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

REPORT OF INVESTIGATIONS NO. 56

THE SETTERS FORMATION IN THE PLEASANT HILL VALLEY, DELAWARE: METAMORPHISM AND STRUCTURE

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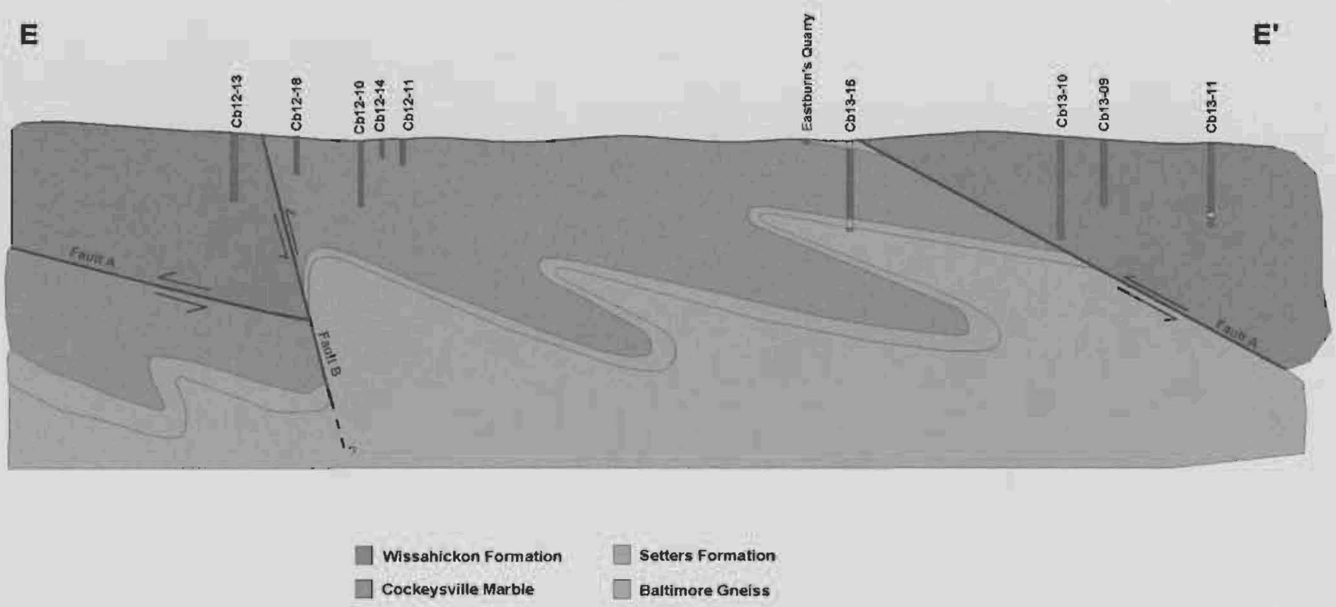

University of Delaware
Newark, Delaware

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ABSTRACT

The Setters Formation, identified on the southeast side of Pleasant Hill valley in well Cb13-16, contains the prograde mineral assemblages (1) microcline, biotite, and sillimanite +/- garnet, and (2) microcline, biotite, sillimanite, and muscovite +/- garnet. These pelitic assemblages allow us to infer peak metamorphic conditions between 620° and 680°C and 4 to 6 kilobars pressure, if P_{H_20}/P_{fluid} is > 0.5. There is some evidence in the drill cuttings to indicate that partial melting accompanied the formation of sillimanite, thus constraining peak temperature to > 640°C.

Peak metamorphic temperatures and pressures estimated for the Wissahickon Formation in thrust contact over the Setters Formation on the southeast side of Pleasant Hill valley fall between 610° and 675°C and 4 to 6 kilobars which is consistant with previous investigations. These temperatures are similar to those estimated for the Setters, and imply the units were metamorphosed under similar conditions.

Woodruff and Plank (1995) mapped a thrust fault contact between the Setters Formation and the Wissahickon Formation along the southeast side of the Pleasant Hill valley and a conformable contact between the Cockeysville Marble and Wissahickon along the northwest side. Subsequent field investigation of the contact on the northwest side of the valley found evidence for a fault boundary, thus we revise the model of Woodruff and Plank (1995) to include a high-angle thrust fault between the Cockeysville and Wissahickon. This fault is similar to the one proposed by Woodruff and Plank (1995) for the northwest side of the Hockessin-Yorklyn anticline.

A revised model for the Mill Creek nappe containing the Landenberg and Hockessin-Yorklyn anticlines and the Pleasant Hill valley, shows the Baltimore Gneiss with its Glenarm Group cover of Setters Formation and Cockeysville Marble exposed in a window through a faulted thrust sheet of Wissahickon Formation. This new model for the Mill Creek nappe is similar to the models proposed for other gneiss dome areas in Maryland and Pennsylvania.

INTRODUCTION

Purpose and Scope

This report describes the Setters Formation (Setters) recently identified by Woodruff and Plank (1995) on the southeast side of Pleasant Hill. In Pleasant Hill a topographic low has developed over the Cockeysville Marble (Cockeysville) to form an elongate valley. This physiographic feature has been informally called Pleasant Hill valley, a term we will use in this report when referring to the marble valley at Pleasant Hill (Figure 2). The Setters occurs as two lithologies along the southeast side of Pleasant Hill valley. In Eastburn's Quarry, the Setters occurs above the Cockeysville Marble as a fine-grained feldspathic quartzite with thin micaceous partings. In well Cb13-16, southeast of the quarry, the Setters occurs as a 60-ft layer of pelitic gneiss lying under 430 ft of Cockeysville. The pelitic layer is significant because it contains pressure- and temperature-sensitive mineral assemblages that allow us to estimate peak metamorphic conditions of the Setters, and thereby refine our models for the metamorphic evolution of the Delaware Piedmont.

Recent research in the central Piedmont (Drake, 1993; Alcock, 1991, 1994) has focused on the contact between the Wissahickon Formation (Wissahickon) and the underlying units, the Baltimore Gneiss, Setters Formation, and Cockeysville Marble. Because understanding the nature of these contacts is important to modeling structures in the Delaware Piedmont, the contacts in Pleasant Hill are reexamined and a new structural model for this area is proposed.

Acknowledgments

We wish to thank Donna Organist for preparing beautiful thin sections from very small, weathered chips of rocks. Her skill and willingness to help made this project possible. We also wish to thank M. L. Crawford, J. Alcock, and N. Spoljaric for helpful reviews and discussions on earlier versions of the manuscript. N. Spoljaric provided x-ray analysis of the rock cuttings.

REGIONAL SETTING

Northern Delaware is located within the central Appalachian Piedmont Province (Figure 1). The rocks are characterized by high-grade regional metamorphism, penetrative deformation, and northwest-directed thrusting. They were metamorphosed and deformed during a subduction-related collision between a volcanic arc, now represented by the James Run Formation and the Wilmington Complex, and the ancient North American continental margin, represented by Middle Proterozoic Baltimore Gneiss and its late Proterozoic-early Paleozoic metasedimentary cover of Setters, Cockeysville, and Wissahickon (Ward, 1959; Thompson, 1979; Wagner and Srogi, 1987; Drake et al., 1989; Higgins, 1990; Drake, 1993).

The contact between the rocks of the volcanic arc and the ancient continental margin is thought to be a fault (Figure 2); however, the nature of the contact in Delaware is controversial because field evidence for the fault is difficult to find (Ward and Groot, 1957; Woodruff and Thompson, 1972, 1975; Thompson, 1979, 1981; Wagner and Srogi, 1987; Valentino and Faill, 1994).

The Baltimore Gneiss, Setters Formation, and Cockeysville Marble are exposed in a series of dome-shaped outcrops that extend northeast from Baltimore, Maryland, to Philadelphia, Pennsylvania (Bascom and Stose, 1932; Hopson, 1964; Crowley, 1976) (Figure 1). Hopson (1964) first described the exposures as mantled-

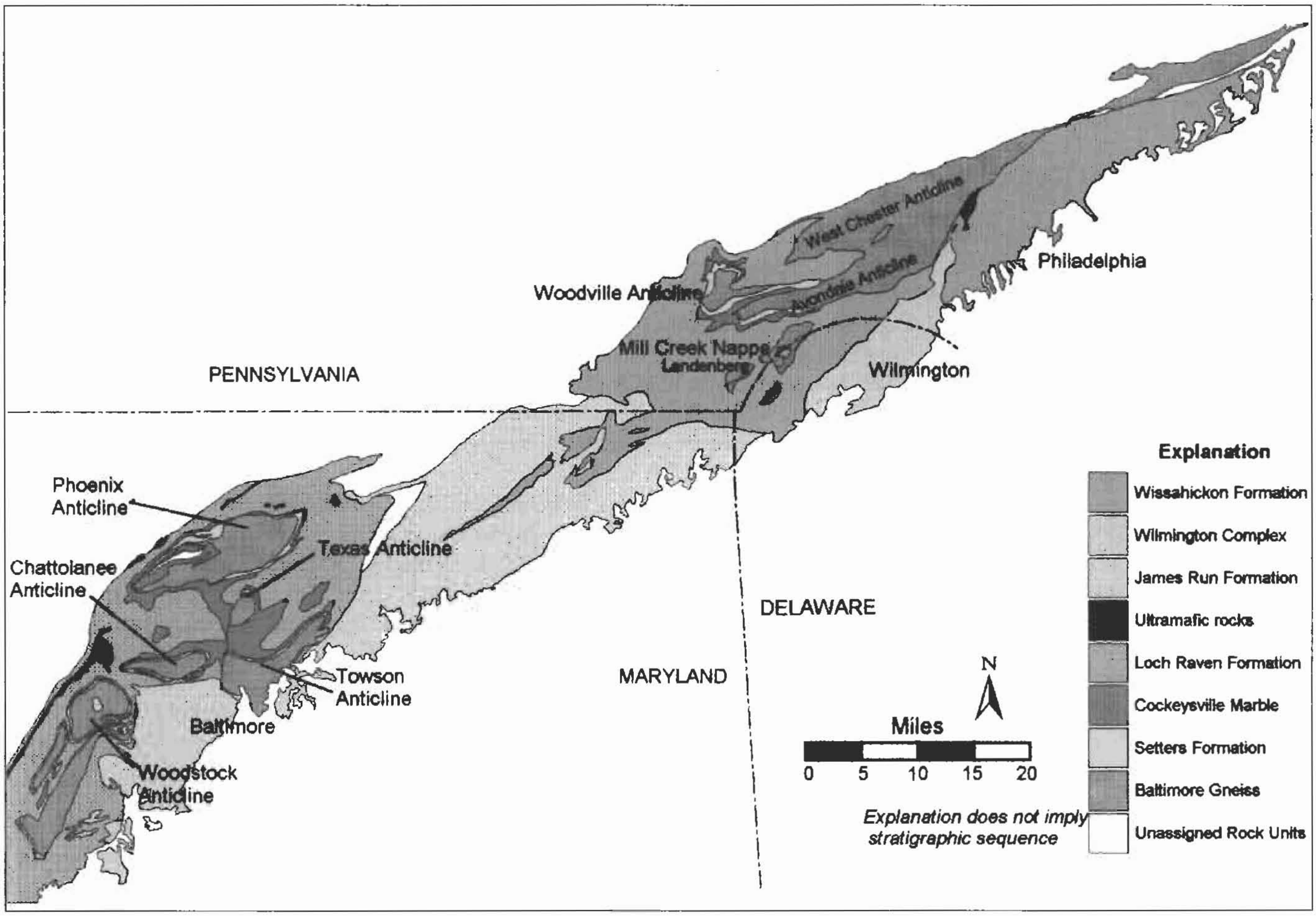

Figure 1. Generalized geologic map of the central Appalachian Piedmont from Baltimore, Maryland, to Philadelphia, Pennsylvania. Shows the outcrops of Baltimore Gneiss and surrounding formations. Adapted from Fisher et al. (1979) and Woodruff and Plank (1995).

gneiss domes, but more recently they have been interpreted to be doubly plunging antiforms or complexly folded nappes (Fisher et al., 1979; Muller and Chapin, 1984; Wagner and Srogi, 1987; Woodruff and Plank, 1991, 1995).

The Baltimore Gneiss in the domes records two periods of metamorphism, one during the mid-Proterozoic, approximately 1,100 ma, and a second during the Paleozoic, 440 to 470 ma (Broedel, 1937; Tilton et al., 1958, 1959; Hopson, 1964). The Setters, Cockeysville, and Wissahickon record only the Paleozoic metamorphism (Tilton et al., 1958, 1959).

The elongate dome-shaped structure that occurs along the Delaware-Pennsylvania border was identified and named the Mill Creek dome by Higgins et al. (1973) but later called the Mill Creek nappe by Srogi (1993). Although, Alcock (1994) refers to it as the Mill Creek dome, we prefer Mill Creek nappe. This structure is revealed in three erosional windows identified as the Landenberg and Hockessin-Yorklyn anticlines and the Pleasant Hill valley (Figure 2). Baltimore Gneiss is exposed in the Landenberg and Hockessin-Yorklyn anticlines, but only the Setters and Cockeysville are exposed in the Pleasant Hill valley where Woodruff and Plank (1995) assumed the Baltimore Gneiss to underlie the Setters, Cockeysville, and Wissahickon at depth.

Metamorphism in the Delaware-Pennsylvania Piedmont increases from northwest to southeast with the highest grade (upper amphibolite to granulite) near the Wilmington Complex (Plank, 1989). This contrasts sharply with the metamorphic grade in the Maryland Piedmont that increases from greenschist to amphibolite grade with the highest grade occurring around the basement-cored nappes (Hopson, 1964; Southwick, 1969; Olsen, 1977).

PREVIOUS INVESTIGATIONS

The Setters Formation was named by Williams (1891) for a spectacular outcrop that occurs along Setters Ridge in Maryland. Here a 160-foot-high ridge of quartzite stands out prominently above a marble valley. Since first described, the Setters has been widely recognized in the Maryland and Pennsylvania Piedmont where it occurs as a discontinuous border around the exposures of Baltimore Gneiss (Knopf and Jonas, 1922, 1923; Bascom and Stose, 1932; Broedel, 1937). Early workers assigned the stratigraphic sequence of Setters, Cockeysville and Wissahickon to the Glenarm Series (Knopf and Jonas, 1922, 1923; Bascom and Stose, 1932; Hopson, 1964; Higgins, 1972). Crowley (1976) raised the Wissahickon to group rank containing the Loch Raven Schist as well as other formations, and he changed the Glenarm series to Glenarm Supergroup containing the Setters Formation, Cockeysville Marble, and the Wissahickon Group. Drake et al. (1989) redefined the Glenarm Group as the Setters, Cockeysville, and Loch Raven Schist.

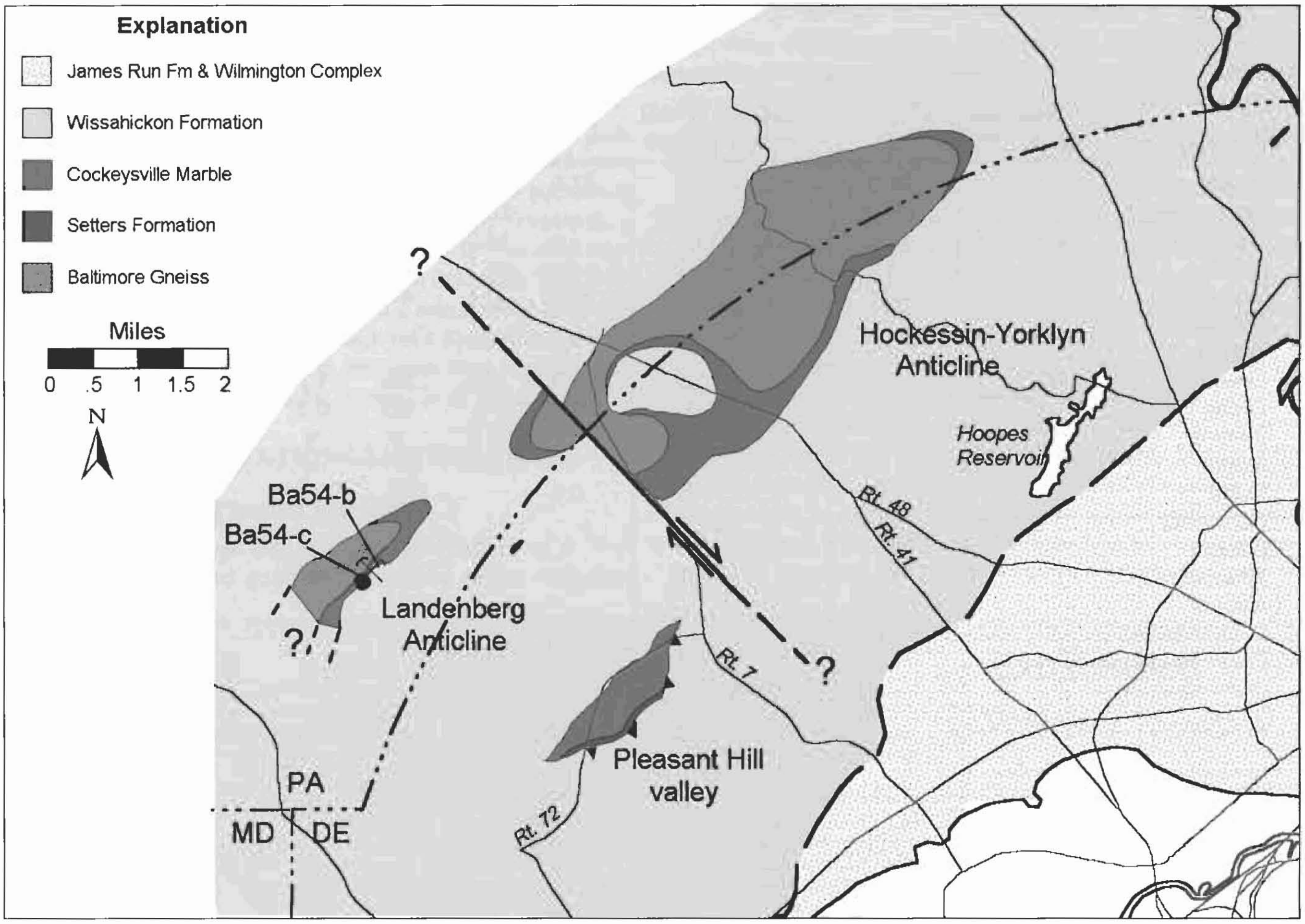

Figure 2. General geology of the Mill Creek nappe in Delaware and Pennsylvania showing three exposures of its Grenville core and/or Glenarm cover. Adapted from Schenck and Plank (1995) and Woodruff and Plank (1995).

Major minerals identified in the Setters Formation are microcline, quartz, biotite, muscovite, and plagioclase (Table 1). Microcline is an essential constituent of the Setters. It is usually more abundant than plagioclase and distinguishes the Setters from the plagioclase-rich lithologies of the Wissahickon and Baltimore Gneiss (Hopson, 1964; Southwick, 1969; Kuhlman, 1975; Woodruff and Plank, 1995).

Three members of the Setters have been described in Maryland by Knopf and Jonas (1929), Broedel (1937), Hopson (1964), and Southwick (1969): (1) a lower member that is a feldspathic quartz-mica schist interlayered with a few thin beds of quartzite; (2) a middle member that is either a feldspathic or micaceous quartzite with thin partings of microcline or muscovite; and (3) an upper member that is a feldspathic mica schist or gneiss that may be garnet-bearing.

Lang (1991) described a pelitic member in the Setters Formation near Cockeysville, Maryland, that contains various assemblages of garnet, staurolite, muscovite, and kyanite. Using geothermobarometry, Lang estimated peak metamorphic conditions in the range of 520° to 600°C at 4.6 to 7.4 kilobars total pressure. These conditions are similar to those estimated for the pelitic rocks in the overlying Loch Raven; consequently, Lang concluded the two units have a similar metamorphic history.

Drake (1993), on the basis of field evidence in Maryland, redefined the Glenarm Group to include the Setters and Cockeysville formations and to exclude the Loch Raven Schist. Drake found the Loch Raven always in thrust contact with the Cockeysville, Setters, or Baltimore Gneiss.

Many models have been proposed to explain the complex regional structures in the West Chester, Avondale, and Mill Creek nappes of the Delaware-Pennsylvania Piedmont. Early debates occurred between McKinstry (1961), who modeled the outcrop pattern of Baltimore Gneiss as culminations on complexly folded anticlinoriums, and Mackin (1962) who suggested the outcrop pattern represents the cores of nappes with gently dipping upright southern limbs and inverted northern limbs. On the basis of detailed mapping and interpretations of magnetic surveys in the Woodville, Pennsylvania area, Alcock (1991, 1994) found evidence to prove that the Wissahickon is not in stratigraphic continuity with the Cockeysville, but overlies and is in thrust contact with a prefolded sequence of Baltimore Gneiss, Setters, and Cockeysville. Originally named the Doe Run thrust by Bliss and Jonas (1916), Alcock redefined the fault and described it as having a gentle but irregular southwest dip. He also recognized northwest directed faults such as the Street Road fault and the Cream Valley fault that placed the sequence of Baltimore Gneiss, Setters, Cockeysville, and Wissahickon over Wissahickon. For a summary of the structural history of the Pennsylvania area see Alcock (1994).

Table 1.
Modal analyses of the Setters Formation in Maryland and Pennsylvania.

	Kuhlman (1975)			Hopson (1964)		Southwick (1969)					Knopf & Jonas
Minerals	**344A**	**344B**	**351**	**H36-1**	**H106-7**	**1**	**2**	**3**	**4**	**5**	**(1929)**
Quartz	14.0	18.7	29.0	58.1	45.4	87.5	36.4	40.4	29.2	32.5	17.6
Plagioclase	1.4	x	0.0	2.4	7.8		28.4	0.3		25.5	9.59
Microcline	54.6	7.1	46.0	19.3	31.5	x	14.0	42.1	1	4.4	40.59
Biotite	18.2	19.9	13.1	12.2	11.2		16.1	9.5	40.4	27.0	20.25
Muscovite	11.1	52.9	11.1	5.6	1.9	10.5	3.4	4.5	21.9	7.5	7.58
Sillimanite											
Garnet									3		
Opaques	x	x	0.7	1.7	1.9	1.3	0.5	2.8	1.7	1.2	0.93
Zircon				x	x	0.3	x	0.3	0.2	x	
Sphene				x	0.1	x	0.6	x	x	x	
Apatite	x	x		0.5			0.2	0.1	x	0.5	
Rutile						0.4					1.52
Carbonate										1.4	
Epidote						x				x	
Tourmaline									0.1		
Allanite											
Chlorite/Biotite	x		x			x					
Clay/Plagioclase					0.2		0.4				
Other Minerals											1.21
Points Counted	1000	1000	1000	1000	1000	1436	1368	1594	1654	1332	

Sample No.	Location
344 A & B	Quarry at Avondale, Pennsylvania
351	Quarry at Avondale, Pennsylvania
H36-1	Clarksville dome, 1.5 miles northwest of Pine Orchard, Maryland
H106-7	Woodstock dome, Marriotsville, Maryland
1	Phoenix dome, 0.5 miles northeast of Little Gunpowder Falls, Maryland
2	Lower Bynum Run about 0.5 miles north of Hookers Mill Road, Maryland
3, 4, & 5	Lower Winters Run about 0.9 miles upstream from Interstate Highway 95, Maryland
Knopf & Jonas	no location reported

Woodruff and Plank (1995) proposed the Hockessin-Yorklyn structure is a nappe with gently dipping limbs on the southeast side and overturned limbs that have been cut by thrusts on the northwest side. In Pleasant Hill they found an inverted sequence of Setters and Cockeysville that is overlain by the Wissahickon on the gently dipping southeast limb. They modeled the inverted sequence as the overturned limb of a basement-cored nappe that is overthrust by the Wissahickon. The northwest limb was modeled as overturned to the northwest with a conformable contact between the Wissahickon and Cockeysville.

Alcock (1991, 1995) identified a metamorphic discontinuity at the Wissahickon-Cockeysville contact in the Landenberg area as additional evidence for the Doe Run thrust. Alcock correlated amphibolite-facies mineral assemblages in the Cockeysville with their distance from the Wissahickon, and postulated that peak metamorphism of the marble occurred after the Wissahickon was emplaced.

Because of the high-grade metamorphism in the Delaware Piedmont, Setters rocks have been difficult to recognize. In Eastburn's Quarry in Pleasant Hill valley, Woodruff and Plank (1995) identified a microcline-rich quartzite that overlies the Cockeysville as a typical Setters lithology (Figure 3). Because the Wissahickon in the central Piedmont usually overlies the marble, this rock had been previously identified and mapped as a psammitic gneiss of the Wissahickon (Woodruff and Thompson, 1972; Porter, 1976). Woodruff and Plank (1995) also reported Setters rocks in a small stream bed adjacent to the quarry, as float in a housing development built in 1990 on the hillside southeast of the quarry, and in the cuttings from well Cb13-16 drilled on the southeast side of Eastburn's Quarry (Figure 3). Thompson (1981) reported outcrops of thinly-laminated, flaggy-splitting, quartz-biotite-plagioclase-almandine gneiss along the southeast side of the Mill Creek nappe in the Hockessin-Yorklyn area. Thompson suggested these rocks be assigned to the Setters Formation because they are similar to the Setters rocks in the Avondale Anticline (Figure 1). Woodruff and Plank (1995) found no microcline-rich rocks either in outcrop or drill holes adjacent to the Hockessin-Yorklyn valley. If Setters exists in this area, it is present in thin and discontinuous layers.

METHODS OF INVESTIGATION

The investigation of the Setters Formation in the Delaware Piedmont consisted of (1) revisiting outcrops in the Pleasant Hill valley, (2) researching well data on file from this area, and (3) petrographic study of samples collected from outcrops and drill cuttings from well Cb13-16 (Figure 3). Data collected from a brief reconnaissance of the Landenberg anticline are also included.

Well Cb13-16, located just southeast of Eastburn's Quarry at an elevation of approximately 200 ft above sea level (Figure 3), was drilled using air percussion equipment to a depth of 580 ft. We observed the cuttings as they were recovered from 320 to 580 ft. Natural gamma ray and caliper logs were run. Gamma ray logs are useful in defining lithologies, thus they were compared with the driller's log to accurately identify the depths at which the rock units change (Figure 4).

Mineral assemblages were identified in five thin sections prepared from cuttings collected at 360, 440, 520, 540, and 560 ft. We were unable to make a thin section from the fine cuttings recovered from a black rock identified between 415 and 420 ft. The minerals in this layer were identified by x-ray diffractometry of powder mounts from the cuttings.

FIELD OBSERVATIONS AND WELL DATA

Pleasant Hill Valley

The Setters crops out in Eastburn's Quarry as a 25-ft layer of fine-grained quartzo-feldspathic gneiss with thin micaceous partings and clusters of garnets. It overlies the dolomitic lithology of the Cockeysville. Although the contact between the units is weathered and covered with soil, the strike and dip of the layering in both units is concordant at N33°E, 23°SE. A compositional layering in the marble defines recumbent isoclinal folds that are overturned to the northwest. The axial planes of the folds dip 20-30° to the southeast and strike between N30°E and N40°E. The compositional layering in a marble core recovered from well Cb12-10 at 410 to 419 ft dips between 30° and 40° (Figure 5). This core is not orientated, but we assume the dip is also to the southeast.

Petrographic analyses of the Setters in Eastburn's Quarry show that the rock varies from an impure quartzite to a quartzo-feldspathic gneiss (Table 2, sample 42339 and 42340). Quartz and microcline are the major phases with biotite present in smaller amounts. Muscovite is absent. The plagioclase is consistently altered to a pale yellow-green clay mineral. The alteration of plagioclase to clay has been noted by Hopson (1964) and Southwick (1969) and may be

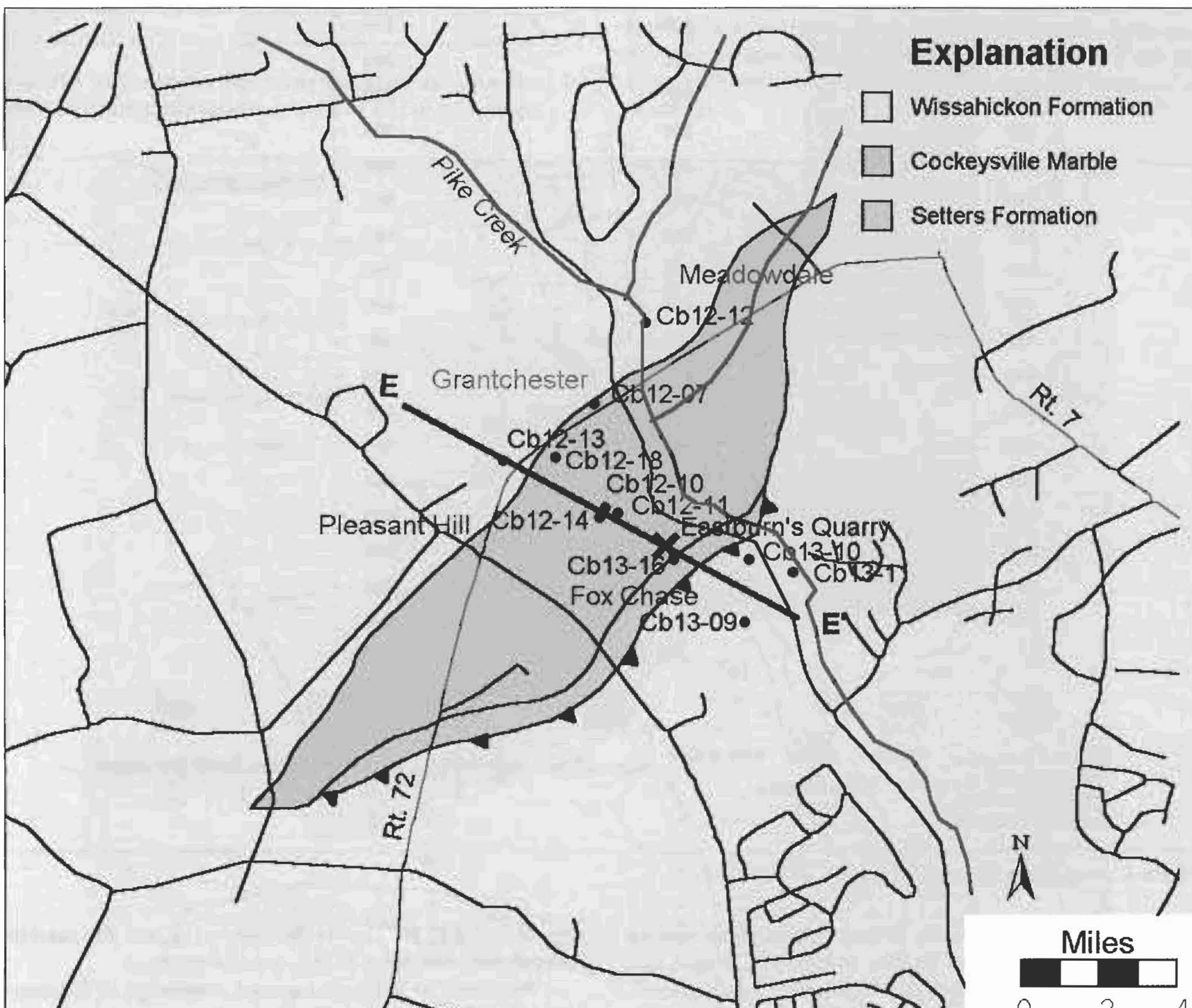

Figure 3. Geologic map of Pleasant Hill valley showing the location of cross section E-E′ (Figure 8) and wells referenced in text (after Woodruff and Plank, 1995).

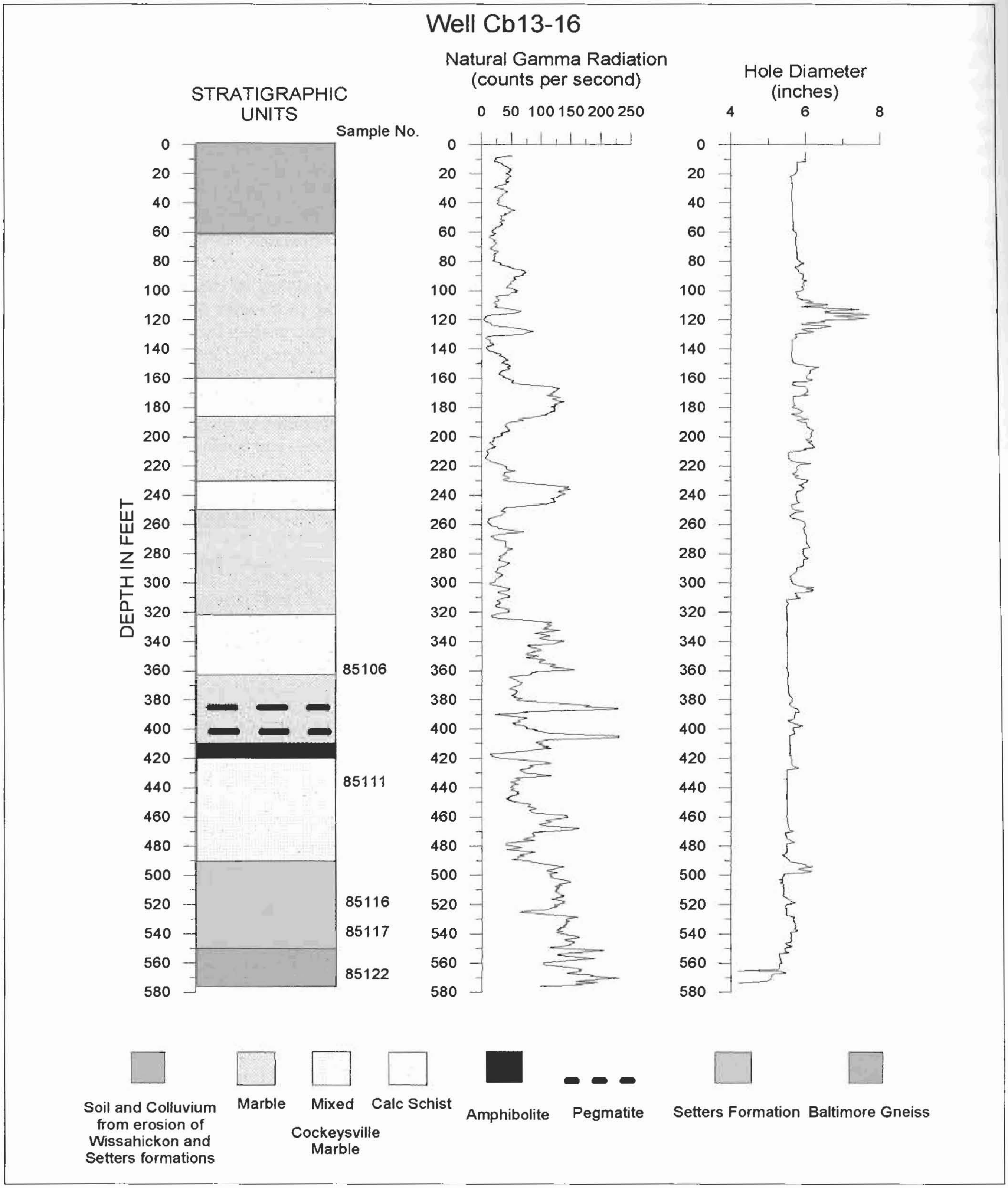

Figure 4. Stratigraphy and geophysical logs of well Cb13-16.

a characteristic feature of the Setters. A micaceous parting in sample 42339 consists of thin stringers of biotite and small recrystallized grains of quartz, microcline, and garnet.

Drill hole data and geophysical logs from well Cb12-12, located northwest of Pleasant Hill valley (Figure 3), indicate Wissahickon lithologies to 190 ft, pegmatite from 190 to 210 ft and Cockeysville from 210 ft to the bottom of the well at 225 ft. This is the only evidence for marble immediately northwest of Pleasant Hill valley.

Wissahickon gneisses exposed northwest of Pleasant Hill valley in the community of Grantchester are mylonitic with zones of very thin, elongated sillimanite nodules and large veins of biotite-bearing, granitic pegmatite that are up to 20 ft in width (Figures 3 and 5). The outcrops are now

Table 2.
Modal analyses of the Setters Formation, Eastburn's Quarry, Delaware, and Broad Run Quarry, Pennsylvania.

	Broad Run		Eastburn's Quarry	
	Ba54-b	Ba54-c	Cb12-a	Cb12-a
Minerals	58205	58206	42339	42340
Quartz	53	21.3	29.5	63.6
Plagioclase	x	x	2.0	0.3
Microcline	40	49.3	56.9	16.0
Biotite	3	12.3	11.0	9.8
Muscovite	2	15	x	
Sillimanite				
Garnet				7.7
Opaques	2	2	0.6	0.2
Zircon	x	x	x	x
Sphene	x	x	x	x
Apatite	x	x	x	2.4
Chlorite/Biotite	x	x	x	
Clay/Plagioclase			x	
Points Counted	300	300	1000	1000

covered with houses, but many boulders are preserved in the landscaping and retaining walls of this development.

Compositional layering in the Wissahickon surrounding Pleasant Hill valley is isoclinally folded. Axial planes of the folds are upright or dip to the southeast between 55° and 90° (Figure 5). The steep dips in the Wissahickon are significantly different from the shallow dips observed in the Setters and Cockeysville.

Pegmatites commonly form along zones of weakness and may mark fault boundaries (Hopson, 1964); thus a series of pegmatites identified along the contact between the Cockeysville and Wissahickon on the northwest side of Pleasant Hill valley may mark a fault boundary (Figure 5).

Landenberg Anticline

Reconnaissance field work indicates the Landenberg anticline is structurally similar to the Hockessin-Yorklyn anticline with an exposed core of Baltimore Gneiss that is overlain by the Setters and Cockeysville on the southeast and is in contact with the Wissahickon on the northwest (Figure 2). The Setters and Cockeysville crop out in a series of abandoned marble quarries along the southeast limb. Petrographic analysis of two thin sections, Ba54-b and Ba54-c, prepared from Setters-type rocks, indicates that the Setters in the Landenberg anticline is a microcline-rich quartzite containing biotite and muscovite (Table 2).

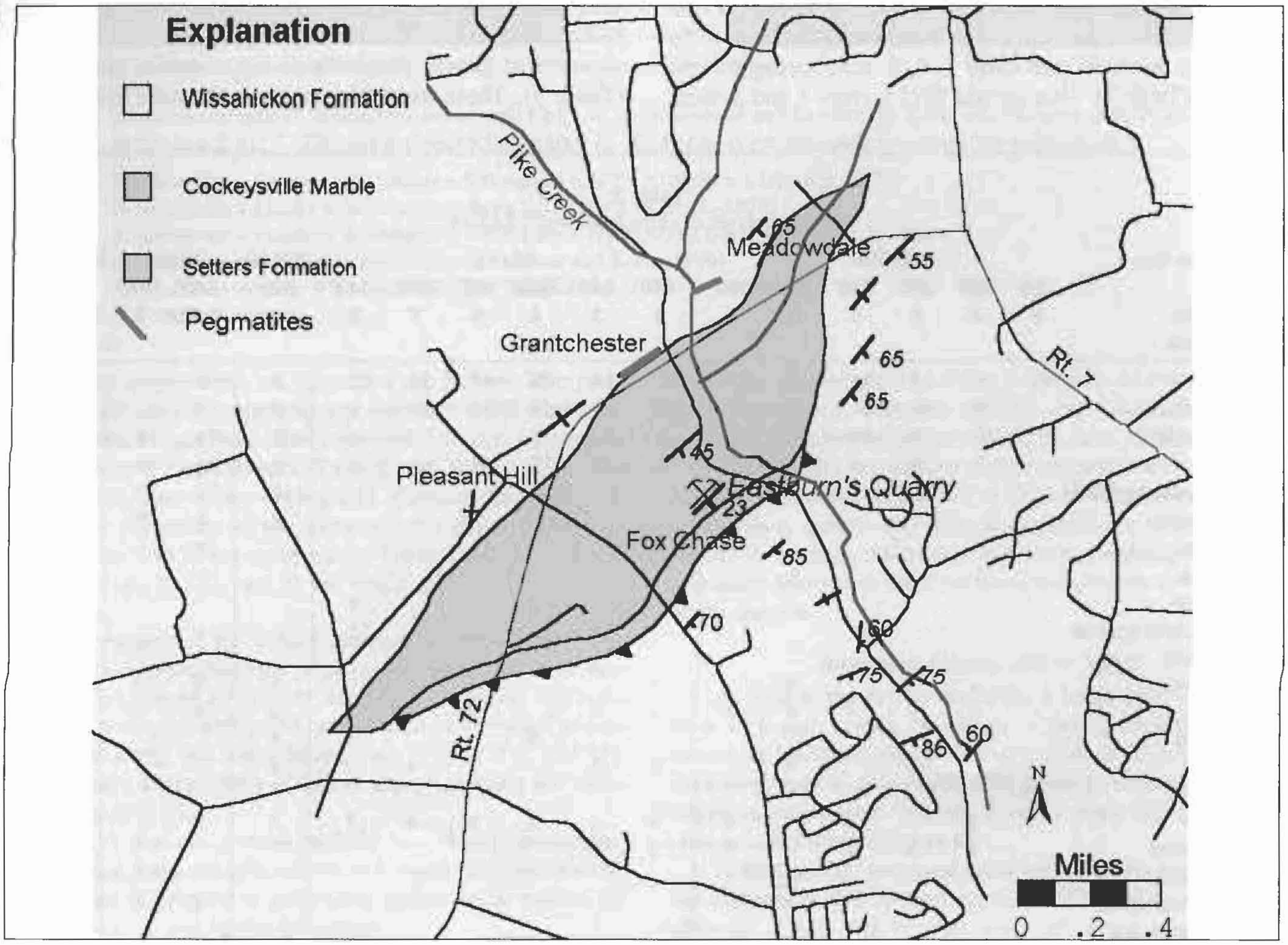

Figure 5. Geologic map of Pleasant Hill valley showing the attitude of the compositional layering in the Cockeysville and Wissahickon. Red lines indicate the location of pegmatite veins. Strike and dips from this study and Branca (1979).

Well Cb13-16

Soil and colluvium, 0 to 60 ft

The driller's log from 0 to 60 ft describes brown silt and sand mixed with rock. Because the Setters is exposed in the stream that flows between the quarry and the drill site, we assume the first 60 ft was a mixture of weathered Setters and debris from the Wissahickon that supports the hill southeast of the drill site.

Cockeysville Marble, 60 to 490 ft

Between 60 and 490 ft the driller reported, "... soft limestone alternating with hard gray green rock." The rock unit is the Cockeysville, and it is mainly composed of alternating lithologies of dolomitic marble and calc-schist. The gamma log shows a low gamma-ray signature for the entire marble interval with an increased gamma-ray response for calc-schist layers (Figure 4). The sharp spikes at 385 and 405 ft indicate pegmatites. The low gamma-ray signature between 415 and 420 ft correlates with a layer of "black rock" (Figure 4).

The cuttings recovered during drilling were fine sand-sized grains mixed with a few chips of whole rock that varied in size between 3 and 10 mm. Fifteen of the largest rock chips recovered between 350 and 490 ft were selected for thin sections.

Petrographic analyses of the 7 chips mounted on thin section 85106 found chip 2 to be pure dolomite, chip 6 to be an impure quartzite, and chips 3, 4, 5, and 7 to be granitic gneisses (Table 3). Thin section 85111, chips 1 and 3, were identified as pegmatites, chips 5 and 7 as granitic gneisses, and chips 4 and 8 as calc silicates. The calc silicates contain calcite, quartz, plagioclase, microcline, diopside, biotite/chlorite, clinozoisite, and scapolite (Table 3). The chips not listed in Table 3 (thin section 85106, chip 1, and thin section 85111, chips 2 and 6) are severely weathered.

X-ray analysis identified the "black rock" between 415 and 420 ft as an amphibolite containing hornblende, quartz, plagioclase, and biotite. A layer of amphibolite in the Cockeysville is unusual and has not been reported in either Maryland or Pennsylvania. Its origin is unknown, but may represent an ash fall or lava flow from the James Run/Wilmington Complex volcanic arc (Thompson, 1979, 1981; Wagner and Srogi, 1987; Higgins, 1990).

Setters Formation, 490 to 550 ft

At 490 ft, the driller noted an abrupt change from the marble to a coarse hard gray rock. This new lithology produced a sharp increase in the gamma-ray response, but does not effervesce in hydrochloric acid (Figure 4). A large fracture recorded by the caliper log at 490 ft marks the contact between this hard gray rock and the softer marbles of the Cockeysville (Figure 4).

Thin sections prepared from 5 chips collected from 520 ft (thin section 85116) and 8 chips collected from 540 ft (thin section 85117) were analyzed to identify this new unit. The chips contain various assemblages of microcline, biotite, muscovite, and sillimanite with minor or trace amounts of garnet, plagioclase/clay minerals, and quartz (Table 3). These assemblages, with abundant microcline

Table 3.
Modal analyses of chips from well Cb13-16.

Sample No.	85106						85111						85116	85117		85122
Depth	360'	360'	360'	360'	360'	360'	440'	440'	440'	440'	440'	440'	520'	540'	540'	570'
Chip No.	2	3	4	5	6	7	1	3	4	5	7	8	all	1,5&6	7	2, 3, 4 6 to 10
Minerals																
Quartz		32	44	31	67	41	33	14	38	41	34	63	2	1		33
Plagioclase		39	46	5	14	12	19	42	28	55	65	2	2	2		24
Microcline		18	3	59		35	38	12	5			3	72	44	5	
Biotite		5	6	4	13	10	5	16	13	4	1		9	29	34	38
Muscovite (sericite)			x	x		x		x					12	17	2	
Sillimanite													2	4	57	
Garnet														x		1
Chlorite					2		x	4	1					x		4
Diopside									15			8				
Clinozoisite-epidote										x	x	13	x	x		
Scapolite												3				
Opaques		x			3		x			x	x		1	3	2	x
Zircon		x	x	x	x	x	x	x		x	x		x	x		x
Sphene									x	x		1	x			
Apatite			x		x		x	x		x	x		x			x
Dolomite	100															
Calcite		x	1	x		x	x	x	x	x	x	7	x	x		
Myrmekite		5	x	1		2	5	12								
Tourmaline																
Clay/Plagioclase					x								x	x		
Other Minerals																
Points Counted	20	100	100	100	84	300	100	76	200	81	100	100	411	372	23	143

Figure 6. A

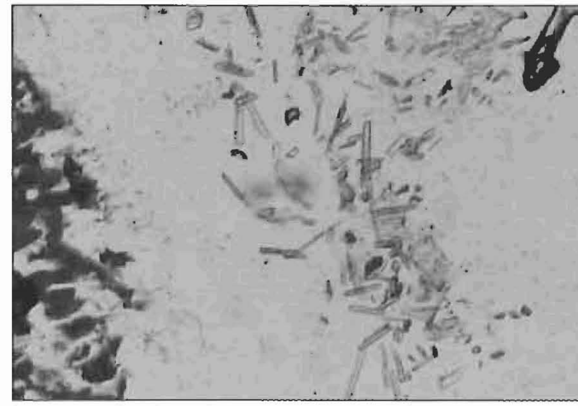

Figure 6. B

Figure 6. C

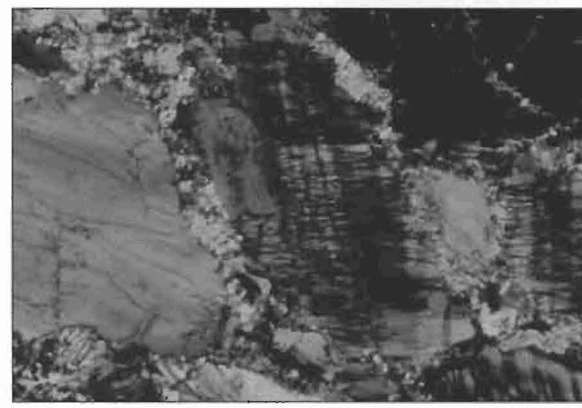

Figure 6. D

Figure 6. Photomicrographs of Setters Formation, well Cb13-16. A. Sillimanite and fibrolite; B. Spray of sillimanite needles inside a microcline grain; C. Fibrolite and microcline grains; D. Microcline grain surrounded by small low relief grains.

1. Muscovite + Quartz = K-feldspar + Sillimanite + H_2O; $X(H_2O) = 1$ (Kerrick, 1972)
2. Muscovite + Quartz = Sillimanite + melt; $X(H_2O) = 1$ (Kerrick, 1972)
3. Muscovite + Quartz = K-feldspar + Sillimanite + H_2O; $X(H_2O) = 0.5$ (Kerrick, 1972)
4. Minimum melting of granite; $X(H_2O) =$ (Spear and Kohn, 1996)
5. Minimum melting of granite; $X(H_2O) = 0.5$ (Kerrick, 1972)

X = concentration P_{H_2O}/P_{fluid}

and minor plagioclase, are typical of the Setters. The presence of sillimanite without quartz indicates a different mineral assemblage than that reported for the Setters of Maryland and Pennsylvania (Table 1 and 3). The difference is probably due to the high-grade metamorphism experienced by the rocks of the Delaware Piedmont. The four chips from 540 ft not recorded in Table 3 (thin section # 85117, chips 2, 3, 4, and 8) are single grains of microcline or garnet.

Microcline is the major mineral in these rocks. The grains show cross-hatched twinning and microperthitic textures. The grains are either equant with sharp contacts (Figure 6 A), or elongated with small, low-relief grains clustered along the grain boundaries (Figure 6 C and D). Myrmekitic intergrowths of quartz and plagioclase are common (Figure 6 B).

Micas that are present include biotite and muscovite. The biotite laths are pleochroic red-brown to light-brown. Muscovite is present as individual grains or as masses of sericite that cluster in discrete zones.

Sillimanite occurs as clusters of fine fibers, as sprays of needles inside feldspar grains, and as elongated blades (Figure 6 A and B). Coarse-grained sillimanite usually forms by the recrystallization of fibrolite as metamorphic grade increases; thus the needles and blades formed as metamorphic conditions increased (Vernon, 1987).

The garnets are dark red and subhedral with embayed grain boundaries. Inclusions of biotite, muscovite, altered plagioclase, quartz, and opaque minerals are scattered randomly throughout the garnet. Microcline, although the most abundant mineral in these rocks, is not present as inclusions in the garnets.

Baltimore Gneiss, 550 to 580 ft

At 550 ft the driller recorded a large increase in the flow of water, a very thin layer of white rock that effervesces in hydrochloric acid, and a change in color of the rock from gray to gray-black. The gamma response shows a slight increase and is more erratic, suggesting another change in lithology (Figure 4).

A thin section prepared from ten chips recovered from the cuttings at 570 ft (thin section 85122) found only five chips (2, 3, 4, 6, and 10) that were sufficiently unweathered to be used for point counting. The minerals identified are biotite, quartz, plagioclase, and pale pink garnet (Table 3). The absence of microcline clearly indicates a lithologic change from the overlying Setters to a biotite-plagioclase gneiss. Elsewhere the Baltimore Gneiss lies stratigraphically below the Setters Formation; thus, the change in lithology probably represents the transition from the Setters to the Baltimore Gneiss.

METAMORPHISM IN THE SETTERS FORMATION

Pelitic rocks are of particular importance in studies of metamorphism because they develop a wide range of index minerals that can be used to estimate metamorphic temperatures and pressures. Pelitic assemblages in the Setters in well Cb13-16 contain the index minerals microcline-biotite-sillimanite +/- garnet and microcline-biotite-muscovite-sillimanite +/- garnet. All phases appear to be in textural equilibrium, as the minerals are observed to be in contact with each other. Most sections also show clear evidence for replacement textures as myrmekite and sericite mixed with larger grains of muscovite are common. In addition, all grains of plagioclase, including those in myrmekite and garnet, have been altered to a green clay mineral.

The presence of sillimanite and quartz indicates metamorphism above the stability of muscovite (Figure 7). Muscovite breaks down either by dehydration or anatectic melting (reactions 1 and 2 respectively) (Kerrick, 1972):

muscovite + quartz = sillimanite + K-feldspar + H_2O (1)

muscovite + quartz = sillimanite + melt (2)

Univariant curves for reactions (1) and (2) are normally plotted on a petrogenetic grid for rocks saturated with quartz (Figure 7). The Setters in well Cb13-16 is quartz poor; however, these same reactions can describe the disappearance of quartz and the appearance of sillimanite in a rock with excess muscovite. In order to estimate the temperature at which these reactions occur we must make an independent estimate of pressure. Pressure estimates of 4 to 6 kilobars for the overlying Wissahickon Formation (Calem, 1987; Plank, 1989; Alcock, 1991, 1995) may provide a reasonable range for the Setters. The petrogenetic grid in Figure 7 shows that if concentration of H_20 in the fluid phase is equal to 100%, $P_{H_20}/P_{fluid} = 1$, and the pressure is between 4 and 6 kilobars, then sillimanite will form in pelitic rocks via reaction 2 at temperatures > 640°C. The amount of melt that forms depends upon the amount of fluid present and the amount of muscovite and quartz in the rocks (Spear and Cheney, 1989). If $P_{H_20}/P_{fluid} < 1$, which is often the case in pelitic rocks (Kerrick 1972, Tracy, 1978, Spear and Cheney, 1989), then the effect is to lower the temperature for the dehydration reaction (1), and raise the temperature for anatectic melting (2) (Figure 7).

Although field evidence for anatexis is usually obvious in rocks exposed at the surface, it is difficult to recognize the effects of anatexis in well cuttings. Well cuttings from well Cb13-16 contain small chips of granitic composition, large subhedral grains of microcline, and a chip with a restite composition composed solely of fibrous sillimanite and biotite (sample 85117, Table 3). These chips may suggest anatexis, but they might represent other origins such as late-stage pegmatites or gneissic layering formed by metamorphic differentiation. It is possible that some of the granitic rocks in the Cockeysville (Table 3) may have been partial melts of Setters that migrated upward into the overlying rocks. If anatexis did occur in the Setters in well Cb13-16, then P_{H_20}/P_{fluid} was close to 1, and the peak metamorphic temperatures were >640°C.

Regardless of the range of possibilities for the fluid compositions in the pelites, we can constrain the peak metamorphic temperatures in the Setters to between 620° and 680°C, if the pressures are between 4 and 6 kilobars (Figure 7). Biotite-garnet geothermometry and fluid inclusion studies would better define the metamorphic conditions that existed in the Setters in Delaware.

For the Wissahickon in the Pleasant Hill area, peak metamorphic temperatures and pressures estimated using garnet-biotite geothermometry and garnet-sillimanite-quartz-plagioclase geobarometry are between 610° and 675°C at 4 to 6 kilobars (Plank, 1989). These estimates suggest that peak metamorphic conditions in the Setters and Wissahickon in Pleasant Hill are similar.

Alcock (1991, 1995) postulated a metamorphic discontinuity at the Wissahickon-Cockeysville contact on the south side of the Landenberg anticline as evidence for the thrust emplacement of the Wissahickon. Because the temperatures estimated for the Setters and Wissahickon in the Pleasant Hill valley are similar, no metamorphic discontinuity can be documented.

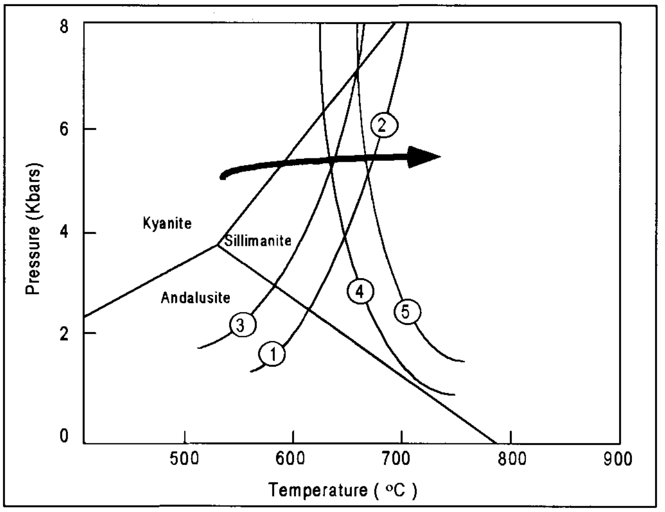

Figure 7. Petrogenetic grid, pressure-temperature diagram. Shown are stability fields for aluminum silicates from Holdaway (1971). Arrow shows PT trajectory postulated for metamorphism of Setters, Pleasant Hill valley.

Calc silicates can also be used as sensitive indicators of metamorphic conditions providing the composition of the fluid phase is known. The calc silicate layers are thought to form by metamorphism of impure dolomite and calcite to form phlogopite, tremolite, diopside, additional calcite, and K-feldspar. Layers rich in aluminum may contain other minerals, such as plagioclase, scapolite, and epidote.

On the basis of an isobaric, 4 kilobar, temperature-fluid composition (T-X) diagram for the system MgO-CaO-SiO_2-$KAlO_2$-CO_2-H_2O, Alcock (1991, 1995) found the assemblages dolomite, calcite, quartz, phlogopite, and tremolite; and calcite, quartz, K-feldspar, phlogopite, and tremolite define an isobaric invariant point at 575°C. He estimated peak temperature for the marble on the south limb of the

Landenberg anticline to be less than 575°C. A brief examination of thin sections from wells in the Cockeysville in the Pleasant Hill and Hockessin-Yorklyn areas revealed a different set of mineral assemblages containing dolomite, calcite, phlogopite, and diopside +/- tremolite and +/- K-feldspar (no quartz). These calc silicate assemblages probably represent higher metamorphic conditions in the Cockeysville in Delaware (see T-X diagram, Alcock, 1995); conditions that are consistent with the sillimanite-bearing assemblages in the Setters. A detailed study of assemblages in the Mill Creek nappe will probably confirm an increasing metamorphic gradient toward the southeast, from < 575°C in the Landenberg area to > 620°C in the Pleasant Hill area.

STRUCTURAL MODEL FOR PLEASANT HILL VALLEY

The three separate exposures of the Mill Creek nappe, (1) the Hockessin-Yorklyn anticline, (2) the Landenberg anticline, and (3) the Pleasant Hill valley, trend N45°E, parallel to the regional strike of the Appalachian Piedmont, and are overturned to the northwest (Figure 2). They have been gently folded about second fold axes that are approximately normal to the regional strike to form the doubly-plunging structures characteristic of the gneiss dome area in the Maryland, Delaware, and Pennsylvania Piedmont. A brittle fault has displaced the Landenberg anticline and the western end of the Hockessin-Yorklyn anticline to the northwest (Woodruff and Plank, 1995) (Figure 2).

Woodruff and Plank (1995) modeled the Hockessin-Yorklyn anticline with a gently dipping upright southern limb and an overturned northern limb that has been cut by thrusts. They modeled the Pleasant Hill valley structure with a gently dipping southeast limb that has been cut by thrusts, and an overturned northern limb where Cockeysville is in conformable contact with the Wissahickon. The interpretation of a thrust on the southeast side of Pleasant Hill valley is based on the exposures in Eastburn's Quarry where the Setters overlies the Cockeysville and underlies the Wissahickon.

In Pleasant Hill valley, foliations and the axial planes of isoclinal folds in the Setters and Cockeysville trend approximately N45°E, are recumbent, and dip between 20° and 45° to the southeast (Figure 5). In contrast, the limbs and axial planes of the isoclinal folds in the Wissahickon adjacent to the marble valley trend N45°E and are either upright or dip steeply to the southeast (Figure 5). This structural discordance suggests the units were deformed before they were juxtaposed, and that the contacts between the Glenarm and the Wissahickon on all sides of Pleasant Hill valley are probably faults.

The line of pegmatites identified along the Cockeysville-Wissahickon contact on the northwest side of Pleasant Hill valley plus the mylonitic fabrics in the Wissahickon suggest a fault boundary (Figure 5). The pegmatites are weak evidence for a fault; however, the fault on the northwest side of the Hockessin-Yorklyn anticline coincides with a similar line of pegmatites (Bascom and Stose, 1932).

Our new model for the Pleasant Hill valley is shown in cross section (Figure 8). On the southeast side, the Wissahickon is placed over the inverted sequence of Setters and Cockeysville on a low-angle thrust as in the Woodruff and Plank (1995) model. The northwest side of the overturned anticline is cut by a high-angle thrust that is similar to the thrust modeled by Woodruff and Plank (1995) for the northwest side of the Hockessin-Yorklyn anticline.

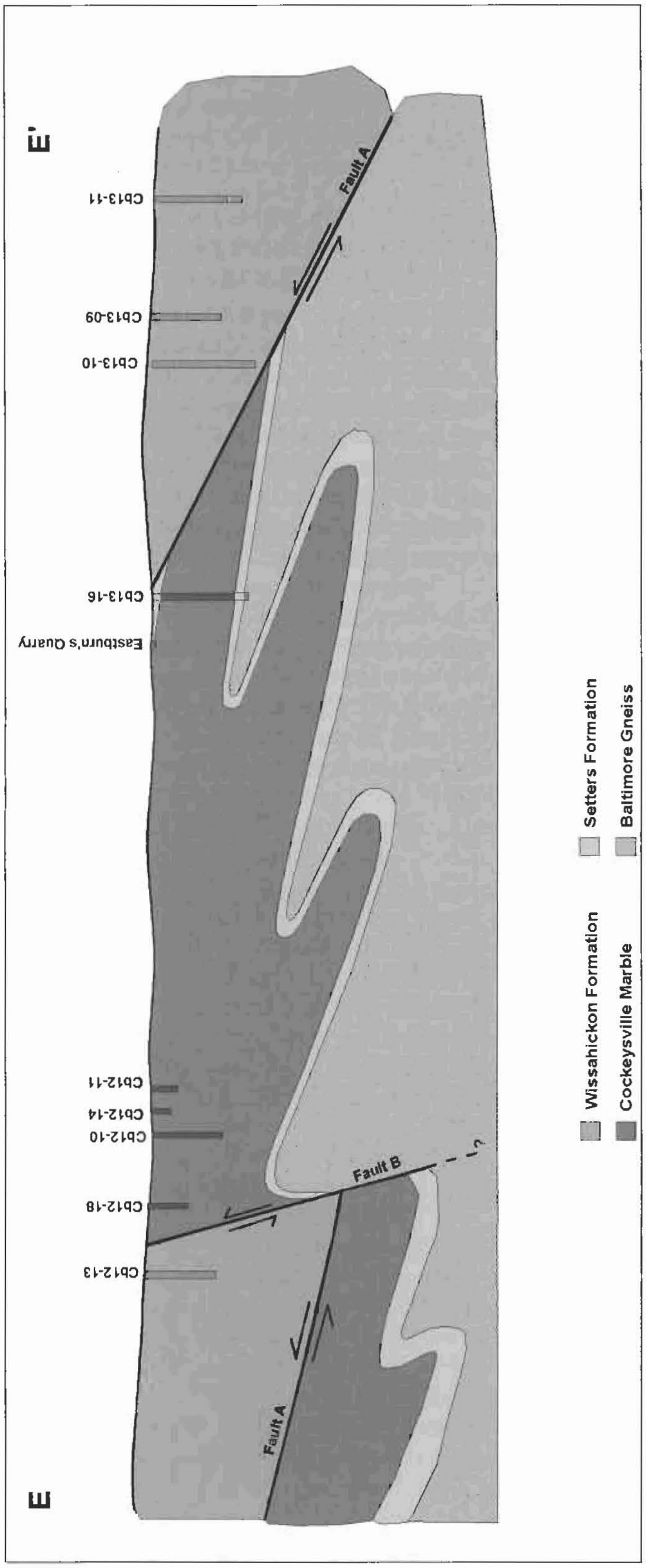

Figure 8. Cross section E-E´, Pleasant Hill valley. Revised from section D-D´ Woodruff and Plank (1995).

In reconstructing the cross sections, the thickness of the units is based primarily on our judgment, constrained only by the outcrop pattern and the observed thickness of the Setters in well Cb13-16. This is maximum thickness; true thickness depends upon the dip of the contacts and the style of the folds.

CORRELATION OF THE MILL CREEK NAPPE WITH SIMILAR STRUCTURES IN MARYLAND AND PENNSYLVANIA

The Mill Creek nappe, with its core of middle Proterozoic Baltimore Gneiss and Glenarm Group cover (Drake, 1993), is one of eleven or twelve basement-cored structures that lie along the metamorphic core of the central Appalachian Piedmont between Baltimore, Maryland, and Philadelphia, Pennsylvania (Figure 1). Recently, Drake (1993) and Alcock (1991, 1994) have questioned the traditional view of stratigraphic continuity in the Glenarm cover sequence and propose that the Setters and Cockeysville constitute the entire Glenarm Group, and that the Baltimore Gneiss and Glenarm have been overthrust by the Wissahickon, or its equivalent unit in Maryland, the Loch Raven Schist. New maps of the Maryland and Pennsylvania Piedmont show complexly folded nappes of Baltimore Gneiss, Setters, and Cockeysville exposed in windows through Wissahickon/Loch Raven thrust sheets (Drake, 1993; Alcock, 1994).

The new cross section (Figure 8) across the Pleasant Hill valley shows the Baltimore Gneiss and its Glenarm cover exposed in a window through a thrust sheet of Wissahickon. The contact on the southeast side of the valley, where Wissahickon lies above an overturned sequence of Setters and Cockeysville, is evidence for the thrust fault. We propose that the contact between the Wissahickon and Cockeysville on the southeast side of the Hockessin-Yorklyn anticline is also a fault of this kind. Later faults have cut the northwest side of the Pleasant Hill valley structure and the Hockessin-Yorklyn anticline to thrust the package of Baltimore Gneiss, Setters, Cockeysville, and Wissahickon over Wissahickon. These later faults are similar to the Street Road fault described by Alcock (1994) in the Avondale-Woodville Pennsylvania area.

We propose the structural relations between units in the Mill Creek nappe in Delaware are similar to those recently described by Drake (1993) and Alcock (1991, 1994) for the other basement-cored structures in the Maryland and Pennsylvania Piedmont. These proposed structural relations for the Mill Creek dome are incorporated into a new map (Figure 9).

The sequence of events implied by these relationships begins with the metamorphism and folding of the Baltimore Gneiss and its Glenarm cover into a nappe. Continued northwest-directed compression placed the rocks of the Wissahickon over the nappe either as a single thrust sheet or

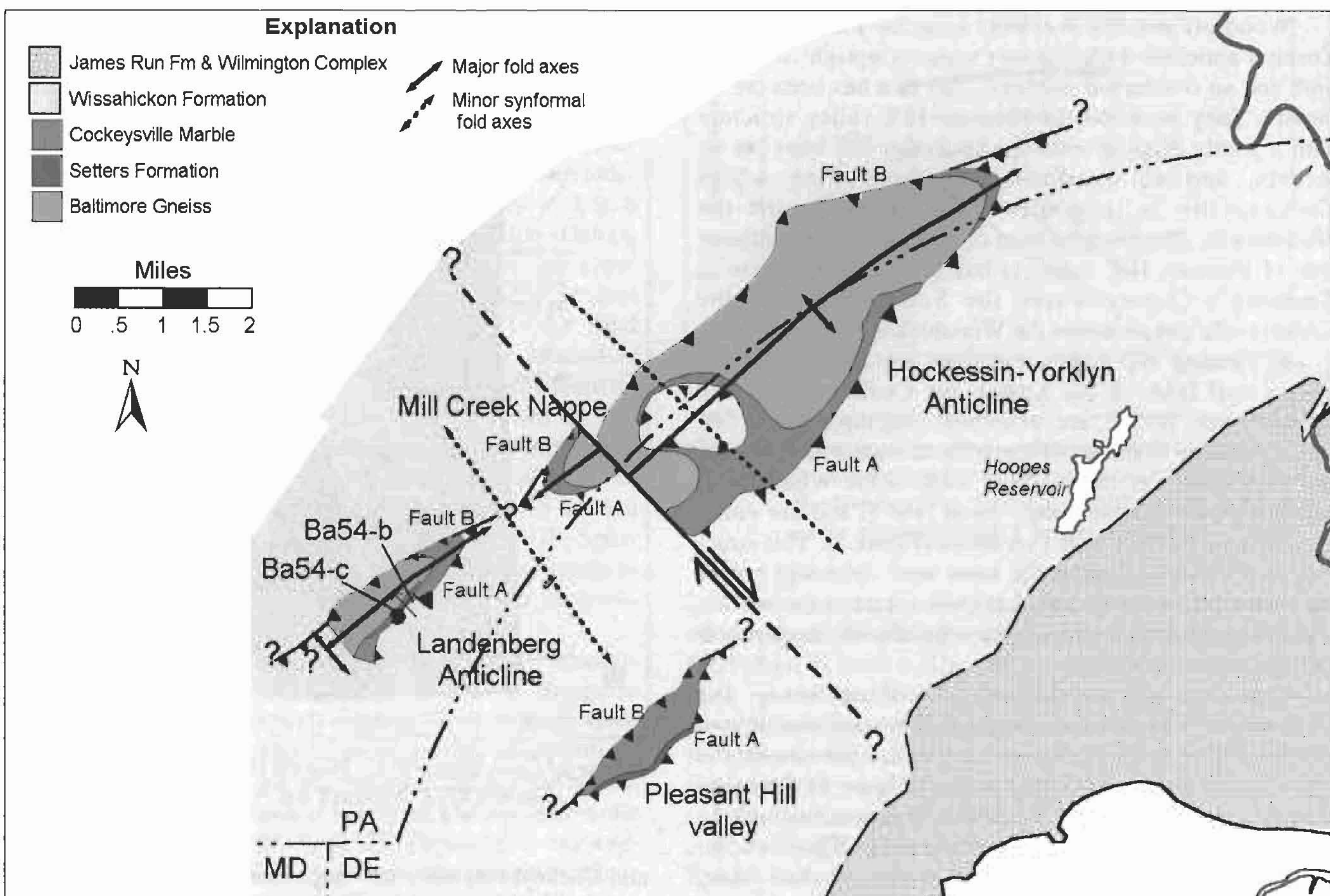

Figure 9. New generalized geologic map showing proposed structural relations for the Mill Creek nappe.

on a series of small fault slices (Fault A). Later thrusts (Fault B) have cut the entire package on the northwest side of these recumbent anticlines (Figure 8 and 9). This sequence is similar to that proposed by Alcock (1991, 1994) for the Woodville and Avondale anticlines and the Landenberg portion of the Mill Creek nappe.

This study makes no attempt to correlate the faults in the Delaware Piedmont with regional faults, only to recognize that the faults in the Mill Creek dome in Delaware are similar to those in the "gneiss dome areas" of Maryland and Pennsylvania. We also note that the structural events described for the Mill Creek nappe follow a chronological sequence similar to that postulated by Alcock (1994) for adjacent areas in Pennsylvania.

CONCLUSIONS

The Setters Formation occurs in Pleasant Hill as two distinct lithologies, a microcline-rich quartzite and a microcline-rich pelitic gneiss. The quartzite is exposed in Eastburn's Quarry where it overlies the Cockeysville Marble in an overturned stratigraphic sequence. The pelitic lithology was recognized in the cuttings from well Cb13-16 where it lies under 430 ft of marble and over Baltimore Gneiss in a normal stratigraphic sequence.

The pelitic gneiss contains the mineral assemblages microcline, biotite, sillimanite +/- garnet and microcline, biotite, sillimanite, muscovite +/- garnet. These assemblages allow us to infer peak metamorphic conditions between 620° and 680°C at 4 to 6 kilobars pressure if the X H_2O is > 0.5. There is some evidence to indicate that partial melting accompanied the formation of sillimanite, constraining peak temperatures to >640°C (Figure 7).

Peak metamorphic temperatures and pressures estimated for the Wissahickon in Pleasant Hill area are 610° to 675°C at 4 to 6 kilobars pressure (Plank, 1989), and are similar to those estimated for the Setters. Similar temperatures imply the units were metamorphosed under similar conditions.

Woodruff and Plank (1995) mapped the contact between the Setters and the Wissahickon on the southeast side of Pleasant Hill valley as a thrust fault. A search for evidence for a fault along the northwest side of Pleasant Hill valley found a significant difference in orientation of folds between the Wissahickon and the Cockeysville-Setters, thin sheared layers of Wissahickon near the contact, and a series of pegmatites that lie along the boundary. This is weak evidence for a fault, but since there is no evidence for a conformable boundary, we suggest the northwest side of the Pleasant Hill valley is cut by thrusts and propose revising the previous model of Woodruff and Plank (1995) to include a steep angle thrust along this boundary. This northwest-directed fault placed the sequence of Baltimore Gneiss, Setters, Cockeysville, and Wissahickon over Wissahickon, is later in time than the thrust on the southeast side of the valley, and is similar to the thrust proposed by Woodruff and Plank (1995) for the northwest side of the Hockessin-Yorklyn anticline and the Street Road fault proposed by Alcock (1994).

Our new model (Figure 8) for the Pleasant Hill valley shows the Baltimore Gneiss and its Glenarm cover of Setters and Cockeysville exposed in a window through a thrust sheet of Wissahickon. We suggest that the contact between the Wissahickon and the Cockeysville on the southeast side of the Hockessin-Yorklyn anticline is a thrust fault. The proposed structural relations between units in the Mill Creek nappe in Delaware are now consistent with those in the other basement-cored structures in the Piedmont of Pennsylvania and Maryland.

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