for the origin of the rocks.

The group II mafic samples are low-K basaltic andesites, and although they do not show boninitic affinities, they have low TiO_2 concentrations (0.3 to 1.16 wt. percent) (Table 3). According to Gill (1981), rocks with low TiO_2 usually form in the forearc in the early stages of subduction. The HFSEs shown on the Pearce spider diagrams for groups I and II are similar to the spider diagrams plotted for Eocene forearc basement samples from the Philippines (Bloomer et al., 1995) (Figure 10). Boninitic affinities of group I, plus the low TiO_2 concentrations of group II, suggest both units may have formed in a forearc or frontal arc.

The grouping of the mafic rocks according to their geochemistry supports the subdivision of the banded gneiss of Ward (1959) by Schenck et al. (2000) into two mappable units, the Rockford Park Gneiss and the Brandywine Blue Gneiss.

Groups III and IV

The group III and IV samples were collected from amphibolites previously mapped as Wilmington Complex type A and B amphibolites by Ward (1959) and hornblende-plagioclase gneisses by Woodruff and Thompson (1972, 1975). The trace element chemistry of these samples allows us to subdivide the amphibolites into groups III and IV, groupings that now define the Faulkland Gneiss and the Windy Hills Gneiss, respectively (Schenck et al., 2000) (Figure 1).

The four samples assigned to group III, HAGLEY, PACKARD, BSP, and HYDE, are quartz amphibolites and amphibolites (Table 2) that plot as basalts and basaltic-andesites on the LeBas diagram (Figure 3). They have REE patterns characteristic of arc rocks, notably moderate REE abundances (La=16x to 47x chondrite), La/Lu ratios between 2.5x and 5x chondrites, sloping LREE patterns, flat HREE patterns, and slight negative Eu anomalies (Figure 11A and Table 3). The range of TiO_2 is from low (0.37) to moderate (0.99). Spider diagrams show enrichment of LILE relative to HFSE, negative Ta and Nb anomalies, and a positive Th anomaly (Figure 12A). The large variation in Ba concentration and "spikey" LILEs indicate interaction with hydrothermal fluids and mobility of these trace elements during metamorphism.

One sample from the Faulkland Gneiss, HERCWEST is different chemically from the group III rocks. This sample plots as basalt on the LeBas diagram, has a flat REE pattern (Figure 13A), and a spider diagram with a small negative Nb anomaly. Ba and Rb are strongly depleted (Figure 13B). The HERCWEST sample has a metamorphic mineral assemblage and texture. It is composed of orthopyroxene, quartz, and plagioclase (Table 2), and texturally the rock is fine-grained with a few large, 0.6 cm, poikiloblastic grains of

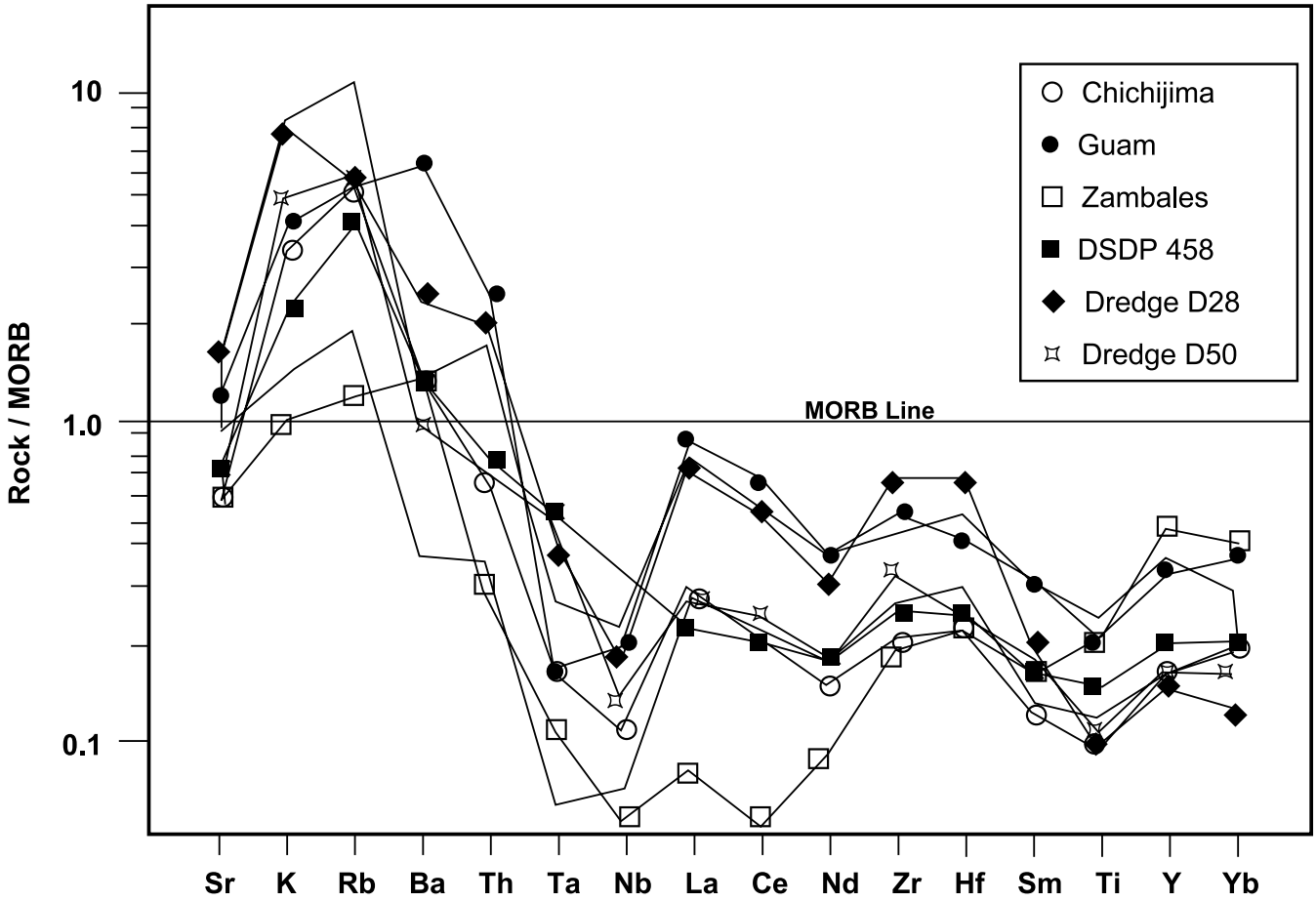

Figure 10. Spider diagrams based on MORB from Eocene forearc basement samples showing that the geochemical signature of the HFSEs for these volcanics is similar to groups I and II, Figure 8. (Adapted from Bloomer et al. 1995, p 10).

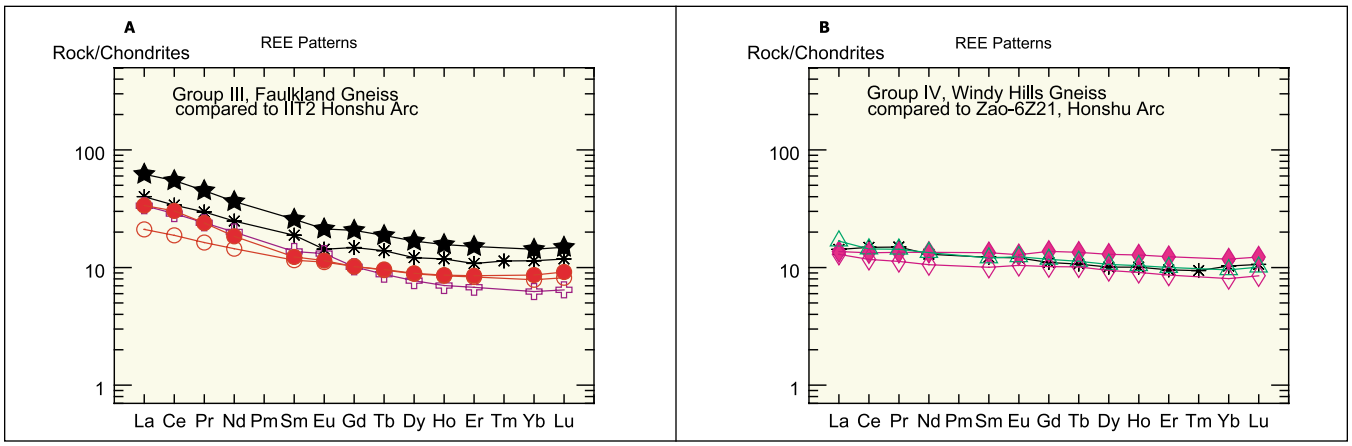

Figure 11. REE patterns for groups III and IV. Chondrite values proposed by Sun and McDonough (1989). A. Group III samples are from the Faulkland Gneiss; compared to IIT2 Takahara volcano, Honshu Arc. B. Group IV samples are from Windy Hills Gneiss; compared to 6Z21 Zao volcano Honshu Arc.
Symbols: closed star, PACKARD; open plus sign, BSP; open circle, HYDE; closed circle, HAGLEY; open triangle, WINDY; open diamond, GREEN; closed diamond, HAVEG. Asterisk is symbol for Takahara volcano, IIT2 and Zao volcano, 6Z21 from the Honshu Arc (Gust et al., 1997).

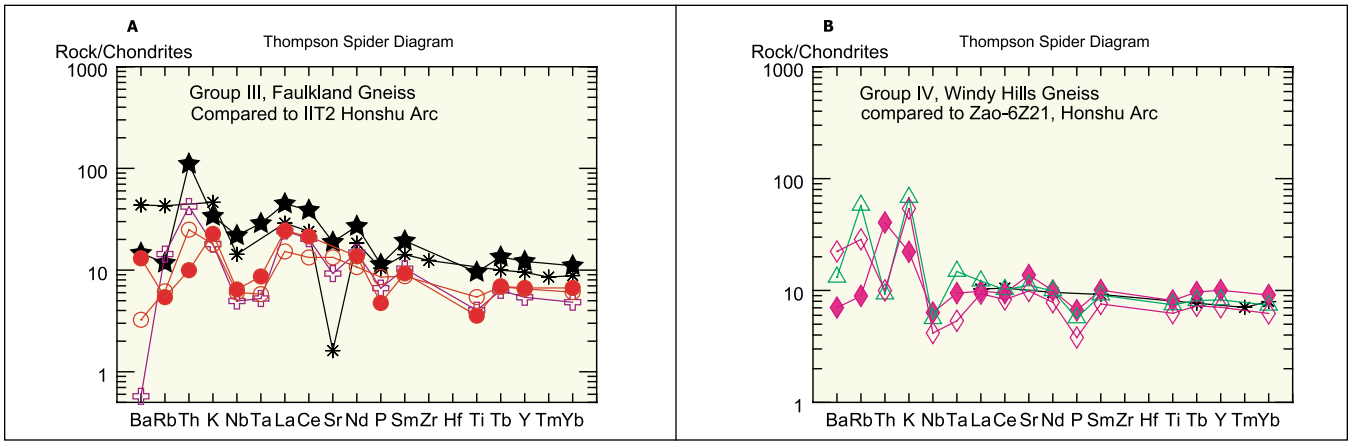

Figure 12. Spider diagrams for groups III and IV using element order and normalizing values of Thompson, 1982.
A. Group III; B. Group VI.
Symbols are same as in Figure 11.

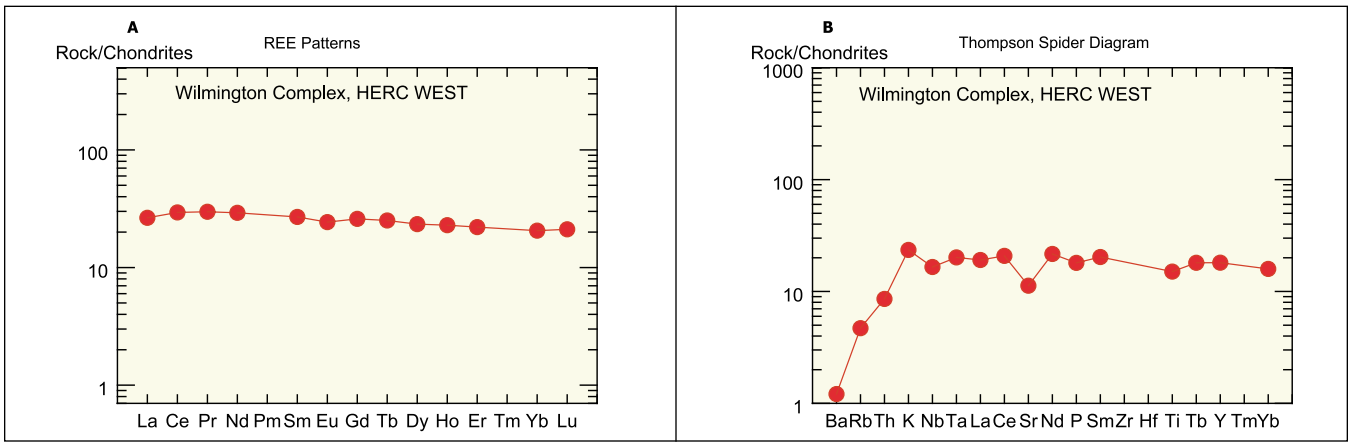

Figure 13. REE patterns (A) and spider diagram (B) for HERCWEST from Faulkland Gneiss.
Symbol: filled circle, HERCWEST.

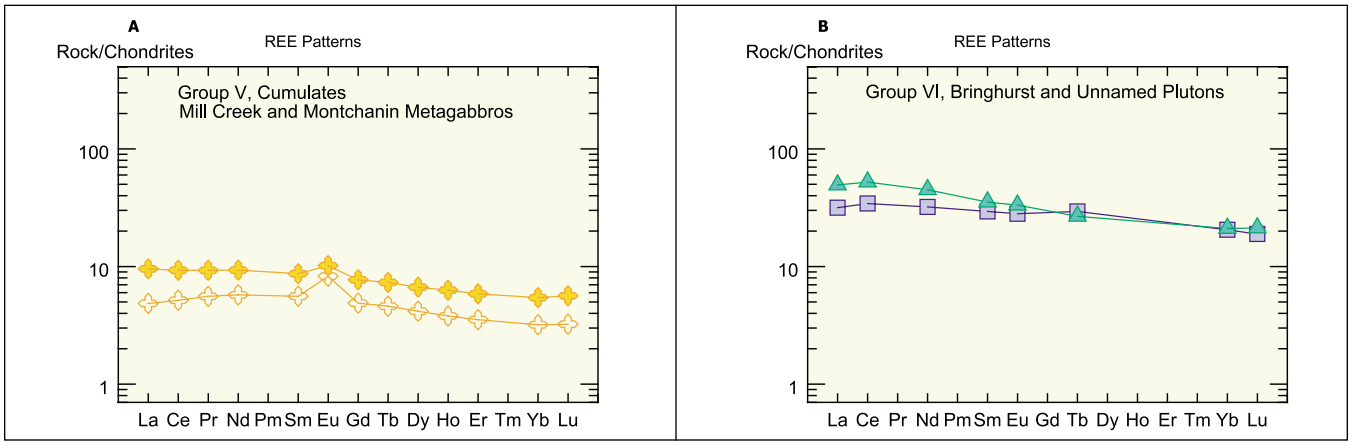

Figure 14. REE patterns for groups V and VI. Chondrite values proposed by Sun and McDonough (1989). Group V samples are cumulates and group VI are undeformed mafic plutons. A. Group V; B. Group VI.
Symbols: closed flower, Mill Creek Metagabbro, MILL CREEK; open flower, Montchanin Metagabbro, BCSP; closed box, unnamed mafic dike WC-3; closed triangle, Bringhurst Gabbro, BRING.

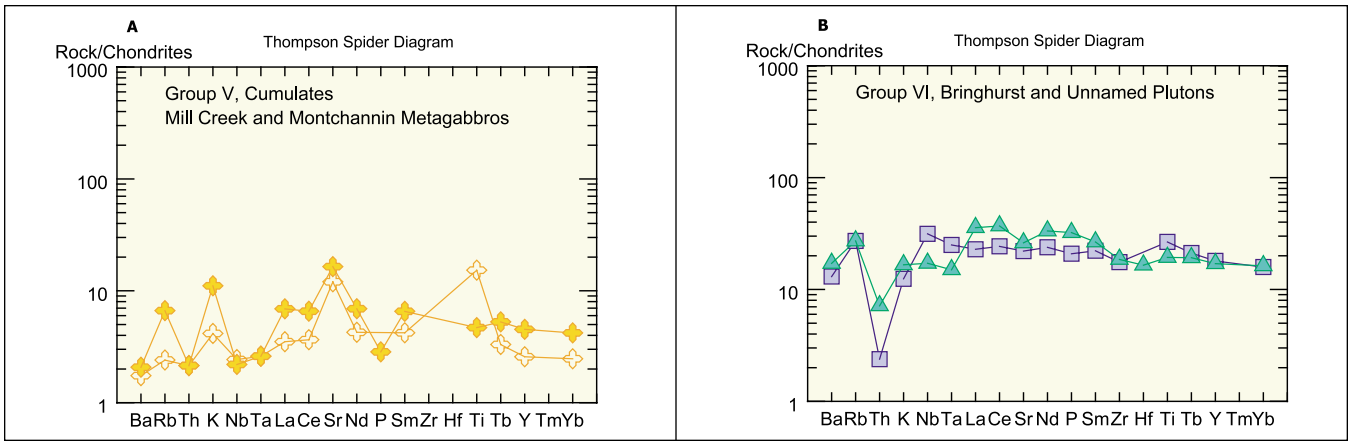

Figure 15. Spider diagrams for groups V and VI using element order and normalizing values of Thompson, 1982.
A. Group V; B. Group VI.
Symbols are same as in Figure 17.

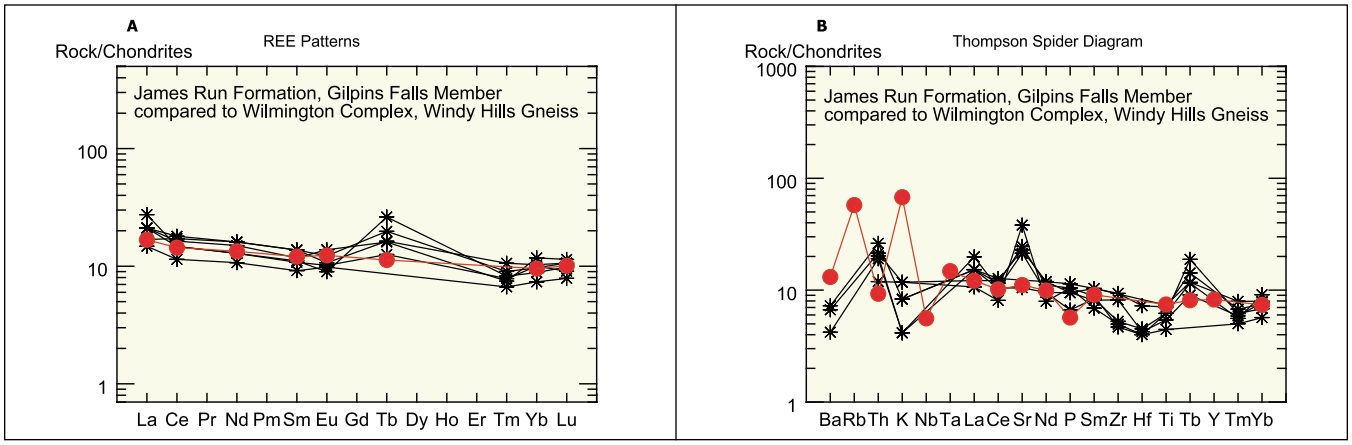

Figure 16. A. REE patterns for pillow lavas from the Gilpins Falls Member*, James Run Formation, Cecil County, Maryland (Higgins, 1990) compared to Windy Hills Gneiss.
B. Spider diagram for same samples*. The Tb enrichment in the Gilpins Falls REE patterns and spider diagrams is an analytical problem (Higgins, 1990).
Symbols: asterisk, Gilpins Falls pillow basalts; filled circle, group IV, WINDY.
*Gilpins Falls pillow lava samples include P-1,vz; P-1,r; PB-2,c; PB3,c; RC-1; and PB-4 (Higgins, 1990).

orthopyroxene with quartzofeldspathic halos. However, the HERCWEST sample is chemically similar to the group VI rocks (see below) and sample JMFMC, an actinolitic amphibolite that was collected from a 0.8 meter-wide dike in the Frenchtown Member of the James Run Formation (R. C. Smith and J. H. Barnes, Pennsylvania Geological Survey unpublished report, 1993) (Figure 16). Group VI rocks and JMFMC are younger intrusions less deformed and metamorphosed than the Faulkland Gneiss. Thus, the geochemistry suggests that there are mafic rocks from more than one source within the Faulkland Gneiss, or that HERCWEST may be a younger intrusive unit that did experience some deformation and recrystallization.

Group IV samples, WINDY, GREEN, and HAGLEY are quartz amphibolites and amphibolites that plot on the LeBas diagram as basalts (Figure 3). REE patterns are flat, La/Lu ratios are 1.1x to 1.6x chondrite, and La concentrations are medium to low (9.9x to 12.8x chondrite; Table 3 and Figure 11B). Spider diagrams show LILEs scattered with small enrichment of LILEs relative to the HFSEs, and negative Nb anomalies (Figure 12B). According to Pearce (1982, 1983), flat REE patterns, spider diagrams with enriched LILEs, and negative Nb anomalies are characteristic of tholeiitic island arc suites. The range of TiO_2 is from 0.65 and 0.84, similar to TiO_2 values for group III (Table 3).

Interpretation. The group III samples were collected from the Faulkland Gneiss, a unit composed of massive amphibolites, metasedimentary rocks, and minor felsic rocks. The group IV samples were collected from the Windy Hills Gneiss, a unit composed of massive felsic gneisses, amphibolites and minor metasedimentary rocks (Schenck et al., 2000) (Figure 1). Although deformation and recrystallization have destroyed most primary textures, the small- and large-scale interlayering of amphibolite with supracrustals and felsic rocks suggests a volcanic origin. The chemistry suggests the volcanics originated in an island arc setting.

In some outcrops the Windy Hills Gneiss resembles the interlayered mafic and felsic gneisses of the Rockford Park Gneiss. The geochemistry indicates group IV rocks are not boninitic, however the HFSEs of group IV, as shown on the spider diagrams, are slightly more abundant but similar to the those of group I (Figure 12B and 5A). It is possible that they are related, and we are looking at a magmatic continuum.

Group V

The Wilmington Complex is intruded by numerous deformed and undeformed mafic plutons. Two variably deformed and metamorphosed mafic plutons, the Montchanin Metagabbro and the Mill Creek Metagabbro, were sampled, analyzed, and assigned to Group V (BCSP and MILLCREEK on Figure 2). As suggested by field observations and petrographic analyses (Table 2), these units are in part cumulates, thus the chemical composition of the rocks is controlled by cumulate phases and is variable. The REE patterns show slight enrichment of the LREEs over HREEs (La/Lu ratio 1.4x to 1.6x chondrite) (Table 3), extremely low abundance of REEs (La concentrations 3.7x to 7.3x chondrite), and well defined positive Eu anomalies (Figure 14A) that are most likely due to the accumulation of plagioclase. The Thompson spider diagrams show depletion in all trace elements, as well as negative Nb anomalies (Figure 15A). TiO_2 in the Montchanin sample (BCSP) is low (0.49) similar to other rocks in the Wilmington Complex, while the TiO_2 in the Mill Creek sample (MILLCREEK) is higher (1.58) probably due to accumulation of ilmenite and perhaps magnetite (Table 3).

Interpretation. The geochemical analyses confirm field observations that these units are metagabbros and suggests they are in part cumulates. In addition, the spider plots with negative Nb and Ta anomalies show the accumulated minerals have preserved some of the characteristics of the arc magmas from which they evolved (Figure 14).

Group VI

Two undeformed and unmetamorphosed mafic plutons with well-preserved igneous minerals and textures were sampled, the Bringhurst Gabbro, BRING, and a thin undeformed, fine-grained mafic dike exposed near the contact between the Brandywine Blue Gneiss and the Faulkland Gneiss, WC3 (Smith and Barnes, unpublished report, Pennsylvania Geological Survey, 1994) (Figure 2). REE patterns (Figure 14B) are relatively flat similar to those reported for plume-enriched mid-ocean ridge basalts (E-MORBs) or backarc-basin basalts (BABBs) (Pearce and Cann, 1973; Smith and Barnes, 1994). The Thompson spider diagrams are flat with pronounced negative Th anomalies (Figure 15B). TiO_2 contents are high, 2.00 and 2.75 wt. percent (Table 3).

Interpretation. The spider diagrams suggest that the mafic dike, WC3, the Bringhurst Gabbro, and possibly the other undeformed dikes and plutons were derived from mantle sources similar to those for E-MORBS and BABBs. Field evidence for intrusion of the group VI magmas into felsic gneisses (Brandywine Blue Gneiss) and for mingling with coeval granitic magmas (Ardentown Granitic Suite) precludes an origin in a mid-ocean ridge environment; therefore, we conclude the group VI magmas are BABBs associated with rifting and extension within the arc. This hypothesis is supported by zircon U-Pb isotopic ages determined for the Ardentown Granitic Suite. A slightly discordant U-Pb age of 422±6.5 Ma was obtained by Secondary Ion Mass spectrometer analysis of zircons from one sample of quartz norite (Bosbyshell et al., 1998), and a more recent age of 434±4 Ma obtained by SHRIMP analysis of zircons from a different sample of quartz norite (John N. Aleinikoff, U. S. Geological Survey, personal communication, 2000). These ages are younger than the 476±6 Ma age reported by J. N. Aleinikoff for the Brandywine Blue Gneiss and suggests arc formation in the Early Ordovician and arc rifting during the Silurian. This interpretation is consistent with regional-scale heating and metamorphism of the Ordovician units (428±8 Ma, John N. Aleinikoff, U. S. Geological Survey, personal communication, 2000) at about the same time as the crystallization of the Arden Plutonic Supersuite.

James Run Formation, Cecil County, Maryland

The rocks of the James Run Formation in Cecil County, Maryland, are volcanic and volcaniclastic rocks that have been intruded by numerous mafic and felsic plutons (Southwick and Fisher, 1967; Higgins, 1971, 1977, 1990). All units are at greenschist to amphibolite facies of metamorphism with preserved volcanic textures. The Cecil County volcanic rocks and the Wilmington Complex volcanic rocks (groups IV) are separated at the Delaware-Maryland boundary by a metamorphosed granodioritic pluton named the Christianstead Gneiss (Figure 1) (Schenck et al., 2000). Detailed maps, petrographic observations, and geochemical data for the Cecil County rocks are found in

Higgins (1990) and Smith and Barnes (unpublished reports, Pennsylvania Geological Survey, 1993; 1994).

The James Run Formation in Cecil County has often been correlated with the Wilmington Complex (Ward, 1959; Higgins, 1971, 1977, 1990). Indeed, Pickett (1976) and Thompson (1979) extended the James Run Formation into Delaware encompassing some of the area previously mapped as Wilmington Complex. In this report we compare the geochemical data from Cecil County with that from Delaware; however, our understanding of the data is limited by our lack of fieldwork in the Maryland Piedmont.

Higgins (1990) divided the James Run Formation in Cecil County into seven formally named members. He reported the major element chemistry for all seven members and trace-element data for the Gilpins Falls Member, a unit composed of metamorphosed pillow lavas and amygdaloidal amphibolites. Higgins noted that low abundances and depletion of HREEs are striking features of the Gilpins Falls metabasalts and concluded that the Gilpins Falls magmas were primitive and associated with a cumulus phase of crystallization, possibly related to the Baltimore Mafic Complex. However, the REE abundances in the Gilpins Falls metabasalts as quantified by La concentration (12.9x to 19.4x chondrite) are significantly higher than the cumulates of our group V (3.7x to 7.3x chondrite) (Table 3). In addition, the REE patterns do not have Eu anomalies (Figure 16A), a common feature of cumulates (Figure 14A). We conclude the geochemical data does not support a cumulate origin for the Gilpins Falls Member.

On the basis of REE patterns and Pearce and Cann discrimination diagrams (1973), Higgins proposed that the Gilpins Falls metabasalts originated as low-K tholeiites of the island arc series. Our plots (Figure 16A & B) agree showing the Gilpins Falls metabasalts have flat REE patterns and spider diagrams similar to those of the Windy Hills Gneiss, group IV, Wilmington Complex (Figures 11B and 12B). These plots are characteristic of tholeiitic island arc suites (Pearce 1982, 1983) and indicate these units are probably products of an evolving magmatic arc.

Smith and Barnes (unpublished report, Pennsylvania Geological Survey, 1993) analyzed both major and trace elements for 3 samples collected from the James Run Formation along the Susquehanna River in Cecil County, Maryland (DGS Data Repository). Two samples are from the Gilpins Falls Member and one is from the Frenchtown Member (JRGFAS, JRGFA, and JRFMV). Although in the field the samples appeared to be metabasalts, the chemistry indicates the Gilpins Falls Member samples are andesites and the Frenchtown Member sample is a dacite. They cannot be directly compared with the mafic samples from the Wilmington Complex, however the REE patterns and spider plots with the negative Nb and Ta anomalies and a positive Th anomaly show an arc affinity (Figure 17A & B). With additional data and geochemical modeling, it may be possible to show that the Gilpins Falls andesites and the Frenchtown Member dacite were derived from fractionation of basaltic magma similar to the Gilpins Falls Member analyzed by Higgins (1990).

Smith and Barnes also analyzed samples from two unmetamorphosed dikes that intrude the James Run Formation in Cecil County. Sample JRFMC is from a dike that cuts the Frenchtown Member and sample JRS cuts the Port Deposit and Happy Valley Branch members (Figure 2). The REE pattern for sample JRFMC (Figure 18A) is similar to the pattern for HERCWEST from the Faulkland Gneiss, (Figure 13A) and to group VI samples (Figure18B) suggesting that it may be a late stage dike.

Amphibolites of the Wissahickon Formation

Trace Element Chemistry

Amphibolites occur abundantly within the Wissahickon Formation as 3-in to 30-ft thick layers that are concordant with the dominant foliation, or as large massive bodies that are several miles long and less then one mile wide (Bascom and Stose, 1932; Plank et al., 2000). Smith and Barnes collected samples of Wissahickon amphibolites from 23 localities in Delaware and Pennsylvania (unpublished reports, Pennsylvania Geological Survey 1994, 2001). They were the first to use geochemical data to identify two amphibolite types. Subsequently Volkert et al. (1996) found two amphibolite types in the Wissahickon Formation in New Jersey. During the present study two amphibolites, HERCRR and WOODDALE, from the Wissahickon Formation in Delaware were sampled and analyzed. For chemical data

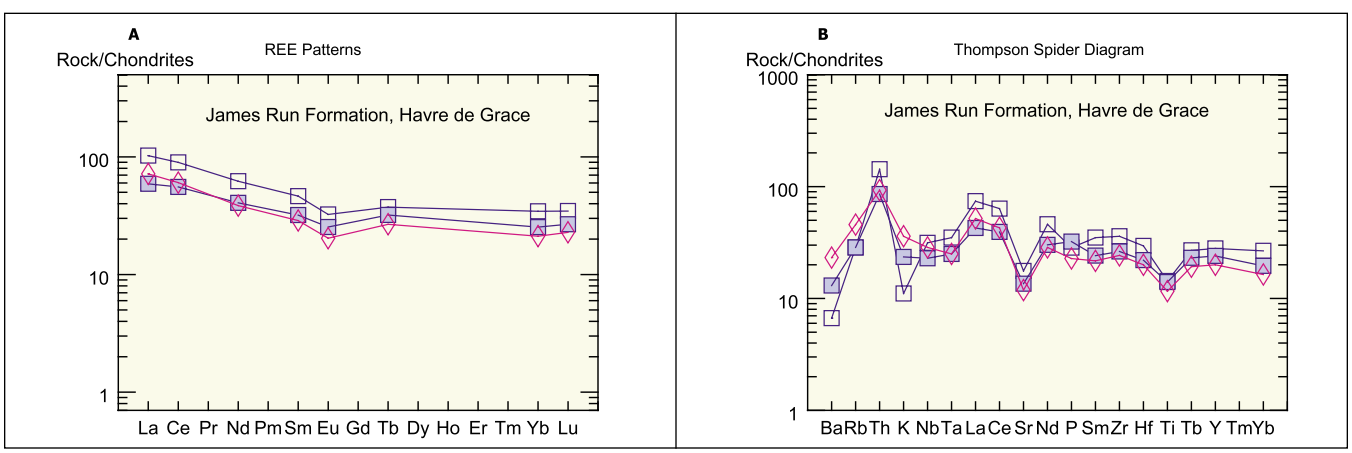

Figure 17. A. REE patterns for 3 samples of James Run Formation, Cecil County, Maryland. Samples JRFAS and JRGFA from Gilpins Falls Member and sample JRFMV from Frenchtown Member (Smith and Barnes, unpublished report, Pennsylvania Geological Survey, 1993). B. Spider diagram for same samples.
Symbols: open square, JRFAS, Gilpins Falls Member; closed square, JRGFA, Gilpins Falls Member; and open diamond, JRFMV, Frenchtown Member; Cecil County, Maryland.

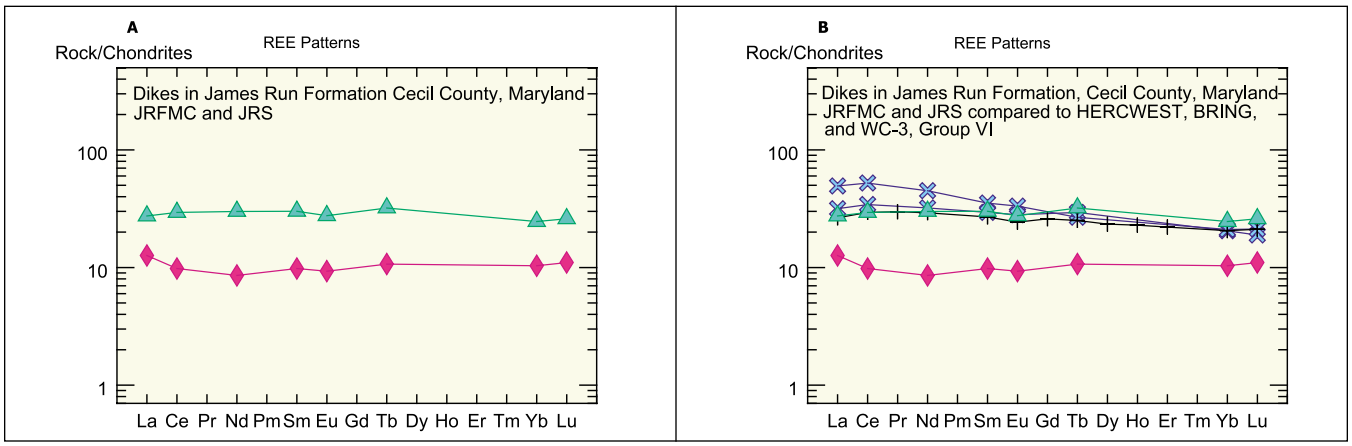

Figure 18. A. REE patterns for samples JRFMC and JRS identified as dikes in James Run Formation, Cecil County, Maryland by R. C. Smith and J. H. Barnes (unpublished report, Pennsylvania Geological Survey, 1993).
B. REE patterns of JRFMC and JRS compared to HERCWEST from Faulkland Gneiss, and to BRING and WC-3, Group VI.
Symbols: closed triangle, dike cutting Frenchtown Member, sample JRFMC; closed diamond, dike cutting Port Deposit and Happy Valley Branch Member, sample JRS; plus sign, HERCWEST; filled cross, BRING and WC-3, Group VI.

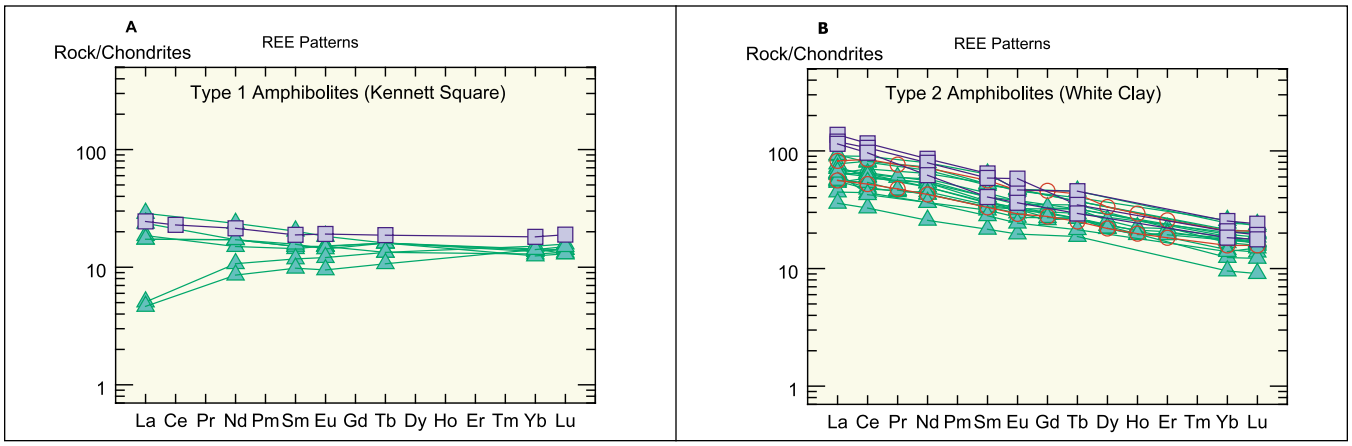

Figure 19. REE diagrams for Wissahickon amphibolites. A. Type 1 (Kennett Square amphibolite). B. Type 2 (White Clay amphibolite).
Symbols: closed triangle, data from Pennsylvania (Smith and Barnes, 1994); filled square, data from New Jersey (Volkert et al., 1996); open circles, data from Delaware, this study.

and sample locations for the two samples from this study plus the Smith and Barnes samples see Table 1, Appendix II, and Figure 2.

Type 1 amphibolites, called the Kennett Square amphibolites by Smith and Barnes (1994; unpublished report, Pennsylvania Geological Survey, 1994 and 2001), have flat REE patterns with slight LREE depletion or enrichment that are characteristic of MORBs (Figure 19A). Smith and Barnes correlate the variation with the map pattern and suggest that the depletion in the east and enrichment in the west represent a transition between normal ocean floor basalts (N-MORB) in the east and plume-enriched ocean floor basalts (E-MORB) in the west. The Thompson spider diagrams for type 1 Kennett Square amphibolites are variably enriched in LILE and depleted in HFSE (Figure 20A). The lack of both a negative Ta-Nb anomaly and a positive Th anomaly suggests an ocean floor affinity (Pearce, 1983).

McEwen (1997) determined the major elements and some trace elements for two Wissahickon amphibolites, Ca34-c from west of Newark (SADDLE, Figure 2), and Cb12-c from near Pleasant Hill valley (COTSWOLD, Figure 2). For a description of the sample locations, see Appendix II. McEwen reported wt. percent TiO_2 and FeO* that are typical of type 1 Kennett Square amphibolites (TiO_2 = 0.18 and 0.98 wt. percent and FeO* = 1.41 and 3.24 wt. percent) (Table 1). Her analyses indicate that the type 1 Kennett Square amphibolites in the study area are not restricted to the area south of the Avondale Anticline but occur in other areas within the Wissahickon Formation.

Type 2 amphibolites, called the White Clay amphibolites by Smith and Barnes (1994), are characterized by high FeO* (12 to 19 wt. percent), moderate to high TiO_2 (1.6 to 4.75 wt. percent) (Table 1), high overall REE abundances, negatively sloped REE patterns (Figure 19B) and spider dia-

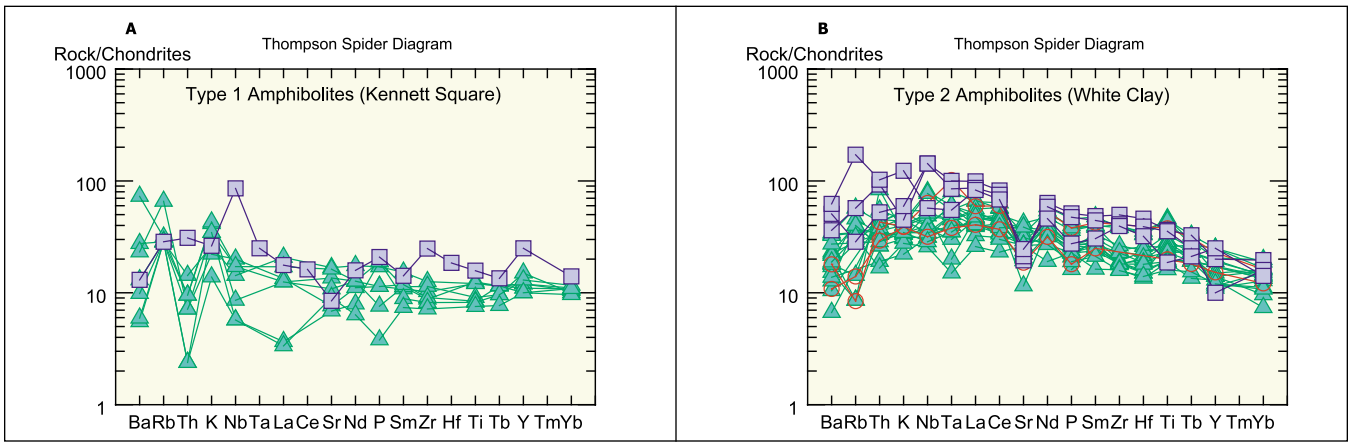

Figure 20. Spider diagrams for Wissahickon amphibolites using element order and normalizing values of Thompson, 1982. A. Type 1 (Kennett Square amphibolite). B. Type 2 (White Clay amphibolite). Symbols are the same as in Figure 19.

grams with the "humped" shape pattern (Figure 20B). These patterns are characteristic of within-plate basalts from either a continental or oceanic setting (Pearce, 1983). Overall, the type 2 White Clay amphibolites have higher concentrations of incompatible elements than the type 1 Kennett Square amphibolites, which is usually explained by smaller degrees of melting and/or a deeper mantle source.

The type section for the type 2 White Clay amphibolite is along the east bank of the Middle Branch of the White Clay Creek, Chester County, Pennsylvania (R. C. Smith and J. H. Barnes, Pennsylvania Geological Survey unpublished report, 2001). At the type section, designated WCCMB, four or more amphibolite layers are separated by pelitic interbeds. The layers do not show evidence for chilled margins and many are distinct from one another chemically, suggesting basalt flows rather than dikes (Appendix II). An outcrop section similar to the type section occurs in Yorklyn, Delaware, along the track of the Wilmington and Western Railroad. Smith and Barnes report that an amphibolite layer from the type section (WCCMBI 10 to 20cm, Figure 2) can be chemically correlated with an amphibolite layer from the Yorklyn outcrop (WCCW+W), a distance of approximately 7 miles (Appendix II, Figure 2).

We have interpreted the micaceous interbeds in the Yorklyn outcrop as fault gouge; however, Smith and Barnes suggest the pelitic interbeds represent metatuffs. They find variable mineralogy and an orientation of mineral grains that are characteristic of metatuffs associated with amphibolites. Additional information is recorded in Smith and Barnes, Pennsylvania Geological Survey unpublished report, 2001.

Volkert et al. (1996) analyzed four samples of crystalline basement recovered from beneath the New Jersey Coastal Plain from Gaventa well No. 88. They recognized an amphibolite that is similar to the Kennett Square amphibolite (type 1) with chemistry suggestive of ocean floor basalts. This amphibolite is enriched LILE and has a REE pattern that is similar to an E-MORB. They also report an amphibolite that is similar to the White Clay amphibolite (type 2); the two samples are from DuPont Repauno Works well No. 85 and Mercer County Park well No. 27, both in New Jersey, and have high-TiO_2 (1.93 to 3.77 wt. percent), high FeO (7.9 to 10.6 wt. percent) and REE patterns typical of ocean island basalts. Volkert et al. (1996) data are included in figures 19 and 20.

Interpretation

Type 1, Kennett Square amphibolites, with MORB-like patterns possibly represent slivers of ocean floor from either the descending slab or overriding plate that were preserved in an Ordovician forearc basin that accumulated sediments of the Wissahickon Formation. Alternatively these amphibolites may be younger and similar to some of the undeformed intrusives of the Wilmington Complex that formed during a phase of arc rifting and back arc spreading.

The type 2 White Clay amphibolites now occur as thin layers that are concordant with the foliation in the metasedimentary rocks of the Wissahickon Formation. Thus, if the Wissahickon sediments accumulated in a forearc basin, then the within-plate geochemistry of the White Clay amphibolites suggests the amphibolites may have been seamounts that were scraped off the descending slab and incorporated into a forearc basin. Alternatively, the Wissahickon Formation may be composed of sedimentary rocks of different ages, seamounts incorporated into a forearc basin of Early Ordovician age, and remnants of Precambrian or Cambrian crust from the colliding plates (Plank et al., 2000).

INTEGRATION

Discrimination Diagrams

Discrimination diagrams use geochemical data to identify magmas from different tectonic settings. We have plotted the Wilmington Complex, James Run Formation, and Wissahickon Formation samples on the Ti vs. V discrimination diagram of Shervais (1982), because Ti and V are HFSEs and thought to be relatively immobile under conditions of hydrothermal alteration and high-grade metamorphism (Shervais, 1982; Rollinson, 1993).

The Ti vs. V plots for the Wilmington Complex and James Run Formation, Cecil County, Maryland (Figure 21), show good correlation between the fields defined by Shervais (1982) and the tectonic settings suggested by the REE patterns and spider diagrams. Group I samples plot in the boninite field defined by Shervais and confirmed by MacLachian and Dunning (1998). This diagram provides additional evidence that these mafic rocks have a boninitic affinity (Figure 21A). Two of the group II samples plot in the arc field; however, the NEWPORT sample taken from a core 82 ft. below sea level plots in the MORB field. Most sam-

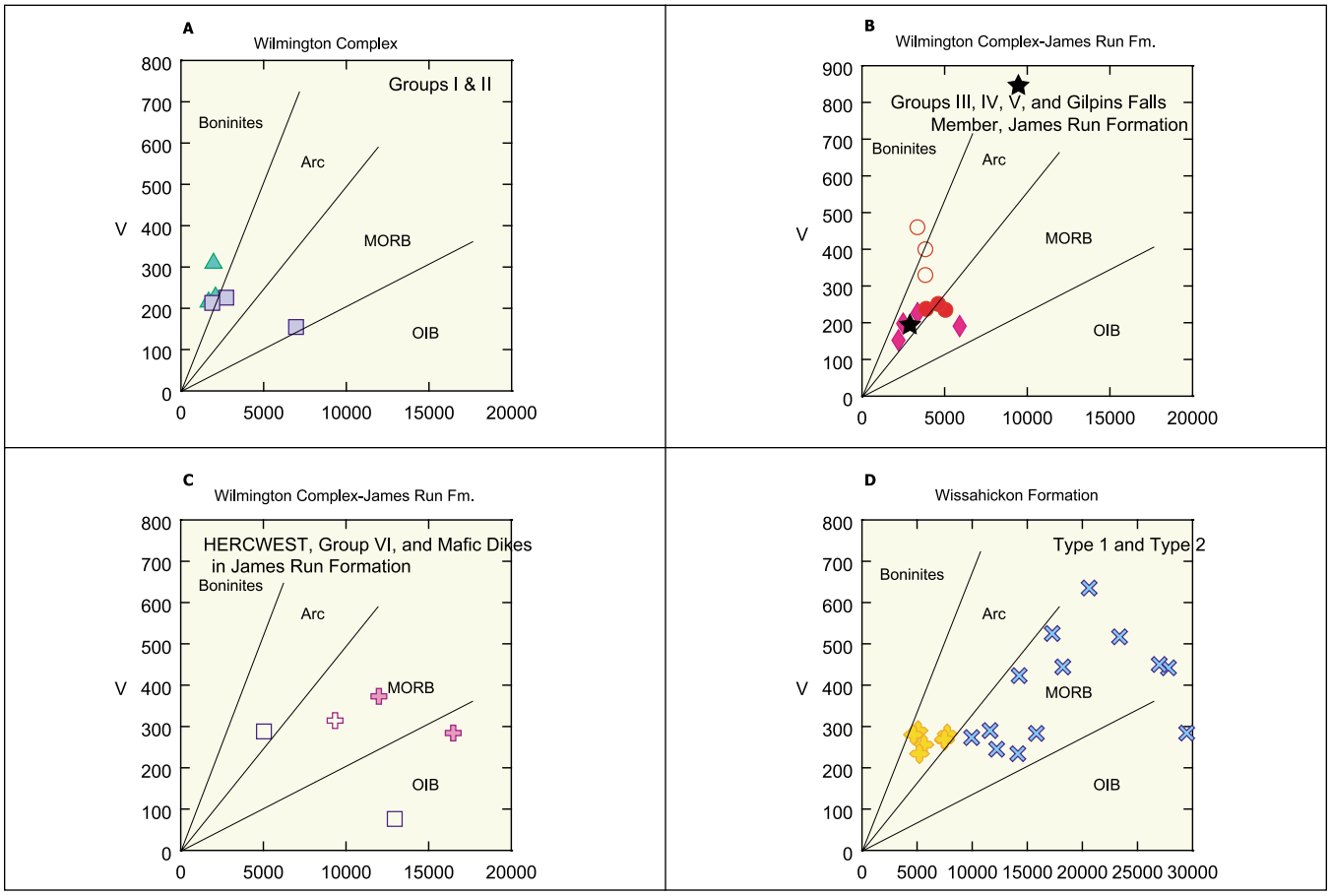

Figure 21. Discrimination diagrams based on Ti vs. V plots by Shervais (1982) of mafic rocks from the Wilmington Complex.

A. Groups I and II. Symbols: closed triangle, group 1; closed square, group II.

B. Groups III, IV, V, and Gilpins Falls Member, James Run Formation, Cecil County Maryland. Symbols: filled diamonds, group III; filled circles, group IV; filled stars, group V; open circles, Gilpins Falls Member.

C. HERCWEST, group VI, and mafic dikes JRFMC and JRS in James Run Formation, Cecil County, Maryland. Symbols: open plus sign, HERCWEST; filled plus sign, group VI (BRING and WC3); open square, JRFMC and JRS.

D. Type 1, Kennett Square amphibolite, and type 2, White Clay amphibolite, Wissahickon Formation. Symbols: filled flower, type 1, Kennett Square amphibolite; filled cross, type 2, White Clay amphibolite.

ples from groups III, IV and V plot in the arc field confirming an arc origin for the mafic rocks of the Wilmington Complex (Figure 21B).

The Ti vs. V plots for the group VI rocks that formed during arc rifting are inconsistent. BRING plots in the MORB field and conforms to the Shervais model while WC-3 plots in the ocean island basalt (OIB) field (Figure 21C). The sample from the Faulkland Gneiss, HERCWEST, also plots in the MORB field. (Figure 21C). Samples JRFMC and JRS from mafic dikes in the James Run Formation, Cecil County, Maryland plot in the OIB and arc fields respectively (Figure 21C).

Ti vs. V plots of the Wissahickon amphibolites effectively discriminate between the type 1 Kennett Square amphibolites and the type 2 White Clay amphibolites (Figure 21D). The type 1 amphibolites with MORB-like REE patterns plot in the arc field, and the type 2 amphibolites with ocean island basalt patterns plot mostly in the MORB field.

A discrimination diagram based on TiO_2-MnO-P_2O_5 was proposed by Mullen (1983). The Mullen diagrams, although they include a "mobile" element MnO, are generally similar to the Ti vs. V diagrams of Shervais (Figure 22). Wilmington Complex groups I, II, III, IV, and Gilpins Falls Member of the James Run Formation in Cecil County, Maryland, plot in fields labeled island arc tholeiites and calc-alkaline basalts (Figure 22A & B). Group VI and HERCWEST samples plot close to or in the MORB field (Figure 22C). Samples from mafic dikes in the James Run Formation, JRFMC and JRS, plot as island arc tholeiites (Figure 22C).

The TiO_2-MnO-P_2O_5 diagram also discriminates between Wissahickon Formation type 1 Kennett Square amphibolite, and type 2,White Clay amphibolite (Figure 22D). Most of the type 1 amphibolites fall in the island arc tholeiite field, and most of the type 2 amphibolites fall in either the MORB or ocean island tholeiite fields.

Plots of type 1 and type 2 amphibolites on the Pearce and Cann (1973) tectonic discrimination diagram based on Zr, Ti, and Y, place these units in the fields that conform to the tectonic settings suggested by the REE patterns. Type 1

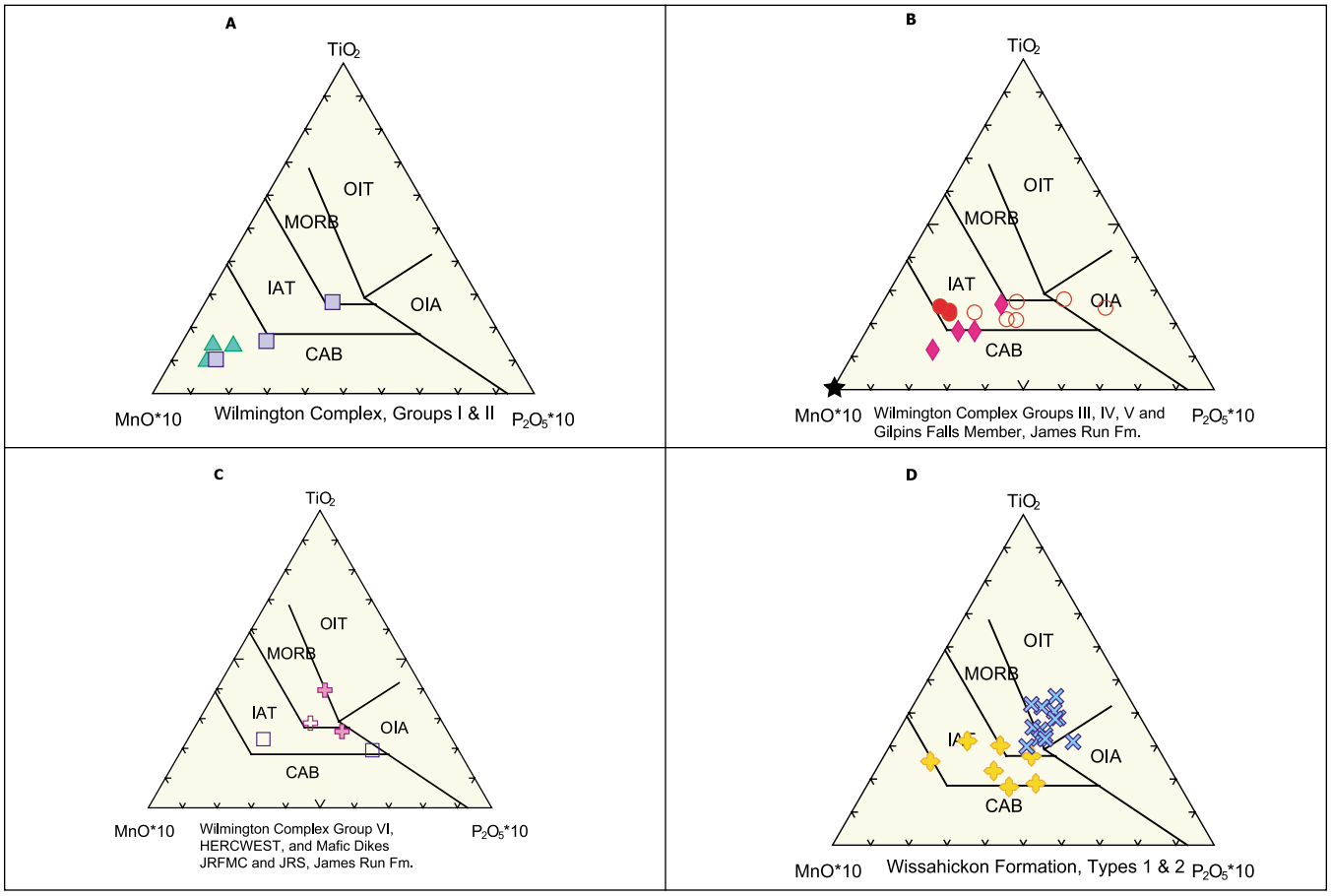

Figure 22. TiO_2-MnO-P_2O_5 discrimination diagrams from Mullen (1983) plotted for mafic rocks and amphibolites from the Wilmington Complex, James Run Formation, Cecil County, Maryland, and Wissahickon Formation amphibolites.
A. Groups I and II.
B. Groups III, IV, V, and Gilpins Falls Member, James Run Formation, Cecil County Maryland.
C. HERCWEST, group VI, and mafic dikes JRFMC and JRS in James Run Formation, Cecil County, Maryland.
D. Type 1, Kennett Square Amphibolite, and type 2, White Clay amphibolite, Wissahickon Formation.
Symbols same as Figure 21. Total iron is reported as FeO*. IAT = island arc tholeiites; MORB = mid ocean ridge basalts; OIT = ocean island tholeiites; CAB = calc alkaline basalts; OIA = ocean island andesites.

Kennett Square amphibolites plot in the ocean-floor field and type 2 White Clay amphibolites plot in the within-plate field.

TiO_2 as Indicator of Location Within Arc

Recent Ocean Drilling Project (ODP) studies of converging plate margins in the western Pacific have observed that the igneous rocks of the forearc are predominately boninitic basalts, low-K tholeiitic basalts with depleted trace-element concentrations, and related silicic differentiates (Taylor et al., 1992; Bloomer et al., 1995). As early arc magmatism in the forearc gives way to normal (mature) arc magmatism the igneous rocks are less depleted in trace elements. Backarc basins form late in the evolution of an arc normally by a three stage progression that begins with rifting of the arc, followed by a stage of initial spreading, and finally mature spreading. The rifting stage is characterized by both slightly depleted arc-like magmas and enriched MORB-like magmas. The mature stage of backarc basin activity is characterized only by MORBs. Thus, backarc and rifted-arc magmas typically have the highest concentrations of HFSE and are the least depleted of any regions of the arc (Gill, 1981; Philpotts, 1990; Ragland, 1989; Rollinson, 1993). The TiO_2 content, as an index of the degree of source depletion, has been used to plot a geochemical transect across the Cenozoic Izu-Bonin arc system and shows a systematic increase in TiO_2 from forearc to backarc regions (Wallin and Metcalf, 1998). Figure 24 is a plot of the TiO_2 content of rocks from the Wilmington Complex on a transect as modified from Taylor et al. (1992). Positioning of the Wilmington Complex samples on the horizontal axis of the diagram was made to match the trend of the Izu-Bonin data. The diagram suggests that the TiO_2 contents of rocks from groups I, II, and III are characteristic of rocks formed in the forearc and the arc; from group IV and the Gilpins Falls Member of the James Run Formation are characteristic of rocks formed in a more mature portion of arc; and from group VI are characteristic of rocks formed during rifting and backarc spreading. Group V rocks are not plotted because they are cumulate gabbros whose TiO_2 content may not reflect magma composition.

The TiO_2 vs. distance diagram implies some geographic systematics; however, the present day spatial relationships in the Wilmington Complex probably do not reflect the original position within the arc. There is an east to west progression as shown on the diagram between forearc rocks, groups I, II, and III and mature arc rocks group IV and the Gilpins Falls Member; however, the group VI rocks that we infer to have formed during arc rifting are located randomly throughout the Wilmington Complex and James Run Formation.

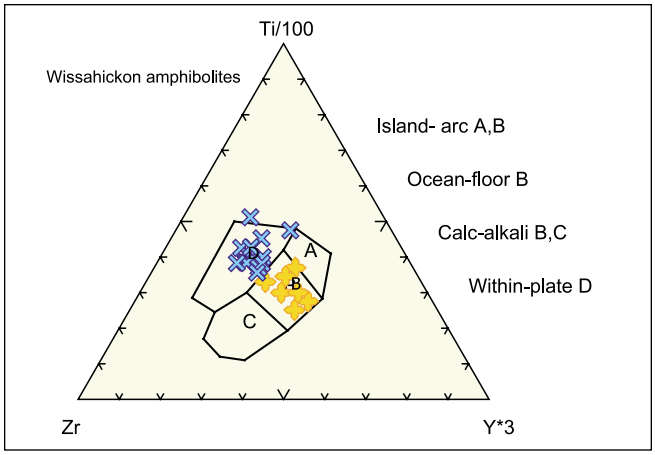

Figure 23. Tectonic discrimination diagram based on Zr, Ti, and Y from Pearce and Cann (1973) for type I and type II amphibolites from the Wissahickon Formation. Total iron is reported as FeO*.
Symbols: filled flowers, type I, Kennett Square amphibolite; filled crosses, type 2, White Clay amphibolite.

Crustal Thickness

Many authors have suggested the low K content of certain rocks (K_2O = < 0.5 wt. percent) may have tectonic and petrogenetic significance. For example, Miyashiro (1974) found the K_2O and SiO_2 content of lavas and the proportion of calcalkaline series in volcanic rock increases with increasing crustal thickness. Leeman (1983) correlated increasing K_2O content of andesites at 55 percent SiO_2 with increasing crustal thickness. All conclude that low-K rocks are rare in continental arcs built on thick crust.

The K-correlations described above are for intermediate to high-silica rocks. Our chemical data has concentrated on basaltic compositions, thus the correlations reported in Plank and Langmuir (1988) are more applicable to our data. They studied the major element systematics of basalts and found that Na_2O and CaO correlate with the thickness of the overlying crust. Using these relationships, they suggest it may be possible to estimate the paleo-crustal thickness of an arc using the immobile trace element Sc, which correlates with Na_2O in modern arc volcanics (Figure 25) (Taylor and McLennan, 1985; Plank and Langmuir, 1993). We use only basalts with MgO compositions between 6 and 8 wt. percent in order to minimize the effects of crustal processes such as crystallization and assimilation. In general, the lower the MgO, i.e.,< 5 percent, the more a magma has crystallized and the more heat it has released to melt and assimilate wallrock.

Only three of our samples from groups II, III and IV, NEWPORT, HAVEG, and GREEN, have MgO values between 6 and 8 wt. percent. We eliminate group I samples from the calculations because they are boninitic and group V because they are cumulates. The ppm Sc values for the three samples, translated to wt. percent Na_2O at 6 wt. percent MgO, equates to depth to the MOHO of 38 km for NEWPORT, 29 km for HAVEG, and 31 km for GREEN (Table 3; Figure 25). Average depth to the MOHO as estimated from

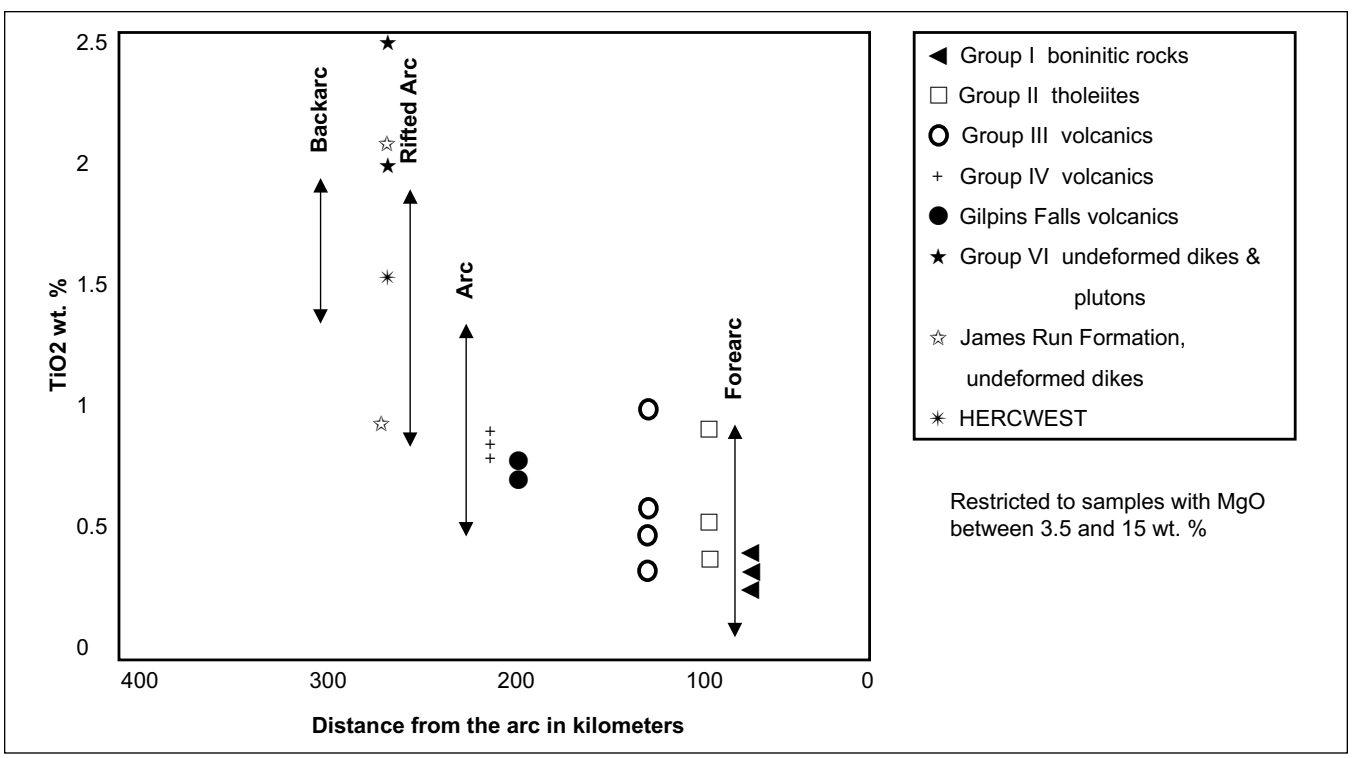

Figure 24. Geochemical transect across the Cenozoic-Izu-Bonin arc system: TiO_2 content vs. distance from the arc (Wallin and Metcalf, 1998) compared with the TiO_2 content of rocks from the Wilmington Complex.

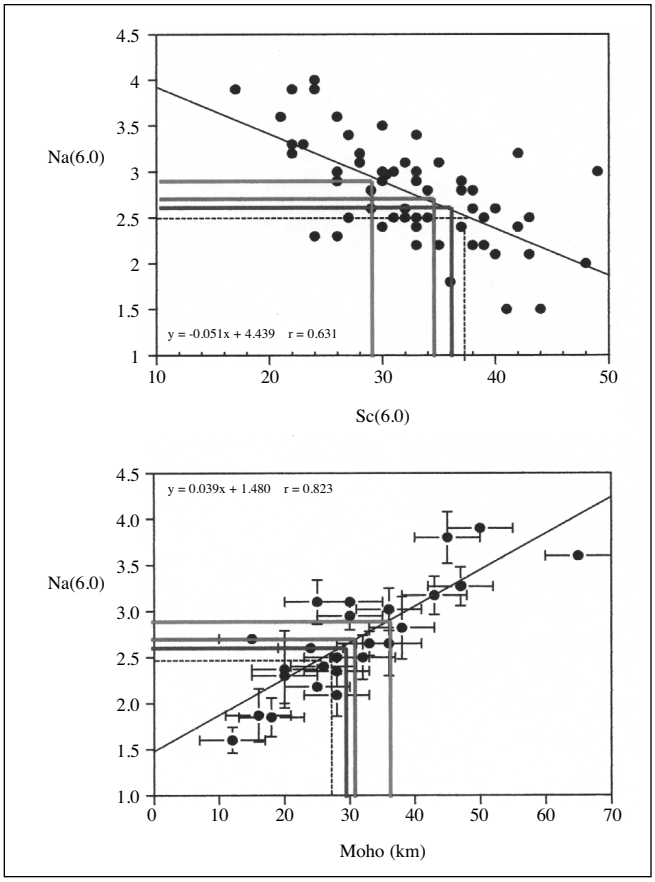

Figure 25. Correlation between Sc (6.0) and Na (6.0) and between Na (6.0) and depth to the MOHO in km. Sc (6.0) = ppm Sc at 6 wt. % MgO, Na (6.0) = wt. % Na_2O at 6 wt. % MgO. (After Plank and Langmuir, 1988 and 1993). Red line correlates Sc value with Na value, and Na value with depth to the Moho for NEWPORT sample. Blue line correlates Sc value with Na value and Na value with depth to the Moho for HAVEG sample. Green line correlates Sc value with Na value and Na value with depth to the Moho for GREEN sample.

these three samples is 32.7 km, thus to a first approximation, the thickness of the Wilmington Complex arc crust was about 33 km. Magmatic arcs with comparable thickness are the Vanuatu and Honshu with an average thickness of 28 km, Java with 30 km, El Salvador-Nicaragua with 32 km, and New Zealand and Kamchatka with 36 km (Plank and Langmuir, 1988). These are transitional arcs, built on thin continental crust or an old volcanic arc. Although there is considerable uncertainty in the analysis, it does suggest that the Wilmington Complex arc may have formed by subduction of oceanic crust beneath oceanic crust or beneath transitional crust with the overriding plate carrying an old volcanic arc or thinned continental crust. We have not found evidence for older igneous or continental rocks within the Wilmington Complex; however, the metasedimentary rocks of the Wissahickon Formation now associated with the Faulkland and Windy Hills Gneisses may be a separate unit and older than the bulk of Wissahickon Formation that surrounds the Wilmington Complex (Plank et al., 2000)

Table 4. Estimates of crustal thickness based on parts per million (ppm) Scandium.
From method of Plank and Langmuir (1988).

Sample	MgO wt. percent	Sc ppm	Na_2O wt. percent	Depth to MOHO
NEWPORT	6.89	29.13	2.95	~ 38 km
HAVEG	7.57	36.51	2.58	~ 29 km
GREEN	7.72	34.42	2.68	~ 31 km

CONCLUSIONS

The geochemistry of mafic rocks in the Wilmington Complex has provided a quantitative basis for grouping rocks. Although intense deformation and high-grade metamorphism have destroyed most original igneous features, we have found a relationship between the geochemical groups and field characteristics that has been helpful in separating and mapping the rock units.

On the basis of the geochemistry of the mafic rocks, we have now mapped two lithodemes, the Rockford Park Gneiss and the Brandywine Blue Gneiss, within what was originally mapped as banded gneiss by Ward (1959) (Schenck et al., 2000). The mafic layers in the Rockford Park Gneiss, group I, are geochemically similar to boninites and are distinctly different from the mafic stringers in the Brandywine Blue Gneiss, group II, that are geochemically similar to and probably originated as low-K arc tholeiites.

The amphibolite of Ward (1959) and Woodruff and Thompson (1972, 1975) includes both massive quartz-bearing amphibolite that interfingers with metasedimentary gneiss and minor felsic gneiss, and layered amphibolite that is associated with felsic gneiss and minor metasedimentary gneiss. The mineralogy of the amphibolites and the association with the metasedimentary gneisses suggest these rocks may be volcanic. Distinctive geochemical signatures for the massive amphibolite and the layered amphibolite define groups III and IV now mapped as the Faulkland Gneiss and the Windy Hills Gneiss respectively (Figure 1) (Schenck et al., 2000). Some of the amphibolites of Ward (1959) have a gabbroic texture and were probably intrusives. The geochemistry of two samples from gabbroic-like rocks indicates they are cumulates. They are designated as geochemical group V, but because the samples are from units that are separated geographically, we have mapped them separately as the Montchanin Metagabbro and the Mill Creek Metagabbro.

Group VI samples are from a relatively undeformed and unrecrystallized pluton and an undeformed dike that intrudes the Brandywine Blue Gneiss. Both units have E-MORB/BABB signatures and are associated with granitic rocks that have a Silurian age of 434±4 Ma (John N. Aleinikoff, U. S. Geological Survey, personal communication 2000). Field evidence for intrusion and mingling with coeval granitic magmas precludes an origin in a mid-ocean ridge environment; therefore, we conclude the pluton and dike were intruded during Silurian rifting and extension within the arc.

Geochemical data from the James Run Formation volcanics in Cecil County, Maryland, are similar to the volcanics in the Wilmington Complex. This suggests the James Run Formation in Cecil County maybe correlative with the Wilmington Complex. We have not correlated the two units because ages determined on rocks from the James Run Formation type section in Baltimore, Maryland, are significantly younger than the Wilmington Complex (James Run

Formation in Baltimore, 454±5 to 464±5 Ma, Horton et al., 1998, compared to 481±4 and 482±4 Ma for the Windy Hills Gneiss and the Faulkland Gneiss in Delaware, John N. Aleinikoff, U. S. Geological Survey, personal communication, 2000).

Geochemical analyses of mafic rocks within the Wilmington Complex and the Wissahickon Formation indicate the rocks formed in an evolving magmatic arc at a converging margin. We suggest a forearc setting for the Rockford Park Gneiss and the Brandywine Blue Gneiss primarily because modern boninites have only been found in situ in forearcs, and as a general rule low-K tholeiitic rocks occur in island arcs on the outward side near the trench (Ragland, 1989; Gill, 1981; Philpotts, 1990). On the basis of the field relationships of the Wissahickon Formation with the Wilmington Complex such as interlayering and xenoliths of Wissahickon in Wilmington Complex metaplutons, we suggest that some of the metasediments of the Wissahickon Formation may also have been deposited in a forearc basin. This forearc model is consistent with the observations that modern forearcs such as the Izu-Bonin-Mariana forearc display considerable complexity consisting of volcanic flows (including boninites), pillow lavas, dikes, plutonic rocks, sediments, and serpentinized peridotite (Bloomer et al., 1995).

The chemical analyses of the volcanic rocks of Group III and IV, now the Windy Hills Gneiss and the Faulkland Gneiss, constrain these rocks to an arc setting.

The undeformed dikes and plutons with MORB-like chemistry that intrude the Brandywine Blue Gneiss, plus possibly the Wissahickon Formation type 1 Kennett Square amphibolite formed during a phase of arc rifting and back arc spreading.

Recognizing that the geochemistry of the mafic rocks of the Wilmington Complex indicates a forearc-arc-backarc model confirms the long-held belief of Ward (1959), Thompson (1979), Crawford and Crawford (1980), Wagner and Srogi (1987) and others that the Wilmington Complex represents the remnant of an evolving magmatic arc.

REFERENCES CITED

Badger, R. L., 1993, Fluid interaction and geochemical mobility in metabasalts: An example from the central Appalachians: Journal of Geology, v. 101, p. 85-96.

Bascom, F., 1902, The geology of the crystalline rocks of Cecil County: Maryland Geological Survey, Cecil County Report, p. 83-148.

Bascom, F., and Stose, G. W., 1932, Description of the Coatesville and West Chester quadrangles, Coatesville-West Chester Folio: U. S. Geological Survey Geologic Atlas of the United States, Folio 223, 15 p. with maps, scale 1:62,500.

Bloomer, S. H., Taylor, B., MacLeod, C. J., Stern, R. J., Fryer, P., Hawkins, J. W., and Johnson, L. E., 1995, Early arc volcanism and the ophiolite problem: A perspective from drilling in the western Pacific, *in* Taylor, B. and Natland, J., eds., Active margins and marginal basins of the western Pacific: Geophysical Monograph 88, American Geophysical Union, p. 1-30.

Bosbyshell, H., Crawford, M. L., and Srogi, L., 1999, Distribution of overprinting metamorphic mineral assemblages in the Wissahickon Group, southeastern Pennsylvania, *in* Valentino, D. W., and Gates, A. E., eds., The mid-Atlantic Piedmont: Tectonic missing link of the Appalachians: Boulder, Colorado, Geological Society of America Special Paper 330, p. 41-58.

Bosbyshell, H., Sinha, A. K., Crawford, M. L., Fleming, P., Srogi, L., Lutz, T. M., 1998, Thermal evolution of a convergent orogen: New U/Pb ages of monazite and zircon from the central Appalachian Piedmont; Geological Society of America Abstracts with Programs, Annual Meeting and Exposition, Toronto, Canada, p. 68.

Carr, M., 1988, Igpet32 for Win95/NT: Terra Softa Inc., Somerset, NJ.

Chace, R. J., 1995, The chemistry and origin of the Ordovician (?) amphibolites of the Wilmington Complex along Red Clay Creek, Delaware: Bryn Mawr, Pennsylvania, Bryn Mawr College, unpublished senior thesis, 41 p.

Crawford, M. L., and Crawford, W. A., 1980, Metamorphic and tectonic history of the Pennsylvania Piedmont: Geological Society of London Journal, v. 137, p. 311-320.

Crawford, A. J., Falloon, T. J., and Green, D. G., 1989, Classification, petrogenesis and tectonic setting of boninites, *in* Crawford, A. J., editor, Boninites: Unwin Hyman, London, p. 1-49.

Coish, R. A., 1989, Boninitic lavas in Appalachian ophiolites: A review, *in* Crawford, A. J., ed., Boninites: London, Unwin Hyman, p. 264-287.

Gill, J. B, 1981, Orogenic andesites and plate tectonics: Springer-Verlag, Berlin, 390 p.

Govindaraju, K., 1994, Compliance of working value and sample designation for 383 geostandards: Geostandards News Letter, v. 18, p. 1-158.

Gust, D. A., Arculus, R. J., Kersting, A. B., 1997, Aspects of magma sources and processes in the Honshu Arc: The Canadian Mineralogist, v. 35, p. 347-365.

Hager, G. M., 1976, Petrologic and structural relations of the crystalline rocks in the Hoopes Reservoir area, Delaware: Newark, Delaware, University of Delaware, unpublished Masters thesis, 79 p.

Hashiguchi, H., Yamada, R., and Inoue, T., 1983, Practical application of low Na2O anomalies in footwall acid lava for delimiting promising areas around the Kosaka and Fukazawa Kuroko deposits, Akita Prefectural, Japan, *in* Ohmoto, H., and Skinner, B. J., eds., The Kuroko massive sulfide deposits: Economic Geology, Monograph 5, p. 387-394.

Hawkins, J. W., Bloomer, S. H., Evans, C. A., and Melchior, J. T., 1984, Evolution of intra-oceanic arc-trench systems: Tectonophysics, v. 102, p.175-205.

Hickey, R. L., and Frey, F. A., 1982, Geochemical characteristics of boninite series volcanics: Implications for their source: Geochimica et Cosmochemica Acta, v. 46, p. 2099-2115.

Higgins, M. W., 1971, Depth of emplacement of the James Run Formation pillow basalts, and depth of deposition of part of the Wissahickon Formation, Appalachian Piedmont, Maryland: American Journal of Science, p. 321-332.

_____ 1972, Age, origin, regional relations, and nomenclature of the Glenarm Series, central Appalachian Piedmont: A reinterpretation: Geological Society of America Bulletin, v. 83, p. 989-1026.

_____ 1977, Six new members of the James Run Formation, Cecil County, northeastern Maryland, *in* Sohl, N. F., and Wright, W. B., Changes in stratigraphic nomenclature by the U. S. Geological Survey, 1976: U.S. Geological Survey Bulletin 1435-A, P. A122-A127.

_____ 1990, The crystalline rocks of Cecil County, Maryland, *in* The geology of Cecil County, Maryland: Maryland Geological Survey Bulletin 37, p. 3-116

Horton, J. W., Jr., Aleinikoff, J. N., Drake, A. A., Jr., and Fanning, C. J., 1998, Significance of Middle to Late Ordovician volcanic-arc rocks in the central Appalachian Piedmont, Maryland and Virginia: Geological Society of America Abstracts with Programs, v. 30, p. 125.

Irvine, T. N. and Barager, W. R. A., 1971, A guide to the chemical classification of the common volcanic rocks: Canadian Journal of Earth Science, v. 8, p 523-548.

Johnson, M. S., and Plank, T. A., 1999, Dehydration and melting experiments constrain the fate of subducted sediments, Geochemistry, Geophysics and Geosystems, 1:1999GC000014, http://gcubed.magnet.fsu.edu/

Kim, J., and Jacobi, R. D., 1996, Geochemistry and tectonic implications of Hawley Formation meta-igneous units: American Journal of Science, v. 296, p. 1126-1174.

Le Bas, M. J., Le Maitre, R. W., Streckeisen, A., and Zanettin, B., 1986, A chemical classification of volcanic rocks based on the total alkali-silica diagram: Journal of Petrology, v. 27, p. 745-750.

Leeman, W. P., 1983, The influence of crustal structure on compositions of subducted-related magmas: Journal of Volcanology and Geothermal Research, v. 18, p. 561-588.

MacLachian, K., and Dunning, G., 1998, U-Pb ages and tectonomagmatic relationships of early Ordovician low-Ti tholeiites, boninites and related plutonic rocks in central Newfoundland, Canada: Contributions to Mineralogy and Petrology, v. 133, p. 235-258.

McEwen, M. M., 1997, The chemistry and origin of amphibolites of the James Run Formation in Delaware: Bryn Mawr, Pennsylvania, Bryn Mawr College, unpublished senior thesis, 44 p.

Miller, D. M., Langmuir, C. H., Goldstein, S. L., and Franks, A. L., 1992, The importance of parental magma composition to calc-alkaline and tholeiitic evolution: Evidence from Umnak Island in the Aleutians: Journal of Geophysical Research, v. 97, p. 321-343.

Miyashiro, A., 1974, Volcanic rock series in island arcs and active continental margins: American Journal of Science, v. 274, p. 321-355.

Mullen, E. D., 1983, $MnO/TiO_2/P_2O_5$: A minor element discriminant for basaltic rocks of oceanic environments and its implications for petrogenesis: Earth and Planetary Science Letters, v. 62, p. 53-62.

Pearce, J. A., 1982, Trace element characteristics of lavas from destructive plate boundaries, *in* Thorpe, R. S., ed., Andesites: New York, John Wiley and Sons, p. 525-548.

Pearce, J. A., 1983, Role of the sub-continental lithosphere in magma genesis at active continental margins, *in* Hawkesworth, C. J. and Norry, M. J., eds., Continental basalts and mantle xenoliths: Shiva Publishers, Nantwich, United Kingdom, p. 230-249.

Pearce, J. A., and Cann, J. R., 1973, Tectonic setting of basic volcanic rocks determined using trace element analysis: Earth and Planetary Science Letters, v. 19, p. 290-300.

Pearce, J. A., van der Laan, S. R., Arculus, R. J., Murton, B. J., Ishii, T., Peate, D. W., and Parkinson, I. J., 1992, Boninite and harzbergite from Leg 125 (Bonin-Mariana forearc): A case study of magma genesis during the initial stages of subduction, *in* Proceedings ODP, Scientific Results, 125, Ocean Drilling Program, College Station, Texas, p. 623-662.

Peccerillo, A. and Taylor, S. R., 1976, Geochemistry of Eocene calc-alkaline volcanic rocks from the Kastamonu area, northern Turkey: Contributions to Mineralogy and Petrology, v. 58, p. 63-81.

Philpotts, A. R., 1990, Principles of igneous and metamorphic petrology: Prentice Hall, Englewood Cliffs, New Jersey, 498 p.

Pickett, T. E., 1976, Generalized geologic map of Delaware (Revised): Delaware Geological Survey Special Publication 9, scale 1:633,600.

Plank, M. O., Schenck, W. S., and Srogi, L., 2000, Bedrock geology of the Piedmont of Delaware and adjacent Pennsylvania: Delaware Geological Survey Report of Investigations No. 59, 52p.

Plank, T. A., 1996, The brine of the Earth: Nature, v. 380, p. 202-203.

Plank, T. A., and Langmuir, C. H., 1993, Tracing trace elements from sediment input to volcanic output at subduction zones: Nature, v. 362, p. 739-742.

_____ 1988, An evaluation of the global variations in the major element chemistry of arc basalts: Earth and Planetary Science Letters, v. 90, p. 349-370.

Ragland, P. C., 1989, Basic analytical petrology: Oxford University Press, New York, 369 p.

Rollinson, H. R., 1993, Using geochemical data: Evaluation, presentation, interpretation: Longman Group UK Ltd., 352 p.

Schenck, W. S., 1997, Stratigraphic classification and nomenclature of the rocks in the Delaware Piedmont: Newark, Delaware, University of Delaware, unpublished Masters thesis, 106 p.

Schenck, W. S., and Plank, M. O., 1995, Data report on rock cores from Red Mill Road, Harmony Road, Prices Corner, and Newport, Delaware: Delaware Geological Survey Open File Report No. 38, 42 p.

Schenck, W. S., Plank, M. O., and Srogi, L., 2000, Bedrock geologic map of the Piedmont of Delaware and adjacent Pennsylvania: Delaware Geological Survey Geologic Map Series No. 10, scale 1:36,000.

Shervais, J. W., 1982, Ti-V plots and the petrogenesis of modern and ophiolitic lavas: Earth and Planetary Science Letters, v. 57, p.101-118.

Shervais, J. W., Shelley, S. A., and Secor, D. T., 1996, Geochemistry of volcanic rocks of the Carolina and Augusta terranes in central South Carolina: An exotic rifted volcanic arc?, *in* Nance, R. D., and Thompson, M. D., eds., Avalonian and Related Peri-Gondwanan terranes of the Circum-North Atlantic: Boulder, Colorado, Geological Society of America Special Paper 304, p. 219-236.

Smith, R. C., and Barnes, J. H., 1994, Geochemistry and geology of metabasalt in southeastern Pennsylvania and adjacent Maryland, *in* Faill, R. T., and Sevon, W. D., eds., Various aspects of Piedmont geology in Lancaster and Chester counties, Pennsylvania: Harrisburg, Pennsylvania, Guidebook for the 59th Annual Field Conference of Pennsylvania Geologists, p. 45-72.

Southwick, D. L., and Fisher, G. W., 1967, Revision of the stratigraphic nomenclature of the Glenarm Series in Maryland: Maryland Geological Survey Report of Investigations No. 6, 19 p.

Srogi, L., 1988, The petrogenesis of the igneous and metamorphic rocks in the Wilmington Complex, Pennsylvania-Delaware Piedmont: Philadelphia, Pennsylvania, University of Pennsylvania, unpublished Ph.D. thesis, 613 p.

Stern, R. J., and Bloomer, S. H., 1992, Subduction zone infancy: Examples from the Eocene Izu-Bonin-Mariana and Jurassic California arcs: Geological Society of America Bulletin, v. 104, p. 1621-1636.

Stern, R. J., Morris, J., Bloomer, S. H., and Hawkins, J. W., 1991, The source of the subduction component in convergent margin magmas: Trace element and radiogenic isotope evidence from Eocene boninites, Mariana forearc: Geochimica et Cosmochimica Acta, v. 55, p. 1467-1481.

Sun, S.-S., and McDonough, W. F., 1989, Chemical and isotopic systematics of oceanic basalts: Implications for mantle composition and processes, in Saunders, A. D., and Norry, M. J., eds., Magmatism in the ocean basins: London, England, Geological Society of London Special Publication 42, p. 313-345.

Taylor, R. N., Murton, B. J., and Nesbitt, R. W., 1992, Chemical transects across intra-oceanic arcs: Implications for the tectonic setting of ophiolites: Geological Society London Special Publication 60, p. 117-132.

Taylor, S. R., McLennan, S. M., 1985, The continental crust: Its composition and evolution: Oxford, Blackwell Scientific, 312 p.

Thompson, A. M., 1979, A summary of the geology of the Piedmont in Delaware, *in* Kraft, J. C., and Carey, W., eds., Selected papers on the geology of Delaware: Transactions of the Delaware Academy of Science, v. 7, p. 115-134.

Thompson, R. N., 1982, Magmatism of the British Tertiary volcanic province: Scottish Journal of Geology, v. 18, p. 49-107.

Volkert, R. A., Drake, A. A., and Sugarman, P. J., 1996, Geology, geochemistry, and tectonostratigraphic relations of the crystalline basement beneath the Coastal Plain of New Jersey and contiguous areas: U.S. Geological Survey Professional Paper 1565-B, 48 p.

Wagner, M. E., and Srogi, L., 1987, Early Paleozoic metamorphism at two crustal levels and a tectonic model for the Pennsylvania-Delaware Piedmont: Geological Society of America Bulletin, v. 99, p. 113-126.

Wallin, E. T., and Metcalf, R. V., 1998, Supra-subduction zone ophiolite formed in an extensional forearc: Trinity Terrane, Klamath Mountains, California: Journal of Geology, v. 106, p. 591-608.

Ward, R. F., 1959, Petrology and metamorphism of the Wilmington Complex, Delaware, Pennsylvania, and Maryland: Geological Society of America Bulletin, v. 70, p. 1425-1458.

Woodruff, K. D., and Thompson, A. M., 1972, Geology of the Newark area, Delaware: Delaware Geological Survey Geologic Map Series No. 3, Scale 1:24,000.

Woodruff, K. D., and Thompson, A. M., 1975, Geology of the Wilmington area, Delaware: Delaware Geological Survey Geologic Map Series No. 4, Scale 1:24,000.

APPENDIX I

Data table for accuracy comparison of Wilmington Complex Samples to standard reference sample JB-3 from Govindaraju (1994)

Sample	**JB-3**	WC-Amp-1	WC-Amp-2	**JB ave**	%RSD	%diff. from Gov
Rb 85	**13**	16.19	16.05	**16.12**	0.6	**24%**
Nb 93	**2.3**	2.16	2.14	**2.15**	0.6	**-6%**
Cs 133	**1.1**	0.942	0.948	**0.945**	0.5	**-14%**
La 139	**8.89**	8.15	8.13	**8.14**	0.2	**-8%**
Ce 140	**21.5**	21.22	21.28	**21.25**	0.2	**-1%**
Pr 141	**3.39**	3.32	3.33	**3.32**	0.3	**-2%**
Nd 146	**15.4**	15.81	15.75	**15.78**	0.3	**2%**
Sm 147	**4.27**	4.25	4.19	**4.22**	1	**-1%**
Eu 151	**1.31**	1.32	1.3	**1.31**	1.2	**0%**
Gd 160 corr	**4.47**	4.73	4.64	**4.69**	1.3	**5%**
Tb 159	**0.75**	0.778	0.757	**0.767**	1.9	**2%**
Dy 162	**4.55**	4.65	4.51	**4.58**	2.1	**1%**
Ho 165	**0.79**	0.964	0.942	**0.953**	1.7	**21%**
Er 166	**2.61**	2.66	2.6	**2.63**	1.6	**1%**
Yb 174	**2.62**	2.51	2.44	**2.48**	2	**-5%**
Lu 175	**0.39**	0.391	0.376	**0.383**	2.7	**-2%**
Hf 178	**2.68**	2.88	2.87	**2.87**	0.3	**7%**
Ta 181	**0.15**	0.151	0.148	**0.15**	1.5	**0%**
Pb 208	**5.5**	5.19	3.96	**4.58**	19	**-17%**
Th 232	**1.3**	1.28	1.29	**1.28**	0.5	**-1%**
U 238	**0.46**	0.48	0.47	**0.47**	1.4	**3%**
Mg 26	**5.2**	5.31	5.08	**5.19**	3.2	**0%**
Ca 44	**9.86**	9.99	9.98	**9.99**	0	**1%**
Sc 45	**33.3**	33.7	33.14	**33.42**	1.2	**0%**
Ti 49	**1.45**	1.42	1.351	**1.38**	3.5	**-4%**
V 51	**383**	386	361.11	**373.55**	4.7	**-2%**
Cr 52	**60.4**	57.37	55.53	**56.45**	2.3	**-7%**
Mn 55	**0.16**	0.179	0.173	**0.18**	2.2	**10%**
Fe 57	**11.88**	11.79	11.51	**11.65**	1.7	**-2%**
Co 59	**36.3**	35.04	33.09	**34.06**	4	**-6%**
Ni 60	**38.8**	32.08	34.34	**33.21**	4.8	**-14%**
Cu 65	**198**	186.62	192.27	**189.45**	2.1	**-4%**
Sr 88	**395**	412.58	413.812	**413.2**	0.2	**5%**
Y 89	**27**	27	26.23	**26.61**	2	**-1%**
Zr 90	**98.3**	100.7	99.91	**100.31**	0.6	**2%**
Ba 137	**251**	236.25	242.076	**239.16**	1.7	**-5%**
Ga-corr	**20.7**	21.5	19.84	**20.67**	5.7	**0%**
Zn-corr	**106**	103.01	96.13	**99.57**	4.9	**-6%**
P_2O_5	**0.29**	0.29	0.33	**0.31**	8.6	**7%**
SiO_2	**51.04**	50.56	50.62	**50.59**	0.1	**-1%**
MnO	**0.16**	0.18	0.17	**0.17**	0.9	**9%**
Fe_2O_3	**11.88**	11.61	11.51	**11.56**	0.6	**-3%**
MgO	**5.2**	5.18	5.08	**5.13**	1.5	**-1%**
TiO_2	**1.45**	1.38	1.35	**1.37**	1.7	**-6%**
CaO	**9.86**	10.09	9.98	**10.04**	0.8	**2%**
Al_2O_3	**16.89**	17.21	17.35	**17.28**	0.6	**2%**
Sr	**395**	402.59	413.6	**408.1**	1.9	**3%**
Ba	**251**	242.03	240.28	**241.16**	0.5	**-4%**
Na_2O	**2.82**	2.72	2.81	**2.77**	2.3	**-2%**
K_2O	**0.78**	0.77	0.79	**0.78**	1.2	**0%**

APPENDIX II

Sample locations and descriptions

Note- These location descriptions were taken from original sources verbatim. DGS descriptions contain mostly English units while there is a mixture of English and metric units contained in the location descriptions of Smith and Barnes.

WILMINGTON COMPLEX

Group I

ROCKFORD, Bd41-b, Sample 43428 Wilmington North Quadrangle
Latitude 39° 46′05″ Longitude 75° 34′27″

Sample from Rockford Park, east of the tower. Large outcrop on steep slope approximately 100 ft. above the Brandywine Creek. Interlayered mafic and felsic gneisses are 6- to 12-in thick and intensely boudinaged. Sample from mafic layer. A thin layer of coarse-grained pegmatite occurs in the outcrop. Banding strikes N40˚E and dips 60-70˚NW.

RAMP, Bd43-a, Sample 43901 Wilmington North Quadrangle
Latitude 39° 46′01″ Longitude 75° 32′46″

Sample from Rt. 202 off-ramp going south onto Interstate-95. Large outcrops of bedrock exposed during construction of the interstate highway. Mafic and felsic rock interlayered on a scale of 6- and 12-in Sample from mafic layer. Strike of layering is N35˚E, dip 60-70˚NW.

NATURAL, Bd22-a, Sample 43900 Wilmington North Quadrangle
Latitude 39° 48′40″ Longitude 75° 33′56″

Sample from a mafic layer in interlayered mafic and felsic gneisses outcropping on a steep slope east of the Brandywine Creek flood plain. This area is part of the Brandywine Creek State Park.

Group II

TOWN, Bd13-d, Sample 43902 Wilmington North Quadrangle
Latitude 39° 49′57″ Longitude 75° 32′22″

Sample from a 12-in mafic layer in massive felsic gneiss. Sample recovered from boulders blasted from bedrock during construction of the Brandywine Town Center, intersection of Rt. 202 and Silverside Road.

ZOO, Bd52-a, Sample 43746 Wilmington North Quadrangle
Latitude 39° 45′33″ Longitude 75° 33′05″

Sample from a single 10-in mafic layer in massive felsic gneiss that crops out on the east side of Park Drive. Park Drive extends along the Brandywine Creek north of the Wilmington Zoo. Outcrop at 50 ft above sea level.

NEWPORT, Cc34-41, Sample 24860, Wilmington South Quadrangle
Latitude 39° 42′37″ Longitude 75° 36′27″

Amphibolite from a core recovered during drilling in Christina River, Newport, for construction of Rt. 141 northbound lanes. Sample from 82 ft below sea level. Hornblende grains define a weak foliation in a thick 10-ft amphibolite layer that occurs between 5-ft felsic layers.

Group III

HAGLEY, Bd31-d, Sample 43545 Wilmington North Quadrangle
Latitude 39° 47′13″ Longitude 75° 34′47″

Rock sample taken from abandoned quarry located on Brandywine Creek below the Hagley Library at 55 ft above sea level. Interlayered mafic and felsic rock with sharp boundaries between layers. Sample from an 8-in, boudinaged, mafic layer. Felsic layers, 2- to 3-in thick, are strongly deformed parallel to the layering and contain flattened 2-in pods of mafic rock. An irregular layer of an undeformed quartzite with small pods of mafic rock occurs adjacent to the sampled mafic layer. A hornblende-rich reaction rim formed between the quartz-rich rock and the mafic rock.

PACKARD, Bc53-a, Sample 42352 Wilmington North Quadrangle
Latitude 39° 45′34″ Longitude 75° 37′08″

Massive quartz-bearing amphibolite with "bright eyes" (magnetite grains with halos of quartz and feldspar). Sample from large boulders excavated during construction of the Hewlett Packard building on Centreville Road. This sample was chosen as representative of the large mass of quartz-bearing amphibolites that occur west of Rt. 141 (Center Road) and south of Rt. 48 (Lancaster Pike).

BSP, Cc12-a, Sample 43478 Newark East Quadrangle
Latitude 39° 44′43″ Longitude 75° 38′10″

Amphibolite interlayered and folded with layers of pelitic schist and garnet-bearing quartzite. Thickness of the layers is variable and ranges between 2 and 15 ft. Axial planes of the folds strike N20°E and dip 90°. The hinge plunges 42°NE. Sample collected from large outcrop along the east bank of the Red Clay Creek approximately 90 yards south of the railroad trestle at an elevation of 120 ft in a development called Spice Mill. The development is adjacent to and across the creek from Brandywine Springs Park. Sample BC-1 collected and powdered by R. Chace.

HYDE, Bc52-j, Sample 43380b Kennett Square Quadrangle
Latitude 39° 45′03″ Longitude 75° 38′54″

Twelve-inch thick amphibolite layer interlayered and folded with layers of biotite gneiss and felsic gneiss. Strike of the axial plane of the folds is N10°E with 90° dip. Sample is from an outcrop on Hyde Run, south of Hercules Road, and east of the Sunnybrook School for the Blind at an elevation of 140 feet. Sample BC-13 collected and powdered by R. Chace.

HERCWEST, Bc52-f, Sample 42168 Kennett Square Quadrangle
Latitude 39° 45′09″ Longitude 75° 38′07″

Coarse-grained massive amphibolite, with domains containing poikiloblastic grains of orthopyroxene, approximately 0.5-in diameter, that are surrounded by halos of quartz and plagioclase. Rounded boulders, probable outcrop, at an elevation of 110 ft are exposed along the north side of a stream draw that drains into the Red Clay Creek. Unnamed stream draw is 0.3 miles north of Faulkland Road. Sample BC-10 collected and powdered by R. Chace.

Group IV

GREEN, Plank, T. A., Cb34-d, Sample 43517b — Newark East Quadrangle
Latitude 39° 42′10″ Longitude 75° 41′33″

Felsic gneiss, fine-grained amphibolite and fine to medium-grained biotite gneiss in 5- to 10-ft layers. Strike of the layering is N40°E with a slight SE dip. Sample is from an amphibolite layer exposed during construction of Green Valley apartment buildings just south of Rt. 2 (Kirkwood Highway) and 0.1 mile east of the abandoned quarry at Choate. Elevation is 60 ft above sea level. Psammitic gneiss of the Wissahickon Formation is exposed just north of Rt. 2 in the small tributary that flows into Pike Creek suggesting the contact between the Wilmington Complex and the Wissahickon may be under Rt. 2.

WINDY, Cb42-c, Sample 43425 — Newark East Quadrangle
Latitude 39° 41′32″ Longitude75° 43′29″

Mafic and felsic rocks interlayered on a scale of 8 to 10 in. Evidence for partial melting along contacts between layers. Intrusive pegmatites and large-scale tight folds. Foliation that is parallel to the axial plane of the folds strikes N75°E and dips steeply to the southeast. The hinge of the fold plunges at 90°. Sample collected from a 10-in layer of fine-grained amphibolite exposed along the south bank of the White Clay Creek under the Windy Hills Bridge, elevation of 50 ft. above sea level.

HAVEG, Cc22-c, Sample 41923 — Newark East Quadrangle
Latitude 39° 43′54″ Longitude 75° 38′02″

Coarse- and fine-grained amphibolites. Coarse-grained amphibolites appear to have intruded the finer-grained amphibolites. Features include "bright eyes," garbenshiefer layers, and quartz-filled fractures. Sample collected from fine-grained amphibolite layer. Rock is exposed along the track of the Wilmington & Western Railroad south of the Greenbank Station and approximately 0.4 mile south of Rt. 41. The outcrop extends for several hundred ft at an elevation of 90-120 ft above sea level. Sample BC-4 collected and powdered by R. Chace.

Group V

BCSP, Bd21-a, Sample 41931 — Wilmington North Quadrangle
Latitude 39° 48′24″ Longitude 75° 34′39″

Sample from amphibolite outcrop in woods north of the upper parking lot in Brandywine Creek State Park. Outcrops are rounded from exfoliation and exhibit some relic gabbroic textures. Mafic grains are sometimes elongated parallel to thin bands of quartz. This weak foliation strikes east-west and dips steeply to the north.

MILLCREEK, Bd55-b, Sample 43475 — Kennett Square Quadrangle
Latitude 39° 43′06″ Longitude 75° 40′34″

Coarse- to medium-grained amphibolite with relict gabbroic texture. Amphibolite grains are sometimes aligned to form a weak foliation that strikes N45°E with a 90° dip. Sample collected from a small quarry at the corner of Mill Creek and Stoney Batter roads at an elevation of 165 ft above sea level.

Group VI

WC3, Smith, R. C., and Barnes, J. H. Wilmington North Quadrangle
Latitude 39° 46′10″ Longitude 75° 35′44″

Fresh, fine-grained gabbro containing fresh, lath-like plagioclase phenocrysts. Outcrop at elevation of 235 ft above sea level on the southeast side of Delaware Rt. 141, approximately 0.2 km northeast of the Conrail (formerly Reading Railroad) overpass, District No. 7, New Castle County, Delaware.

BRING, Smith, R. C., and Barnes, J. H. Wilmington North Quadrangle
Latitude 39° 46′32″ Longitude 75° 30′36″

Fresh, medium- to fine-grained orthopyroxene-bearing felsic (?) diabase (norite?) from outcrop on north side of Shellpot Creek, 35±4m east northeast of the powerline over the creek. Sample block collected 15 to 25 cm from contact with coarse-grained magnetite-rich felsic gneiss. The contact trends N10°E, 45°SE, the mafic unit being on top. The sample was collected 0.5 km southwest of the bridge carrying Interstate-95 over Marsh Rd.

JRFMC, Smith, R. C., and Barnes, J. H. Havre de Grace Quadrangle
Latitude 39° 35′04″ Longitude 76° 05′55″

Very dark green, fine-grained, actinolite amphibolite from the Frenchtown Member of the James Run Formation. From an internal chilled zone in an asymmetric 0.8-meter-wide dike with only one chilled zone (equals one sheeted dike?) 6 meters north of benchmark A148 and 54 meters northwest of the centerline of the bridge carrying Rt. I-95 over the northeast bank of the Susquehanna River. The unsampled unit adjacent to JRFMC consists of a 5- to 6-meter-wide, medium-grained actinolite-chlorite-quartz-trace sulfide mafic zone trending N33°E, 81°SE, and containing minor epidote-bearing boudins or pillows.

JRGFAS, Smith, R. C., and Barnes, J. H. Havre de Grace Quadrangle
Latitude 39° 35′20″ Longitude 76° 06′09″

Dark-gray, fractured and microveined, very fine-grained James Run Gilpins Falls amphibolite flow having common 1- to 2-mm amygdules. Sample collected from Conrail railroad cut on the northeast shore of the Susquehanna River, 285 ft southeast of the northwest end of this part of the railroad cut, 225 feet northwest of the southeast end of the outcrop, and approximately 220 ft southeast of sample JRGFA, Cecil County, Maryland.

JRGFA, Smith, R. C., and Barnes, J. H. Havre de Grace Quadrangle
Latitude 39° 35′21″ Longitude 76° 06′10″

Dark-gray, fractured, fine-grained amphibolite flow from the James Run Formation having common 2- to 5-mm amygdules filled with felsic minerals. Sample collected from the Conrail railroad cut on the northeast shore of the Susquehanna River. This sample is from near the northwest contact of the Gilpins Falls amphibolite, based on Higgins (1990) Cecil County map. It is 65 ft southeast of the northwest end of this part of the railroad cut and 325 ft southeast of a small, unnamed stream. This area is 0.64 km southeast of the Conrail bridge over Happy Valley Branch, Cecil County, Maryland.

JRFMV, Smith, R. C., and Barnes, J. H. Havre de Grace Quadrangle
Latitude 39° 35′03″ Longitude 76° 06′10″

Gray, medium-grained, amygdaloidal metabasalt from the Frenchtown Member of the James Run Formation. Rounded felsic amygdules range from 0.2 to 0.5 cm and flattened actinolite blebs from 0.5 to 1.5 cm, the latter outlined by disseminated opaque oxides. This sample is from 25 to 50 cm below the top of a 2-m-thick amygdaloidal unit 1.05 m north of benchmark A148, 48 m north of the centerline of the bridge carrying Interstate Route 95 over the northeast bank of the Susquehanna River, Cecil County, Maryland. (This is 6 m stratigraphically above the site from where sample JRFMC was collected).

JRS, Smith, R. C., and Barnes, J. H. Havre de Grace Quadrangle
Latitude 39° 35′03″ Longitude 76° 05′54″

Very dark green, fine-grained, dense actinolite-chlorite-magnetite amphibolite dike from the James Run Formation containing fair cleavage. It is 0 to 2.5 cm northwest of a southeast contact of a 3.1-m-wide dike that trends approximately N28°E, 65°SE, cutting the gradational contact of the Port Deposit Granite and the Happy Valley Branch Member of the James Run Formation. Sample collected from the northeast side of the Conrail railroad cut 1,085±25 ft. northwest of Happy Valley Branch and 1,000±25 ft. southeast of the southwest projection of U. S. Route 222 onto the railroad, Cecil County, Maryland.

WISSAHICKON AMPHIBOLITES

Sample locations and descriptions

White Clay amphibolite

WOODDALE, Bc42-f — Kennett Square Quadrangle
Latitude 39° 46′16″ Longitude 75° 38′26″

Sample from back wall of Wooddale quarry, near large fold of amphibolite that is surrounded by pegmatites. Axial plane of the fold strikes N45°E and dips 89-90°NW. The fold axis plunges 60°SW. Base of quarry is approximately 150 ft above sea level.

HERCRR, Bc52-c, Sample 42295 — Kennett Square Quadrangle
Latitude 39° 45′38″ Longitude 75° 38′10″

Coarse-grained amphibolite interlayered and interfingered with felsic, psammitic, and pelitic layers. Folds with axial planes striking N10°E, dipping 15°NW. The fold axis plunges 30°SW. Sample is from outcrop on west side of the Wilmington & Western railroad track, 210 yards south of Rt. 48 (Lancaster Pike) at Hercules Research Center. Elevation is 125 ft above sea level. Sample BC-14A collected and powdered by R. Chace.

WCCMB, Smith, R. C., and Barnes, J. H — West Grove Quadrangle
Latitude 39° 47′20″ Longitude 75° 48′09″

Medium-grained-greenish black amphibolite-mafic gneiss containing trace chalcopyrite and iron sulfide from 0 to 7 cm (1.5 to 6.5 cm freshest and analyzed) above the base of a 0.5-m-thick metabasalt, which is the lowest one observed at the site. Seven centimeters above the base, there is an unanalyzed 1-cm friable mica zone. Smith and Barnes suggest the micaceous layers maybe metamorphosed tuffs. Mineral foliation in the outcrop is parallel to the flow (?) top and trends N72°W, 30°S.

WCCMB through WCCMBIV are samples of five metabasalt flows from a single exposure, with I stratigraphically lowest and IV highest. Smith and Barnes have designated this outcrop as the type section for the White Clay amphibolite (unpublished report, Pennsylvania Geological Survey, 1994 and 2001). The WCCMB series is located on the east side of Middle Branch, White Clay Creek, where it makes the right angle bend from flowing east to south, 0.46 km east of the confluence with Indian Run. Location is 1.35 km northeast of Chesterville, Franklin Township, Chester County.

WCCMBI 10-20 cm, Smith, R. C., and Barnes, J. H. — West Grove Quadrangle
Latitude 39° 47′20″ Longitude 75° 48′09″

Fine- to medium-grained, dark greenish black amphibolite. Includes two 1-mm quartzose layers. Consists of somewhat crenulated, blue-green hornblende, andesine, and quartz, as well as opaque oxides, titanite, and biotite and trace epidote-rimmed allanite, apatite, and zircon. Collected from 10 to 20 cm above the base of WCCMBI, or just above the approximately 2-cm mica zone containing abundant primary allanite-cored euhedral epidote. Based on thin section, this micaceous layer is a crenulated albite-quartz-biotite schist containing minor hornblende, opaque oxides, allanite, epidote, and trace fluoroapatite and zircon. The location is as the rest of the WCCMB type-locality samples.

WCCMBII, Smith, R. C., and Barnes, J. H — West Grove Quadrangle
Latitude 39° 47′20″ Longitude 75° 48′09″

Dark, medium fine-grained hornblende-plagioclase foliated metabasalt from 2.5 to 4.5 cm above the base of a 1.7±0.1-m-thick metabasalt, the sampled base of which is mafic. (This 1.7-m-thick unit occurs above a 4.5-m-thick micaceous metasediment or meta-tuff. R. T. Faill sampled it 1.1±0.2 m below the top). The location is as the rest of the WCCMB type-locality samples.

WCCMBIII, Smith, R. C., and Barnes, J. H West Grove Quadrangle
Latitude 39° 47′20″ Longitude 75° 48′09″

Medium-grained, dark gray amphibole-plagioclase gneiss containing a few 2-mm biotitic patches that could be flattened amygdules. This sample is from 0 to 8 cm (1.5 to 7.0 freshest and analyzed) above the base of a higher 0.5-m-thick metabasalt. Beneath this sample is a 0.5-m micaceous layer, then 1.7 m of metabasalt, then 4.5m of metasediment, then the lowest 0.5-m-thick metabasalt from which WCCMBI was collected. Above the 0.5 m metabasalt from which WCCMBIII was collected is 1.0 m of metasediment and then 4+ m of metabasalt. The location is as the rest of the WCCMB type-locality samples.

WCCMBIV, Smith, R. C., and Barnes, J. H West Grove Quadrangle
Latitude 39° 47′20″ Longitude 75° 48′09″

Dark, medium fine-grained hornblende-plagioclase foliated metabasalt from 0.5 to 4.5 cm above the base of a >4m-thick metabasalt that is the highest exposed and sampled unit in the section. The location is as the rest of the WCCMB type-locality samples.

WCCW+W, Smith R. C., and Barnes, J. H. Kennett Square Quadrangle
Latitude 39° 48′29″ Longitude 75° 40′16″

The amphibolite sample was collected from a large outcrop along the Wilmington and Western Railroad track approximately 150 yards east of the NVF Plant in Yorklyn Delaware. The outcrop is adjacent to the contact between the Cockeysville Marble and the Wissahickon Formation and the layering dips 30 to 45° SE off the southeast flank of the Mill Creek Nappe. The sample was collected approximately 55 m northeast of the southwest end of the railroad cut and approximately 7 m southwest of the northeast end, at an elevation of 200±10 ft above sea level, 1.20 km east southeast of arc marker 8 and 1.3 km slightly west of south of arc marker 9, New Castle County, Delaware.

Medium-grained, greenish black, slightly pyritic amphibolite. Consists of olive hornblende, andesine, and quartz as well as minor opaque oxides and trace apatite. Titanite, biotite and epidote appear to be absent, unlike the situation in the same flow at the type locality. Collected from 13 to 19 cm below the top, or 3 to 9 cm above the base, of a 0.20-m thick basalt flow. The layer just below this basalt is 0.15 m thick and very rich in biotite and sucrosic feldspar.

The section in this road cut consists, from the top down, of 2.1 m of metabasalt having some micaceous interbeds, 0.08 m micaceous layer, l.l m gneissic, 0.07 m micaceous layer, 0.30±0.05 m metabasalt, 0 to 0.12 m quartz boudins and micaceous layers, 0.50 m metabasalt, 0.25 m micaceous layer, 0.2 metabasalt (sampled as WCCW+W), 0.15 m micaceous layer, 0.58 m metabasalt, 0.01 to 0.02 m micaceous layer, 0.15 m gneiss, 0.3 m pegmatite. Gneiss 5 m to the southwest or 3±0.5 m lower stratigraphically is sillimanite-bearing.

This outcrop containing five amphibolite beds is herein designated as the principal reference section of the White Clay Creek amphibolite lithodeme (R. C. Smith, J. H. Barnes, unpublished report, Pennsylvania Geological Survey, 2001).

YRKLYN, Smith, R. C., and Barnes, J. H. Kennett Square Quadrangle
Latitude 39° 48′32″ Longitude 75° 40′05″

Coarse-grained hornblende gneiss with a somewhat gabbroic texture. Sparse large pyroxene grains containing rounded inclusions. Visual estimate of 1 percent pyroxene and 3 percent opaque oxides. Collected from a sulfide-bearing outcrop 0.3 m above the level of Delaware Route 82 northeast of Yorklyn, on the north side of Red Clay Creek, 122±m west of Snuff Mill Rd., and 1.25 km southeast of the point at which Delaware Rt. 82 crosses the Pennsylvania-Delaware state line.

LANS, Smith, R. C., and Barnes, J. H West Grove Quadrangle
Latitude 39° 46′21″ Longitude 75° 46′03″

Dark greenish hornblende-andesine gabbroic gneiss containing disseminated pyrite. The sampled outcrop is located on the southwest side of the northwest end of the upper level railroad cut and on the east side of White Clay Creek at a point 0.68 km south southeast of the intersection at Landenberg, London Britain Twp., Chester Co. Elevation is 235±10 ft above sea level.

WCCW, Smith, R. C., and Barnes, J. H West Grove Quadrangle
Latitude 39° 44′38″ Longitude 75° 47′38″

Medium-grained, dark greenish black hornblende-andesine gneiss collected from outcrop 0.2 m below natural surface on the southwest side of a 340-ft. knoll 13±0.5 m below the crest and 8±0.5 m above creek level. Mineral orientation may trend N70°W, 60°S, but this is very uncertain because of wet stained surfaces. The sampled outcrop is 1.1 km north of Strickersville and 2.95 km northwest of the Arc Corner, between Indiantown Rd. and Pennsylvania Rt. 896, London Britain Twp., Chester Co.

LANM, Smith, R. C., and Barnes, J. H West Grove Quadrangle
Latitude 39° 46′36″ Longitude 75° 45′45″

Medium-grained hornblende-andesine (?) gabbroic gneiss, outcrop in cut on southwest side of Saw Mill Road at an elevation of 365±15 ft above sea level and a point 0.92 km east southeast of the crossroads at Landenberg, New Garden Twp., Chester Co.

GREENLAWN2, Smith R. C., and Barnes, J. H. Coatesville Quadrangle
Latitude 39° 53′16″ Longitude 75° 48′09″

Fine-to-medium-grained, slightly weathered, bluish-green crenulated amphibolite. Consists of bluish green hornblende, andesine, quartz, epidote, and biotite. Contains accessory opaque oxides and titanite. Foliation 9±1 m to the west trends N22°E, 20°NW. Collected from weathered outcrop 0.3 m above road level on the north side of Green Lawn Road at an elevation of 45±10 ft This is 190±20 m west of Pennsylvania Route 841 through Green Lawn, West Marlborough Township, Chester County.

WCCN2, Smith, R. C., and Barnes, J. H. West Grove Quadrangle
Latitude 39° 45′38″ Longitude 75° 46′04″

Medium-grained, dark greenish black hornblende-andesine-biotite gneiss collected from a slightly weathered and possibly slumped outcrop on the SW side of an abandoned railroad cut on the SW side of White Clay Creek. The sample was collected 3.5±0.5 m above creek level, where the cut trends N47°W. This is 1.95 km S of the crossroads at Landenberg of 1.25 km NW of Milepost 1 1/2 of the Mason and Dixon Line, London Britain Township, Chester County.

MP5, Smith, R. C., and Barnes, J. H Kennett Square Quadrangle
Latitude 39° 46′55″ Longitude 75° 43′47″

Medium-grained hornblende-plagioclase gneiss with somewhat gabbroic texture. Collected from an outcrop on the southeast side of an abandoned railroad grade 132±8 m southwest of a tributary to Branch Run coming from the southeast, at a point 0.35 km southwest of Milepost 5 of the Mason and Dixon Line, or 0.6 km southwest of where Limestone Rd. crosses the Delaware state line south of Kaolin. Sample collected about 20 m into Delaware.

LANN, Smith, R. C., and Barnes, J. H West Grove Quadrangle
Latitude 39° 46′26″ Longitude 75° 46′11″

Dark greenish hornblende-andesine gabbroic gneiss from an outcrop about 10 m north of the north end of a small quarry on the west side of Penn Green Rd. The sample was collected from within 20 cm of road level, at an elevation of 180±10 ft above sea level, on the maximum curvature of the road, 0.45 km south of the intersection at Landenberg, London Britain Township, Chester County.

WCC, Smith, R. C., and Barnes, J. H Newark West Quadrangle
Latitude 39° 44′24″ Longitude 75° 46′25″

Medium-grained hornblende gneiss that has a N55°W(?) trending foliation near the sample site. Collected from outcrop 0.8 m above rapidly rising creek level (five inches of rain from tail end of unforecast hurricane!) and about 2 m west of the bank of White Clay Creek at a point 55±5 m south of the confluence with a tributary from the west. The sampled outcrop is 2.00 km N15°E of the Arc Corner, London Britain Township, Chester County.

Kennett Square amphibolite

LUCK, Smith, R. C., and Barnes, J. H Kennett Square Quadrangle
Latitude 39° 49′50″ Longitude 75° 43′03″

Fresh, medium-grained hornblende-plagioclase gabbroic gneiss containing accessory titanite. Foliation trends approximately N20°E, 25°NW. Outcrop at an elevation of 330±10 ft above sea level on a new road on the south side of Hillendale Road, 0.85 km west of Five Points, Kennett Township, Chester County.

KS, Smith, R. C., and Barnes, J. H Kennett Square Quadrangle
Latitude 39° 50′21″ Longitude 75° 41′52″

Fresh, medium-grained hornblende-plagioclase gabbroic gneiss having foliation that trends N59°E, 48°SE. Accessory opaque oxides are commonly rimmed with titanite. Collected from a small quarry at an elevation of 275±15 ft on the west side of Pennsylvania Route 82 (Creek Road) at a point 1.1 km northeast of Five Points, Kennett Township, Chester County.

WICK, Smith, R. C., and Barnes, J. H West Grove Quadrangle
Latitude 39° 49′00″ Longitude 75° 50′05″

Banded medium-to coarse-grained hornblende-epidote-plagioclase gneiss containing possible minor chlorite. Some of the epidote is concentrated in <1-cm blebs that could be relict amygdules. Large, pleochroic clinopyroxene is concentrated in bands. Accessory opaque oxides and titanite are present. Sample from probable outcrop on the west side of South Gurnsey Road, 57±3 meters south of Avondale-New London Road, 0.9 km northwest of Wickerton, London Grove Township, Chester Co.

ROSE, Smith, R. C., and Barnes, J. H Kennett Square Quadrangle
Latitude 39° 50′35″ Longitude 75° 39′32″

Fresh, medium- and coarse-grained hornblende-clinopyroxene-plagioclase gneiss from a boulder near the east end of an about 150- m-long series of hornblende gneiss boulders and outcrops on the south rim of Hill 392. Abundant opaque oxides and titanite are present. Joints and gneissic banding trend N59°E, 68°N, but the boulder could be rotated. Sample collected from near the southeast corner of a 3 by 3-meter boulder at an elevation of 370±10 ft above sea level, 0.7-km southeast of Rosedale, Kennett Township, Delaware County.

BRNTML, Smith, R. C., and Barnes, J. H Kennett Square Quadrangle
Latitude 39° 50′16″ Longitude 75° 39′04″

Medium- to coarse-grained hornblende-plagioclase-clinopyroxene gneiss containing sparse titanite and rare opaque oxides from an outcrop about 0.2 meters above the level of Burnt Mill Road, on the east side of the road just south of where it bends west toward Kennett Square. This outcrop is 1.35 km north of milepost 10 of the Mason-Dixon Line, Kennett Township, Chester County.

CHFD, Smith, R. C., and Barnes, J. H — Wilmington North Quadrangle
Latitude 39° 51′44″ Longitude 75° 35′40″

Medium-grained hornblende-plagioclase-clinopyroxene gneiss from a natural outcrop that contains 1-mm to 1-cm felsic bands and lenses that trend N42°E, 52°SE. Accessory opaque oxides, many rimmed with titanite. Sample collected at an elevation of 280±20 ft above sea level on the northwest side of a hill overlooking Brandywine Creek, 725±25 meters south of the railroad intersection at Chadds Ford Junction, Birmingham Township, Delaware County.

BRANDY2, Smith, R. C., and Barnes, J. H — Wilmington North Quadrangle
Latitude 39° 51′12″ Longitude 75° 35′50″

Dark, very fresh, medium-grained hornblende-plagioclase-clinopyroxene gneiss containing clusters of small, opaque oxide grains and separate, sparse titanite. The sample is from the southwest side of a railroad cut where the foliation trends N60°E, 52°SE. Sampled at the base of the outcrop 82 meters northwest of the bridge over the railroad at Brookfield, Pennsbury Township, Chester County.

COTSWOLD, McEwen, M., Cb12-c, Sample 43506 — Newark East Quadrangle
Latitude 39° 44′54″ Longitude 75° 33′08″

Amphibolite, massive to weakly foliated with narrow quartz veins paralleling the foliation. A new development northwest of Pleasant Hill valley called Cotswold Hills. Workman directed us to large area, approximately 500 x 300 yards, of bluish amphibolite (8/25/93). Rock had been blasted and amphibolite float covered the area. Elevation 320 ft above sea level. Sample collected and analyzed by M. McEwen.

SADDLE, McEwen, M., Ca34-c, Sample 43507 — Newark West Quadrangle
Latitude 39° 42′02″ Longitude 75° 46′53″

Covered Bridge Farms, Saddle Circle. Small stream with many amphibolite boulders. Boulders described by the landowners as the remains of a ledge of black rock that was blasted during the construction of Covered Bridge Farms.