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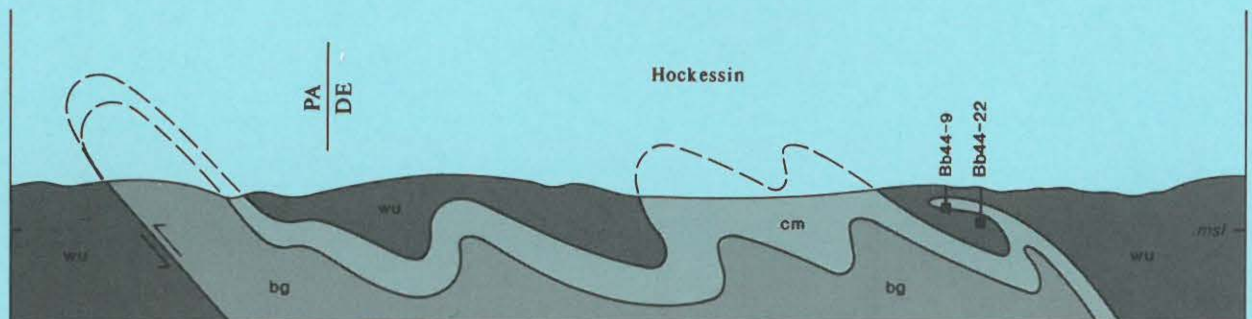

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by

Kenneth D. Woodruff

and

Margaret O. Plank

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William H. Werkheiser

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ABSTRACT

The effect of rapid growth in the Hockessin and Pleasant Hill areas in northern Delaware has caused concern about possible declines in ground-water recharge to the underlying Cockeysville Formation. The Cockeysville is a major source of ground water (aquifer) in the Hockessin area from which about 1.5 million gallons of water per day is withdrawn for public water supply, even though it receives recharge over a relatively small area of 1.6 square miles. The Cockeysville in the Pleasant Hill area is currently used as a source of water supply for individual domestic users and one school. Results of ground-water exploration in the Pleasant Hill area suggest that the Cockeysville is capable of yielding several hundreds of gallons per minute to individual wells for water supply.

A two-year investigation was undertaken to map the extent of the Cockeysville Formation and address questions of long-term ground-water yields, the sources of recharge, and the effects of additional development on ground-water supplies. Results of various field studies were integrated to determine the basic geologic framework and those elements that particularly affect ground-water supply.

The Cockeysville Formation is composed predominately of coarsely crystalline dolomite marble, calcite marble, and micaceous calc-schist and is estimated to be between 400 and 800 ft thick. The regolith or weathered zone that overlies the unweathered part of the Cockeysville Formation is highly variable in thickness, ranging from several feet to more than 150 ft. The regolith receives and stores most of the recharge. Solution cavities in the Cockeysville act as important ground-water reservoirs. Outside the valleys the Cockeysville is massive and relatively unweathered with little potential for high ground-water yields.

The northeast-southwest trending Hockessin-Yorklyn valley lies on the upper limb of a large antiform (Mill Creek Dome) that is overturned to the northwest and cored by Grenville age Baltimore Gneiss. The Cockeysville unconformably overlies the Baltimore Gneiss with no intervening Setters Formation. Gneisses of the Wissahickon Formation crop out on the southeastern edge of the valley. All units dip to the southeast at about 25 to 45 degrees. Rocks of the Wissahickon Formation and Baltimore Gneiss function as ground-water flow barriers with little or no interchange of water between these formations and the Cockeysville Formation.

To the southwest in the Pleasant Hill valley area an inverted sequence of the Setters and Cockeysville formations is overlain by the Wissahickon Formation. This inverted sequence is interpreted as the overturned limb of a basement-cored antiform that has brought the Wissahickon directly over the Setters.

The two valleys are detached from each other by a major northwest trending strike-slip fault that cuts off the southwestern end of the Hockessin valley. There is no evidence to suggest that the Cockeysville Formation in the Hockessin-Yorklyn area is hydrologically connected to the Cockeysville in the Pleasant Hill area.

The detailed ground-water investigation was limited to the Hockessin area, where public water supplies have been developed. Ground-water withdrawals have significantly lowered water levels since heavy pumping began in the 1960s. In 1992, ground-water levels in the stressed part of the aquifer were below streambeds, so that all ground-water discharge was through wells. The Cockeysville is recharged by (1) infiltration of precipitation, (2) leakage from streams, and (3) ground-water flow from the adjacent low-yielding noncarbonate aquifer. Because a significant portion (0.55 Mgal/d) of recharge to the aquifer occurs through infiltration from streams, including sinkholes in streambeds, protection of surface-water quality is critical to maintain the integrity of the ground-water supply. Although the noncarbonate aquifer provides relatively small amounts of ground water to the Cockeysville aquifer in the subsurface, it does provide base flow to streams that cross the Cockeysville and recharge to the Cockeysville through leakage from streams.

Ground- and surface-water samples were analyzed for major ions, trace elements, nutrients, and radon; none of the concentrations exceeded the U.S. Environmental Protection Agency's Maximum Contaminant Levels for the constituents analyzed. However, nitrate and chloride concentrations indicate that water in the aquifers has been affected by human activity.

In 1990, 8.2 Mgal/d of water entered the Mill Creek Basin (Hockessin area) from precipitation and 0.52 Mgal/d was released from ground-water storage. Of the total water available, 4.76 Mgal/d was removed from the basin through evapotranspiration, 2.48 Mgal/d through streamflow, and 1.48 Mgal/d was withdrawn from public-supply wells. In the stressed part of the Cockeysville, all ground-water discharge in 1990 (1.48 Mgal/d) was from wells. Of this total, 0.65 Mgal/d was from infiltration of precipitation, 0.55 Mgal/d was from leakage from streams, 0.06 Mgal/d was from ground-water flow from adjacent noncarbonate aquifers, and 0.22 Mgal/d was released from ground-water storage. During the period 1978-1990, ground-water withdrawals were about equal to total recharge to the aquifer, 1.6 Mgal/d.

INTRODUCTION

John H. Talley

New Castle County, Delaware, is undergoing rapid urbanization as a result of residential and commercial growth. This growth has caused increasing concern on the part of planning officials about the adequacy of existing water supplies, which are obtained from both ground water and surface water. Of particular concern are environmentally sensitive areas in the Hockessin (1.6 mi^2) and Pleasant Hill (0.6 mi^2) valleys that are underlain by the Cockeysville Formation, a major source of water for both public and private water supplies. The Cockeysville, mostly a dolomite marble, weathers deeply in the outcrop areas to a sandy overburden which functions as a ground-water storage reservoir. High yield wells are generally completed in the deeper unweathered rock where solution cavities and fractures provide hydraulic connection with the weathered zone and may yield several hundreds of gallons per minute to individual wells. Most of the present withdrawals are in the Hockessin area, the larger of the two areas, and include 1.5 million gallons per day by a public water purveyor.

Before 1964, the Cockeysville was used primarily as a source of ground water for domestic wells. In 1964, high-yielding production wells were installed in the Hockessin area for public water supply. As new public water supply wells were installed and placed into service, water levels in the aquifer declined and shallow wells became unproductive. As a result, the State of Delaware imposed withdrawal and pumping water-level limits as part of their allocation program to ensure proper management of the resource.

Although the Cockeysville in the Hockessin area receives direct recharge on an outcrop area of only 1.6 mi^2, more ground water is withdrawn from this aquifer per square mile than any other fractured-rock aquifer in Delaware. The location of the Cockeysville Formation with respect to other wellfields in New Castle County indicates its importance as a source of water in relation to the infrastructure.

The land over the marble and adjacent areas is undergoing intensive development with large tracts being converted from farming or other open space to residential developments and commercial centers. This development is thought to be a potential problem for water-supply availability in the aquifer because increased impervious cover on top of the aquifer could reduce the amount of recharge to ground-water systems. The effects of changes in land use on the long-term ground-water yields from the Cockeysville were not known until this report.

In addition to a possible reduction in water quantity, the quality of ground water could also be affected by residential and commercial growth. The calcitic and dolomitic rocks that comprise the aquifer are subject to dissolution. The resulting solution features act as preferential pathways for water movement, making the aquifer especially vulnerable to contamination from human activity. Sinkholes, which are surface expressions of subsurface cavities, have been documented (Talley, 1981), and their formation may be accelerated by heavy ground-water withdrawals or alteration of natural drainage. Sinkholes provide a pathway for rapid infiltration of surface water into the subsurface, thereby increasing the potential for introduction of any contaminants that may be present in surface water.

Because of the Cockeysville's unique hydrogeology, its importance as a source of water supply for the region, and its sensitivity to ground-water quality degradation, New Castle County has designated the aquifer's known outcrop areas as the Cockeysville Formation Water Resources Protection Area (WRANCC, 1993). Certain land use restrictions apply in these protected areas including minimum lot sizes and prohibition of bulk storage of hazardous materials.

Purpose and Scope

The Water Resources Agency for New Castle County (WRANCC) and the Delaware Department of Natural Resources and Environmental Control (DNREC) requested that the Delaware Geological Survey (DGS) and the U.S. Geological Survey (USGS) undertake an investigation to map and describe the geology and ground-water hydrology of the Cockeysville Formation, and to evaluate the ground-water production potential of the Cockeysville in the Hockessin area. The report is presented in two sections. Results of various field studies were integrated to determine the basic geologic framework and those elements that particularly influence ground-water supply.

The DGS was charged with refining the existing geologic map of the Cockeysville Formation in the Delaware Piedmont in the Hockessin and Pleasant Hill areas. The first section, "Geology of the Cockeysville Formation" by Woodruff and Plank, defines the geologic framework and identifies those structural and stratigraphic elements that directly influence ground-water occurrence and flow. Details of petrologic studies are also presented in order to document the mineralogy and to identify various rock units.

The hydrologic investigation, included as the second section by Werkheiser, was conducted by the USGS under a Joint-Funded Program with the DGS. Its purposes were to (1) determine the amount of ground water available from the Cockeysville Formation on a sustained basis, (2) determine the effects of additional development on ground-water recharge, and (3) make a preliminary assessment of ground-water quality. Because of the significance of the Cockeysville aquifer to public water supply, the study emphasizes the Hockessin area.

Geologic and hydrologic data were analyzed to define the geohydrologic framework, aquifer properties, potentiometric surfaces, and directions of ground-water flow. Chemical analyses of ground- and surface-water collected during 1990 and 1991 were used to describe water quality. Water budgets were prepared from streamflow, precipitation, water-use, and ground-water data collected during 1990.

A summary report to the sponsoring agencies was presented in October 1991 (Woodruff, 1991). This bulletin is more comprehensive and provides additional documentation and detail not provided in the summary report.

Locations of Study Areas

The areas of investigation for both the geologic and hydrologic portions of the studies included portions of the Delaware Piedmont. Geologic mapping was conducted in the two known outcrop areas of the Cockeysville Formation, Pleasant Hill and Hockessin-Yorklyn (Fig. 1).

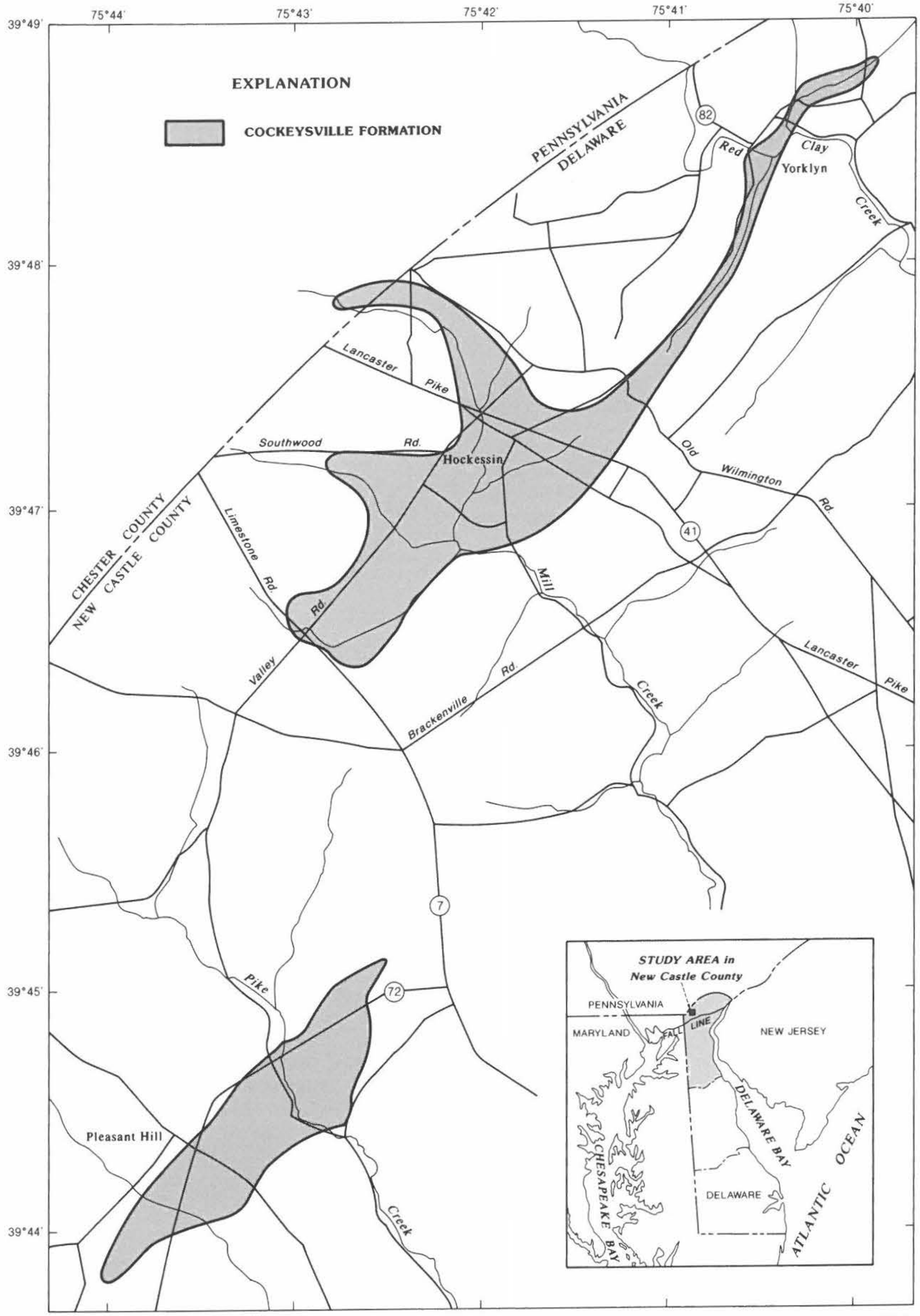


Figure 1. Map showing locations of study areas.

The hydrologic portion of the investigation was conducted in the Hockessin-Yorklyn area and the drainage areas of the streams that flow across the formation—Mill Creek and two unnamed tributaries to Red Clay Creek (Fig. 2). Streams in these drainage basins originate in non-carbonate, crystalline rocks that surround the Cockeysville Formation. Mill Creek exits the southern end of the study area. Streams in the Red Clay Creek Basin flow toward Red Clay Creek, which is in the eastern part of the study area. The study area comprises 5.6 mi^2, of which 3.7 mi^2 is in the Mill Creek Basin and 1.9 mi^2 is in the Red Clay Creek Basin.

Acknowledgments

Funding for this investigation was provided by the WRANCC and DNREC. That portion of State and County funding applied to the USGS portion of the program was matched by federal funds. The Artesian Water Company provided financial and logistical support for the construction and operation of a continuous-record streamgage on Mill Creek and water-use information. Subdivision maps used in the gravity survey were provided by the New Castle County Department of Public Works. Technical reports and drilling data submitted to the County by consulting firms as required for certain land use applications were used where applicable.

The authors wish to express appreciation and thanks to landowners and private citizens who allowed use of their property for field mapping, drilling, access to their wells for testing and sampling, operation of streamgages and precipitation stations, and other field activities. In particular, appreciation is extended to John J. McGrellis, Mrs. W. Glasgow Reynolds, John A. Faraone, Michael J. and Naomi W. McCafferty, Robert E. Mitchell, and the National Vulcanized Fibre Company.

The field experience of other geologists familiar with the study area was drawn upon freely. The contributions of Allan M. Thompson, University of Delaware, James A. Alcock, Pennsylvania State University at Ogontz, and C. Gil Wiswal, West Chester University are gratefully acknowledged. John H. Talley, DGS, assisted in all phases of the project. Field assistance was provided by Roland E. Bounds, William S. Schenck, and Charles T. Smith of the DGS.

The late J. Peter Wilshusen, formerly with the Pennsylvania Geological Survey, provided an independent review of the work in progress. Robert R. Jordan, Richard N. Benson, and John H. Talley of the DGS, reviewed both reports. Jonathan Edwards, Jr., Maryland Geological Survey, and Mary Emma Wagner, University of Pennsylvania, reviewed the report by Woodruff and Plank. The report by Werkheiser was reviewed by Kenneth D. Woodruff, DGS, and James R. Nicholas, USGS. Tim Auer and Jean Hyatt, USGS, drafted the illustrations.

GEOLOGY OF THE COCKEYSVILLE FORMATION

Kenneth D. Woodruff and Margaret O. Plank

INTRODUCTION

Regional Setting

The study area (Fig. 1) is located in the Appalachian Piedmont Province of northern Delaware and is underlain by igneous and metamorphic rocks of probable Proterozoic to early Paleozoic age. The oldest rocks, consisting of layered gneisses, migmatites, and amphibolites, are exposed in a series of anticlinal structures extending from near Baltimore, through northern Delaware, and into southeastern Pennsylvania. These comprise the basement complex known as the Baltimore Gneiss (Williams, 1892; Bascom et al., 1909; Bascom and Stose, 1932; McKinstry, 1961; Hopson, 1964; Higgins, 1972; Wagner and Crawford, 1975) and are considered to be pre-Taconic North American continental margin, first deformed and metamorphosed during the Grenville Orogeny (ca 1,100 Ma). Uncomformably overlying the basement complex is a sequence of late Proterozoic to Ordovician metasedimentary rocks. It was originally named the Glenarm Series by Knopf and Jonas (1922, 1923) and included, from the basal unit upward, the Setters Formation, Cockeysville Formation, Wissahickon Formation, Peters Creek Schist, Cardiff Conglomerate, and Peach Bottom Slate.

There have been a number of attempts to revise the stratigraphy of the Glenarm Series, particularly the Wissahickon Formation (Hopson, 1964; Southwick, 1969; Higgins, 1972). One of the most extensive revisions was proposed by Crowley (1976). Working in Maryland, he raised the Glenarm to a supergroup and the Wissahickon to a group by subdividing the Wissahickon into the Loch Raven Schist, Oella Formation, Piney Run Formation, Sykesville Formation, Pleasant Grove Schist, and Prettyboy Schist. Recently, as a result of detailed mapping in Virginia and Maryland, a series of tectonostratigraphic terranes have been identified, and it has been suggested that the terms "Glenarm" and "Wissahickon" be abandoned. The rocks comprising the North American basement and its sedimentary cover are to be termed the Baltimore Terrane (Gates et al., 1991). At approximately the same time, Horton et al. (1991) published a preliminary tectonostratigraphic map of the central and southern Appalachians and placed the Wissahickon in Delaware and Pennsylvania within the Potomac terrane. They stated that the Potomac terrane is an allochthonous thrust sheet containing basement and a cover sequence of turbidites and ophiolitic melange. Avery A. Drake (oral communication, 1994) visited the Delaware Piedmont and suggested that the Delaware Wissahickon is not correlative with the cover sequence of the Potomac Terrane, but with the Loch Raven Schist of the Baltimore Terrane as defined in Maryland.

Any attempt to fit the rocks in this study area into revised classifications or tectonostratigraphic terranes is beyond the scope of this project, and the terms "Glenarm Series" and "Wissahickon Formation" as used by Knopf and Jonas (1923) are retained.

In Delaware, two units of the original Glenarm Series, the Cockeysville Formation and the Wissahickon

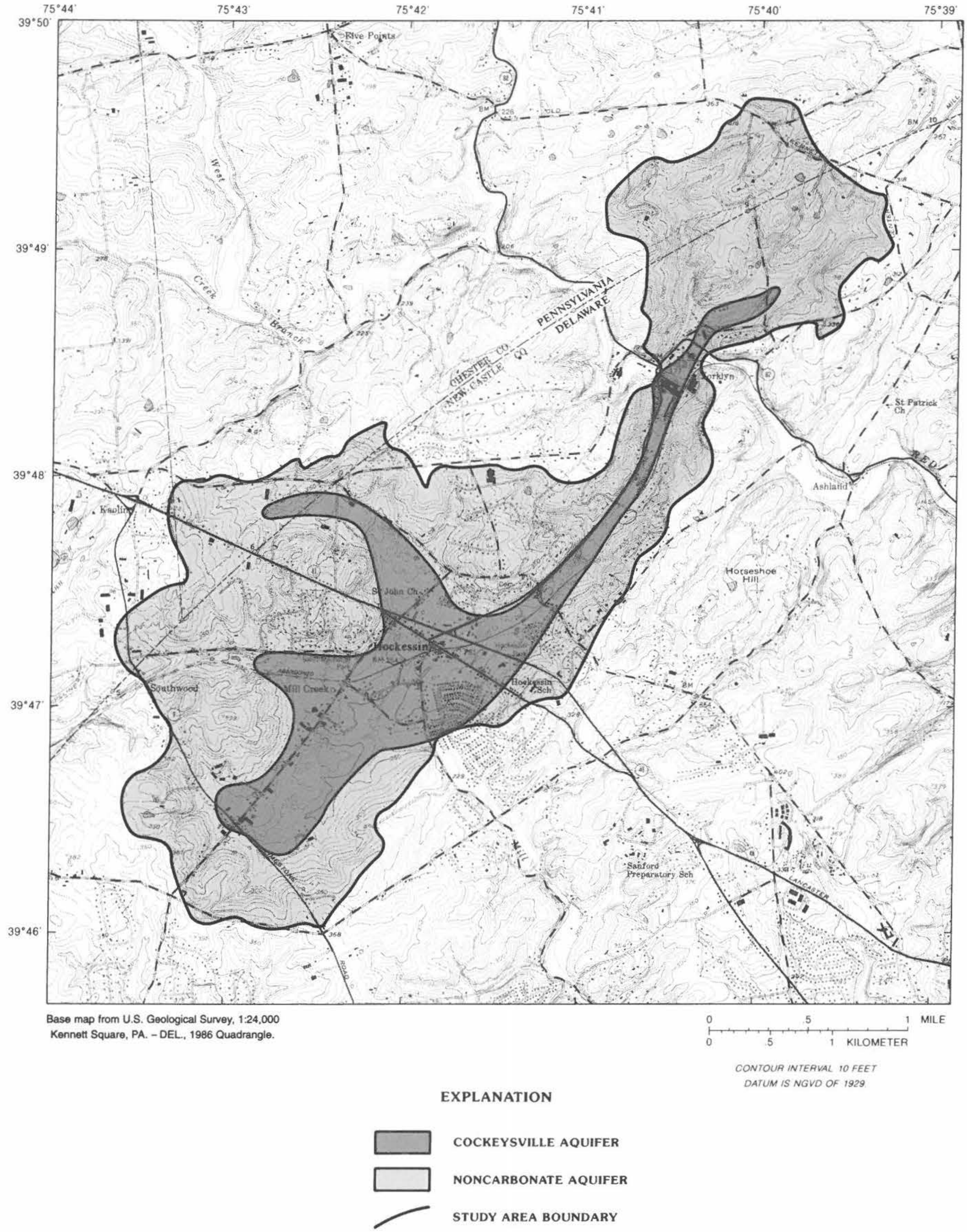


Figure 2. Map showing location of study area for the geohydrology portion of the study.

Formation, have been identified and mapped (Bascom and Stose, 1932; Ward and Groot, 1957; Woodruff and Thompson, 1972). The protoliths of these formations were originally deposited as sedimentary cover on the Baltimore Gneiss during the late Proterozoic to Ordovician (Higgins, 1972). The Cockeysville represents shallow-water carbonates deposited on the continental margin (Choquette, 1960), whereas the Wissahickon represents deep-water sediments (Hopson, 1964). Much of the Wissahickon shows repetition of layers characteristic of distal turbidites (Hopson, 1964; Thompson, 1976; 1981).

A major regional deformation occurred during the Taconic Orogeny (480-435 m.y.) (Horton et al., 1991) when the North American basement, the Baltimore Gneiss, and its sedimentary cover collided with a volcanic arc (Higgins, 1972, 1990; Thompson, 1976, 1981; Muller and Chapin, 1984; Wagner and Srogi, 1987; Drake et al., 1989). During this collision the rocks were highly metamorphosed, folded to form basement-cored anticlines or nappes, and stacked by a series of thrusts. Accompanying metamorphism in the upper amphibolite facies thoroughly recrystallized the rocks now underlying the Piedmont of Delaware and, together with the intense deformation, obliterated most of the original sedimentary structures. The arc complex in Delaware is represented by the Wilmington Complex (Thompson, 1976; Pavlides, 1981; Wagner and Srogi, 1987).

Evidence of post-Taconic folding in Delaware has been discussed by Thompson (1981) and has also been documented in this study. Mesozoic and younger brittle structures, joints and faults, overprint the entire region.

Previous Work

The presence of marble in northern Delaware was recognized by Booth (1841) during the first geological survey of Delaware. He described several occurrences, but lack of funding prevented publishing a geologic map to accompany his report. Bascom and Miller (1920) mapped the marble in the Pleasant Hill area and originally assigned it to the Baltimore Gneiss; however, their map did not extend east into the Hockessin area. Bascom and Stose (1932) completed mapping in northern Delaware and correlated the carbonate rocks in both valleys with the Cockeysville Formation in Maryland. At the same time they reassigned all of the rocks south of the Avondale Anticline in Pennsylvania, except the Cockeysville Formation, to the Wissahickon Formation. The scale of this early mapping was 1:62,500. The most recent published map of areas underlain by the Cockeysville in Delaware is that of Woodruff and Thompson (1972) at a scale of 1:24,000. The formation contacts shown on their map were used by New Castle County agencies for regulatory purposes; contacts on the revised map resulting from the current investigation are now used.

Methods of Investigation

Field Mapping

The main goals of the geologic field investigation were to locate precisely the boundary of the Cockeysville Formation in the Hockessin-Yorklyn valley and the Pleasant Hill valley, determine local structure and thickness of the marble, and locate areas of unmapped marble outside of the two valleys. The outcrop area has significant planning and regulatory implications because of land-use restrictions for areas underlain by the Cockeysville. The structure and thickness, which influence ground-water occurrence and availability, are needed as input for any future ground-water modeling studies.

Test Drilling

Nine test holes, including a 530-foot deep hole (Bb35-16), were drilled to obtain data on lithology, contact location, water-table elevation, and depth of weathering (Fig. 3). Eight of these holes were cored at selected depths. One hole (Bb44-30), located south of the Cockeysville outcrop in the Hockessin area and immediately adjacent to well Bb44-22, was continuously cored to 100 ft. In addition, a bottom-hole core (291-297 ft below land surface) was obtained from the existing well (Bb44-22). Analysis of geophysical logs indicated that Bb44-22 penetrated both the Wissahickon and Cockeysville formations, but the unit beneath the Cockeysville could not be determined from available data. Holes deeper than about 100 ft and the continuously cored hole were drilled by a waterwell contracting firm. Continuous coring was done with conventional rotary and wire-line coring equipment. The deeper holes were drilled using air rotary equipment and cored with a conventional 10-foot long, 2 3/8-in. diameter core barrel. Shallow holes were drilled with the University of Delaware's combination auger-rotary rig and cored with a 5-foot long, 2-in. diameter core barrel.

Geophysical Logging

Both the USGS Southeastern Region logging equipment and that of the DGS were used to run geophysical logs in previously existing test or observation wells and in the 530-foot-deep test hole (Bb35-16). Logs include natural gamma, gamma density, focused and single point electric, temperature, caliper, sonic, neutron porosity, and televiewer. The natural gamma-ray log was particularly useful in defining lithologies within the Cockeysville.

The borehole sonic televiewer log was the most definitive log in locating fractures and solution cavities. It was also used to determine the orientation of planar structures such as foliation and fractures. The log measures the amplitude of the acoustic signal reflected from a 360 degree scan of the borehole wall and is referenced to magnetic north by an internal compass. The dip of a planar surface cutting the borehole can be calculated directly from the log, and these log-derived dips were used to supplement structural information measured from surface exposures. The focused resistivity log and, to a lesser degree, the single-point resistance log were also useful in mapping fractures in boreholes.

Gravity Survey

Approximately 300 gravity measurements were made in and adjacent to the study area using a Worden Prospector gravity meter. The locations of the gravity stations, base station information, and raw field data are on file at the DGS. The majority of measuring point elevations were taken from the tops of man-hole covers for the New Castle County sewer system. These are generally surveyed to a precision

Figure 3. Map showing location of wells and test holes drilled in support of this investigation.

of 0.01 ft; the elevations and locations are recorded in the files of the New Castle County Department of Public Works. Other elevations were obtained from the USGS and the U. S. Coast and Geodetic Survey.

In those areas served by public sewers, gravity measurements could be made at spacings that averaged about 300 ft. In other areas, spacings varied from about 300 ft to one-half mile. The gravity measurements were reduced to Bouguer values using the 1967 Gravity Formula and hand contoured at an interval of 1 milligal (mGal). No terrain corrections were made.

The results of the gravity work are integrated with the discussion of geologic structure presented later in this report. Both the gravity data and the aeromagnetic data of Henderson et al. (1963) were used to guide or constrain interpretations of geologic structure.

Petrographic Analyses

To aid in the identification of the various units, thin sections were prepared and modal estimates made by viewing through a polarizing microscope. Up to 1,000 points were counted per slide.

ROCK UNITS OF THE STUDY AREA

The geologic units in the Piedmont as described and mapped by Woodruff and Thompson (1972) include two units of the Glenarm, the Wissahickon and the Cockeysville formations, and the Wilmington Complex of Ward (1959) (Table 1). The area north of the Hockessin-Yorklyn valley was mapped as a questionable unit. In this study, that area, plus an additional area west of Hockessin, was identified and mapped as Baltimore Gneiss, the oldest unit in the central Piedmont (Plate 1). Another new finding is a thin layer of Setters Formation overlying the Cockeysville in Pleasant Hill valley.

TABLE 1

Rocks of the Delaware Piedmont

ROCK UNITS		LITHOLOGIES
WILMINGTON COMPLEX		mafic & felsic gneisses (may be pyroxene-bearing); noritic, charnockitic, gabbroic, and dioritic plutons; amphibolites
GLENARM SERIES	WISSAHICKON FORMATION	psammitic and pelitic gneisses, amphibolites, and serpentinite
	COCKEYSVILLE FM.	calcareous schist & dolomitic marble
	SETTERS FORMATION	biotite-microcline quartzite
BALTIMORE GNEISS		quartzo-feldspathic gneiss, biotite gneiss, biotite hornblende gneiss, and amphibolites

Although it is possible to identify several lithologies within each of the geologic units, the stratigraphic or intrusive relations between them are uncertain. Lithologies identified by the authors of this report are named according to Blucher and Frey (1994).

Throughout the central Piedmont Province it has been traditional to define an unconformity between the Baltimore Gneiss and the Glenarm Series, conformable contacts between the formations of the Glenarm Series, and thrust contacts between the Glenarm and the Wilmington Complex (Knopf and Jonas, 1922, 1923; Hopson, 1964; Higgins, 1972, 1990; Crowley, 1976; Thompson, 1976; Hager, 1976). Although, recently, many workers have recognized that the Wissahickon may be allochthonous and composed of several distinct lithologic units (Wagner and Srogi, 1987; Drake et al., 1989; Alcock, 1989; Wagner et al., 1991), the traditional interpretation is followed here, and the map shows the Wissahickon in Delaware conformably overlying the Cockeysville in the Hockessin-Yorklyn area. On the southeast side of Pleasant Hill Valley there is evidence for a fault contact between the Wissahickon and an inverted sequence of Setters and Cockeysville.

With the exception of the Wilmington Complex, none of the units in Delaware has been dated; therefore, estimating their ages depends upon correlation with similar units in Maryland or Virginia. Radiometric dating of the Baltimore Gneiss in Maryland found the gneiss was recrystallized at about 1,100 Ma during the Grenville orogeny (Tilton et al., 1958). The age of the Glenarm has been a major geological controversy for nearly a century, with the best estimate being latest Proterozoic to Ordovician (Higgins, 1972; Drake et al., 1989). The Wilmington Complex can possibly be correlated with the Chopawamsic Formation in Virginia and may represent the erosional remnants of a volcanic arc of Cambrian or older age (Pavlides, 1981; Wagner and Srogi, 1987; Drake et al., 1989; Horton et al., 1989; Higgins, 1990). Dating of a Wilmington Complex gneiss and a pluton yielded ages of 441 Ma and 502 Ma, respectively (Grauert and Wagner, 1975; Foland and Muessig, 1978). The 441 Ma age was interpreted as the age of granulite-facies metamorphism, and the 502 Ma as the age of igneous crystallization.

The thicknesses of the Baltimore Gneiss, Cockeysville, and Wissahickon are difficult to determine because these units have been repeated by intense folding and faulting. Thompson (1976) estimated that the Cockeysville in Delaware may be less than 1,000 ft thick, and the Wissahickon may be more than 8,000 ft thick.

Geologic Units Adjoining Cockeysville Formation

Baltimore Gneiss

The Baltimore Gneiss did not appear as a unit on the map of Woodruff and Thompson (1972), but Higgins et al. (1973) postulated the presence of the gneiss beneath a deep magnetic low in northern Delaware. The feature is apparent on the aeromagnetic map of Henderson et al. (1963) and was termed the "Mill Creek Dome." The occurrence of the gneiss between Hockessin and Yorklyn was partially mapped by Gohn et al. (1974). Temporary exposures created by construction activity were used to confirm that the unit underlies the ridge on the northwest side of the Hockessin-Yorklyn Valley and extends from Limestone Road northeast to Yorklyn and into Pennsylvania (Plate 1). Natural exposures occur in small stream valleys cutting the ridge north of Yorklyn Road and in the valley of Red Clay Creek north of Yorklyn. There is no evidence of Baltimore Gneiss in the Pleasant Hill area.

The gneiss in the Mill Creek Dome, unlike that in other areas, has been difficult to recognize because of the high-grade metamorphism in the overlying Glenarm rocks. Highly metamorphosed biotite gneisses of the Wissahickon are often impossible to distinguish from the biotite gneisses of the Baltimore Gneiss. Features that characterize the Baltimore Gneiss are (1) intense migmatization, (2) highly variable strikes of foliation, (3) general absence of sillimanite and primary muscovite, and (4) relic granulite facies assemblages containing orthopyroxene.

Three lithologies have been identified within the Baltimore Gneiss in the study area: biotite gneiss, hornblende-biotite gneiss, and amphibolite with or without pyroxene. Modes of the three lithologies are presented in Table 2. Pegmatites are abundant and occur on all scales.

The fabric in the gneisses grades from weakly to strongly layered. Amphibolite layers are abundant and vary in thickness from a fraction of an inch to as much as ten or more feet. Strikes and dips of foliations are variable, except along the southeastern boundary where foliations parallel those in the Cockeysville and Wissahickon formations.

TABLE 2

Modal analyses of the Baltimore Gneiss

	Biotite Gneiss								Hornblende-Biotite-Gneiss			Amphibolite		
Minerals	Bb25-s	Bb34-b	Bb34-c	Bb42-b	Bb25-p	Bb25-q	Bb25-b	Bc11-b	Bb25-r	Bb35-b	Bb24-a	Bb14-a	Bb23-h	Bb34-d
Quartz	49.9	35.5	28.5	33.7	40.0	37.3	33.1	34.3	36.5	44.3	19.5	9.0	7.1	0.3
Plagioclase	38.2	30.3	45.6	48.8	29.4	47.8	40.9	39.5	46.0	45.6	56.4	26.0	36.4	32.5
K-feldspar	x	12.3	1.8	1.6	12.8		0.2	4.4	x					
Myrmekites		0.6	0.3		0.3			x	x					
Biotite	9.2	20.3	23.6	12.4	13.0	13.5	25.4	19.5	2.5	0.8	7.8	16.6	1.1	
Muscovite	2.4	1.0		2.0	4.3		0.4		1.0	tr				
Garnet			x			1.4	x	x	3.7	x	2.6			
Clinozoisite/Ep				x					0.5					
Hornblende			x						9.8	9.0	7.9	47.2	54.1	51.0
Actinolite														x
Chlorite				x										
Orthopyroxene										4.9		1.2		
Clinopyroxene												11.8		
Opaques	0.3		x	0.5	x	x		x	x	0.3	0.9	0.6	0.7	3.2
Sphene	x	x	0.2	1.0	x			2.3	x			0.6	0.6	
Apatite			x		0.2	x	x	x		x	x			
Scapolite				x										x
Zircon	x	x	x	x	x	x	x	x						
No. of Points	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000

DGS Outcrop Number	Sample Number	Location (see Appendix 2 for map coordinates)
Bb25-s	41798	Marten's Autohaus, Rt. 82 & Hockessin-Yorklyn Road
Bb34-b	41805	Old Wilmington Road adjacent to Friends Meeting House
Bb34-c	41967	West Ridge, Old Wilmington Road
Bb42-b	41819	Stenning Woods
Bb25-p	41842	Yorklyn, adjacent to pool and tennis courts
Bb25-q	41940	Nine Gates Road, north of marble valley
Bb25-b	42363	North of NVF office building, Yorklyn
Bc11-b	58158	Pegmatite quarries, Burnt Mills, Pennsylvania
Bb25-r	42312	North of Hockessin-Yorklyn Road
Bb35-b	41942	Top of stream draw, north side of Hockessin-Yorklyn Road
Bb24-a	42362	Auburn Mill Road
Bb14-a	58155	Marshall's Bridge Road
Bb23-h	58135	Chandler Mill Road, Donahue property
Bb34-d	42364	Old Public Road

x: traces
Ep.: Epidote

Textures in the Baltimore Gneiss are crystalloblastic suggesting complete recrystallization of the rocks. No original sedimentary or igneous textures were recognized.

Setters Formation

The Setters Formation, the basal unit of the Glenarm Series, had not been previously mapped in Delaware. In many localities in Pennsylvania and Maryland, the Setters is missing between the Baltimore Gneiss and Cockeysville Formation, presumably due to non-deposition or to tectonic thinning on the limbs of tight folds. Its absence in Delaware was, therefore, not considered unusual.

The Setters is predominantly an impure quartzite that varies from a feldspathic or micaceous quartzite to a feldspathic mica schist or gneiss (Table 3). Microcline is an essential constituent of the schists and gneisses and serves to distinguish it from the microcline-poor schists and gneisses of the Wissahickon Formation (Hopson, 1964; Kuhlman, 1975).

In Eastburn's Quarry, on the southeast side of Pleasant Hill valley, a fine-grained garnet-bearing gneiss overlies carbonate rocks (Plate 1). The gneiss had been identified in earlier work (Porter, 1976) as Wissahickon because of its lithology and stratigraphic position. It was found during this study that this gneiss petrographically resembles descriptions of the Setters Formation in Pennsylvania and Maryland, as it has the characteristic microcline-quartz-biotite assemblage. In the Setters in Pennsylvania and Maryland, muscovite is usually a major phase, whereas in this quarry muscovite is absent. This variation is due either to higher-grade metamorphism in the Delaware Piedmont or to different original bulk rock composition. In this quarry, the foliations in the newly recognized Setters and the marble strike N33°E and dip 23°SE.

Southeast of Eastburn's quarry, the Setters is exposed in a deep swale; the hillside southeast of the swale is probably underlain by the Wissahickon as indicated by abundant float. Along strike to the southwest, fine-grained gneisses that appear to be Setters can be found as float.

Rocks belonging to the Setters were not found either in outcrop or in drill holes in the Hockessin-Yorklyn area.

Wissahickon Formation

The Wissahickon in Delaware comprises an extensive sequence of pelitic and psammitic metasedimentary gneisses with interlayered amphibolites and lenses of serpentinite (Bascom and Miller, 1920; Bascom and Stose, 1932; Thompson, 1976, 1981).

The pelitic gneisses contain biotite, quartz, plagioclase (oligoclase to andesine), and various iron-titanium oxides. Staurolite, sillimanite, orthoclase, muscovite, and garnet vary systematically with metamorphic grade. Cordierite appears in a few places adjacent to the Wilmington Complex (Table 4). Metamorphic grade increases eastward to above the second sillimanite isograd as documented by the presence of sillimanite and orthoclase and the absence

TABLE 3

Modal analyses of the Setters Formation

Minerals	Cb12-a	Cb12-a	Cb12-a	Kuhlman (1975) 344A	Kuhlman (1975) 334D	Kuhlman (1975) 351	Hopson (1964) H36-1	Hopson (1964) H106-7	Southwick (1969) 2	Southwick (1969) 3
Quartz	30.7	28.3	63.6	14.0	34.0	29.0	58.1	45.4	36.4	40.4
Plagioclase	2.1	1.9	0.3	1.4	x	0.0	2.4	7.8	28.4	0.3
Microcline	50.4	63.4	16.0	54.6	57.3	46.0	19.3	31.5	14.0	42.1
Biotite	16.1	5.9	9.8	18.2	4.0	13.1	12.2	11.2	16.1	9.5
Muscovite		x		11.1	1.7	11.1	5.6	1.9	3.4	4.5
Garnet			7.7							
Opaques	0.7	0.5	0.2	x	x	0.7	1.7	1.9	0.5	2.8
Zircon	x	x	x				x	x	x	0.3
Sphene	x	x	x				x	0.1	0.6	x
Apatite	x	x	2.4	x	x		0.5		0.2	x
Chlorite/Biotite	x			x	1.6	x				
Clay/Plagioclase	x							0.2	0.4	
Points Counted	1000	1000	1000	1000	1000	1000	1000	1000	1368	1594

DGS Outcrop Number	Sample Number	Location (see Appendix 2 for map coordinates)
Cb12-a	42339	Southeast side of Eastburn's quarry, gneiss overlying marble, Delaware
Cb12-a	42340	Southeast side of Eastburn's quarry, gneiss overlying marble, garnet-rich layer, Delaware
	344A	Quarry at Avondale, Pennsylvania
	334D	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
	2	Lower Bynum Run about 0.5 miles north of Hookers Mill Road, Maryland
	3	Lower Winters Run about 0.9 miles upstream from Interstate Highway 95, Maryland

x: traces

TABLE 4

Modal analyses of the Wissahickon Formation

Minerals	Pelitic Gneiss: samples arranged left to right in a west to east sequence						Psammitic Gneiss						Amphibolite	
	Ca23a	Ca35b	Cb14b	Bc21r	Bc24b	Bd31b	Cb13-9	Bb25c	Bb33d	Bb33c	Bb33-16	Bb33b	Bc32b	Bc32o
Quartz	18.2	7.8	27.5	37.4	28.7	18.1	25.6	39.9	41.8	23.3	36.4	51.2	6.6	7.0
Plagioclase	16.7	30.1	14.1	6.1	7.3	16.4	41.9	33.4	25.6	38.8	34.5	27.3	35.4	43.0
Biotite	21.3	32.6	26.6	28.0	30.6	10.8	27.4	22.1	30.5	36.4	21.8	21.1	3.0	x
Garnet	5.8		1.0	7.5	3.3	9.6	1.6	1.7		1.1	2.3			1.0
Opaques	0.8	0.6	2.7	x	1.2	4.2	3.2	0.8	0.2		1.0	0.2	5.2	
Muscovite	35.2	19.2	4.1	x					1.7	0.2	3.5	0.2		
Staurolite	2.0						x							
Sillimanite	x	4.1	11.3	14.2	15.0	17.6	0.3		x	x	x	x		
Orthoclase		5.6		6.8	13.9	6.0		2.1						
Cordierite						17.3								
Hornblende	x		12.7										49.5	49.0
Zircon		x	x	x	x	x	x	x	x	x	x	x	x	x
Sphene		x	x	x			x	x	x	x	x	x	0.3	
Calcite											x			
Apatite		x							0.2	0.2	0.5	x		
Points counted	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000

DGS Well or Outcrop Number	Sample Number	Location (see Appendix 2 for map coordinates)
Ca23a	41818	Northwest of Newark
Ca35b	41938	North of Newark on Creek Road and White Clay Creek
Cb14b	41934	Intersection of Limestone Road and Stoney Batter Road, northeast corner
Bc21r	41946	Saint Patricks Cemetery
Bc24b	42325	Quarry, Winterthur
Bc31b	U of De M-6	Brandywine Creek, one-half mile north of Montchanin
Cb13-9	80160	South of Pleasant Hill Valley, cuttings from 105 feet
Bb25c	42342	Railroad cut at NVF, Yorklyn
Bb33d	42332	McGovern Road
Bb33c	42335	Deerfield, Route 48 at state line
Bb33-16	60628	North of Hockessin and east of Route 48, core from 37-41 feet
Bb33b	41941	Wellington Hills, outcrop in stream
Bc32b	U of De H130	Railroad cut on Copeland property, Red Clay Valley
Bc32o	U of De H129	Red Clay Creek, west bank opposite Mt. Cuba picnic grove

x: traces

of primary muscovite. Estimated peak temperatures of metamorphism increase from 650°C west of Newark to 750°C east of Red Clay Creek and pressure estimates vary from 4 to 7 kilobars (Calem, 1987; Plank, 1989). Isograds based on the progress of discontinuous reactions show a complex pattern reflecting (1) the regional increase in grade from northwest to southeast, (2) heat from a local source in the east, possibly the Wilmington Complex as suggested by Wagner and Srogi (1987), and (3) post-metamorphic folding of the Mill Creek Dome.

The psammitic gneisses contain quartz, plagioclase, and biotite. Contacts between the pelitic and psammitic rocks are usually gradational, and these two lithologies may be considered end members in a continuous series of bulk rock compositions from dominantly pelitic to dominantly psammitic (Hager, 1976).

The amphibolites are composed primarily of plagioclase and hornblende. Although the origin of the amphibolite is unknown, the composition suggests an igneous source, possibly basalt flows, pyroclastics, or gabbroic dikes or sills. The abundance of the amphibolites increases eastward, suggesting proximity to a magma source in the east. Locally occurring pods of ultra-mafic rocks, now metamorphosed to serpentinite, may represent fragments of oceanic crust that were tectonically emplaced (Thompson, 1976, 1981).

Granitic pegmatites of various kinds are ubiquitous within the Wissahickon. The largest of these pegmatites, although probably generated by partial melting and metasomatism during metamorphism, indicate intrusion along planes of weakness that are usually parallel to the regional northeast-southwest structural trend.

Modes of the three major lithologies are shown in Table 4. The modes of the pelitic samples are arranged in a west to east sequence to illustrate the change in index minerals, and concomitantly, the increase in metamorphic grade.

Cockeysville Formation

Field Description

In northern Delaware, the Cockeysville Formation underlies the broad, flat valleys of the Hockessin-Yorklyn and Pleasant Hill areas. Elevations of the valley floors range from 180 to 300 ft. Because the marble is easily eroded, there are no natural bedrock exposures of the formation in Delaware. The lack of surface exposure, scarcity of float, and low relief on the valley floors are usually evidence of underlying marble. Float, predominantly fragments of amphibolite and quartz derived from the nearby ridges, occurs locally over the Cockeysville and is usually confined to stream channels. The approximate contact with the adjacent rocks at higher elevations is marked by a topographic break that can easily be seen in the field and usually can be identified on 7.5-minute topographic maps. Local knowledge of the unit comes from well or test hole data and from several abandoned quarries. The unweathered Cockeysville is exposed with the Setters Formation in Eastburn's Quarry southwest of the intersection of Rt. 72 and Upper Pike Creek Road in Pleasant Hill valley (Plate 1). Extremely weathered marble can be found around other abandoned, water-filled quarries located in the development of Morningside on the east side of Rt. 72 in Pleasant Hill Valley, and west of the intersection of Old Lancaster Pike and Mill Creek Road in Hockessin.

Mapping

Plate 1 shows revisions to the map of Woodruff and Thompson (1972) that resulted from this study. In Pleasant Hill Valley changes to the southeastern contact were based on drill hole data and on identification of the Setters Formation. The position of the Wissahickon over an inverted Setters-Cockeysville sequence requires a faulted southeastern edge.

In the Hockessin-Yorklyn area, the extension of the Cockeysville north along Southwood Road (Fig. 1, Pl. 1) beneath nearly all of the development of Southwood is based on data from test hole Bb33-36 and on topographic expression. Drilling and coring to a depth of 95 ft indicated a typical sequence of weathered calc-schist grading to unweathered marble with depth. The mapped western edge of the Cockeysville outcrop area, along Limestone Road, was moved slightly eastward as a result of new drill hole data and exposures (Plate 1).

Test holes Bb34-53, 54, and 55 (Fig. 3) were spaced so as to straddle the previously mapped contact with the Wissahickon near Hockessin and to verify the presumed southeasterly dip of the contact (Fig. 4). Minor changes to the previously mapped southeastern edge of the Cockeysville were made between Hockessin and Yorklyn.

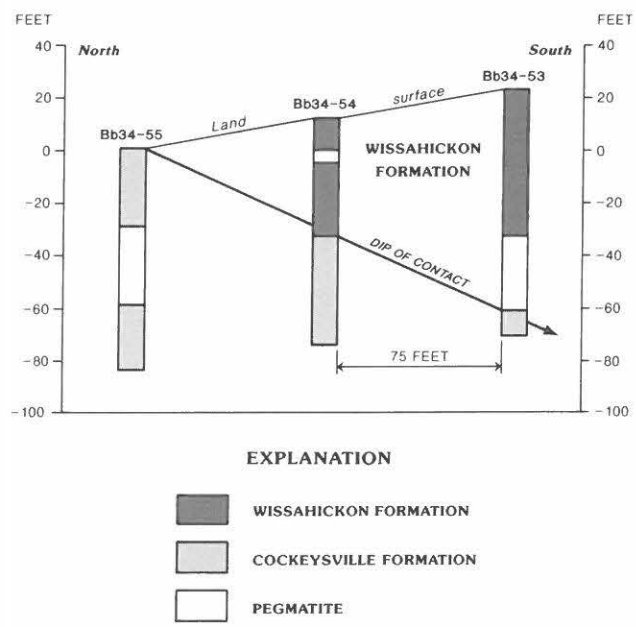


Figure 4. Diagram showing Wissahickon-Cockeysville contact south of Hockessin. Zero represents approximately 280 ft above sea level.

As previously mapped, core holes Bb25-23 and Bb25-24 confirmed that a narrow arm of the Cockeysville extends northeast of Yorklyn. Although the position of the extreme northeastern contact with the Wissahickon is uncertain, topography, elevations, and lack of float on the valley floor strongly suggest that the Cockeysville extends to the northeast and pinches out near the intersection of Center Mill Road and Old Kennett Road (outside of the study area). The intersection would be near that identified by Booth (1841) as Klair's

Marble Quarry, and inquiries confirmed that this area was part of the original Klair property. However, no drill hole data exist and the presence of the Cockeysville was not verified.

A small area of Cockeysville was mapped by Leis (1975) just south of Mill Creek Meeting House on the north side of a small stream passing beneath Doe Run Road near Yeatmans Mill Road. The outcrop has since been destroyed, but Cockeysville float was found at this location. The occurrence is shown on Plate 1. It is probably the crest of a small fold or a piece of Cockeysville caught within a block of Wissahickon. The Wissahickon is exposed in outcrop only a few yards to the southwest.

A small stream valley (outside the study area) just west of Brandywine Creek may also be underlain by marble. This location is near a marble quarry described by Booth (1841) and is not far from Pennsylvania marble localities described by Bascom and Stose (1932). No outcrops of marble occur in the stream, and only Wissahickon Formation rocks are visible in nearby outcrops; however, the remnants of an old lime kiln are incorporated into a rock wall next to the small stream valley.

Lithology

Major rock types within the Cockeysville of northern Maryland include calc-schist, dolomite marble, calcite marble, calc-silicate marble, and calc-gneiss (Choquette, 1960; Otton et al., 1975). In Delaware, dolomite marble, calcite marble, and calc-schist have been identified. The dolomite marble makes up the greatest percentage of the known Cockeysville in Delaware and is a pure, coarsely crystalline, blue-white marble. Locally it may contain streaks or thin bands of calc-silicate minerals. Calcite marble is also a coarsely crystalline, blue-white marble that occurs in thin layers, attenuated lenses, pods, and small patches within thicker layers of dolomite marble or calc-schists. Calc-schist is a fine- to medium-grained, light-gray rock that is phlogopite-rich and strongly foliated. Phlogopite may concentrate at the boundary between the calc-schist and the marble.

Although interbedded calc-schist and marble may occur throughout the Cockeysville, we found from gamma-log responses that the calc-schist is most common in the upper 250 ft of the formation. The gamma-ray log response in the calc-schist (Fig. 5) is much higher than in the purer marble owing to the presence of the potassium-bearing minerals microcline and phlogopite. Where unweathered calc-schist occurs near the top of the formation the gamma-ray signature may often be mistaken for that of the Wissahickon Formation. Borehole temperature logs in the calc-schist facies or in portions of the Cockeysville with abundant phlo-

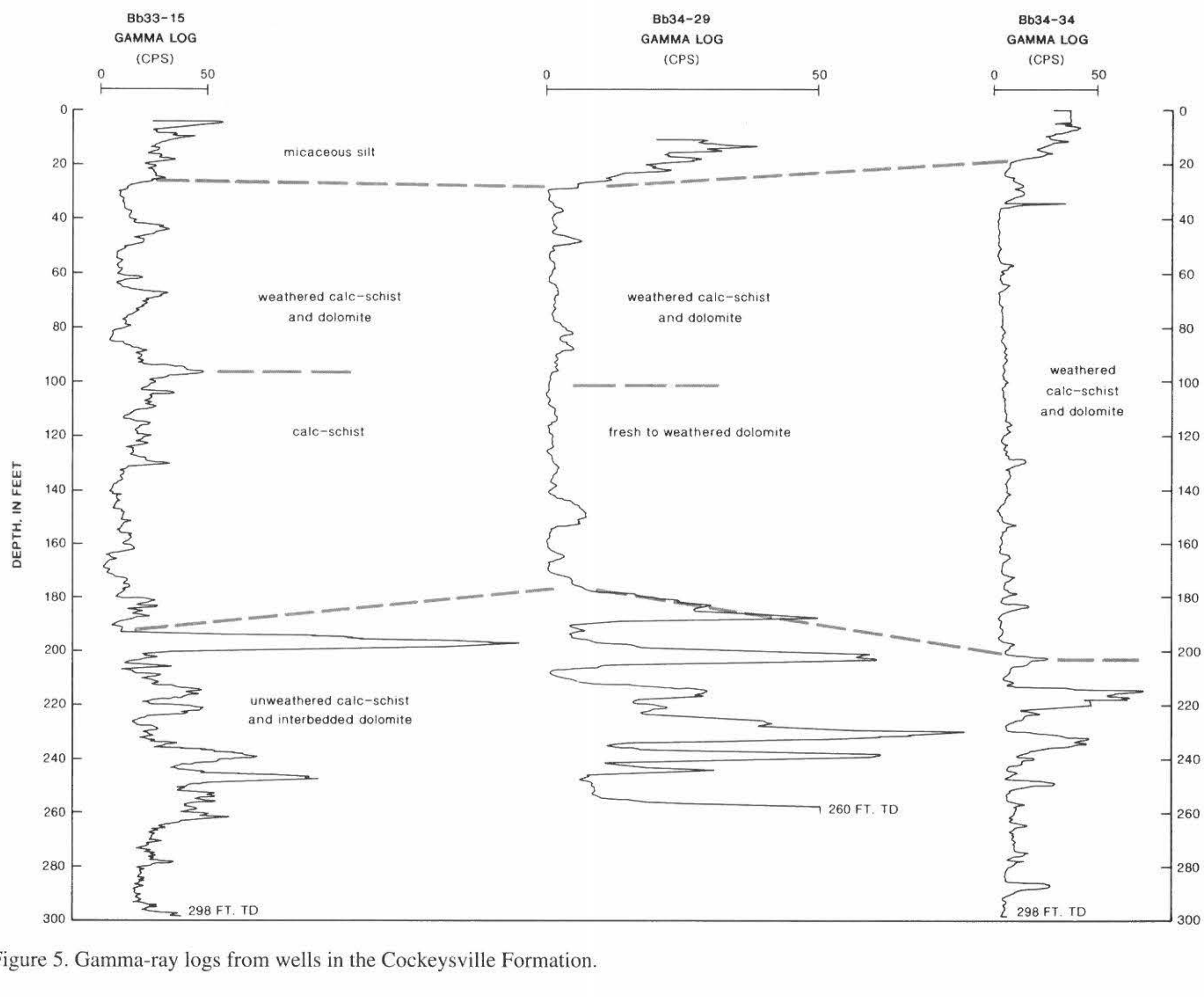


Figure 5. Gamma-ray logs from wells in the Cockeysville Formation.

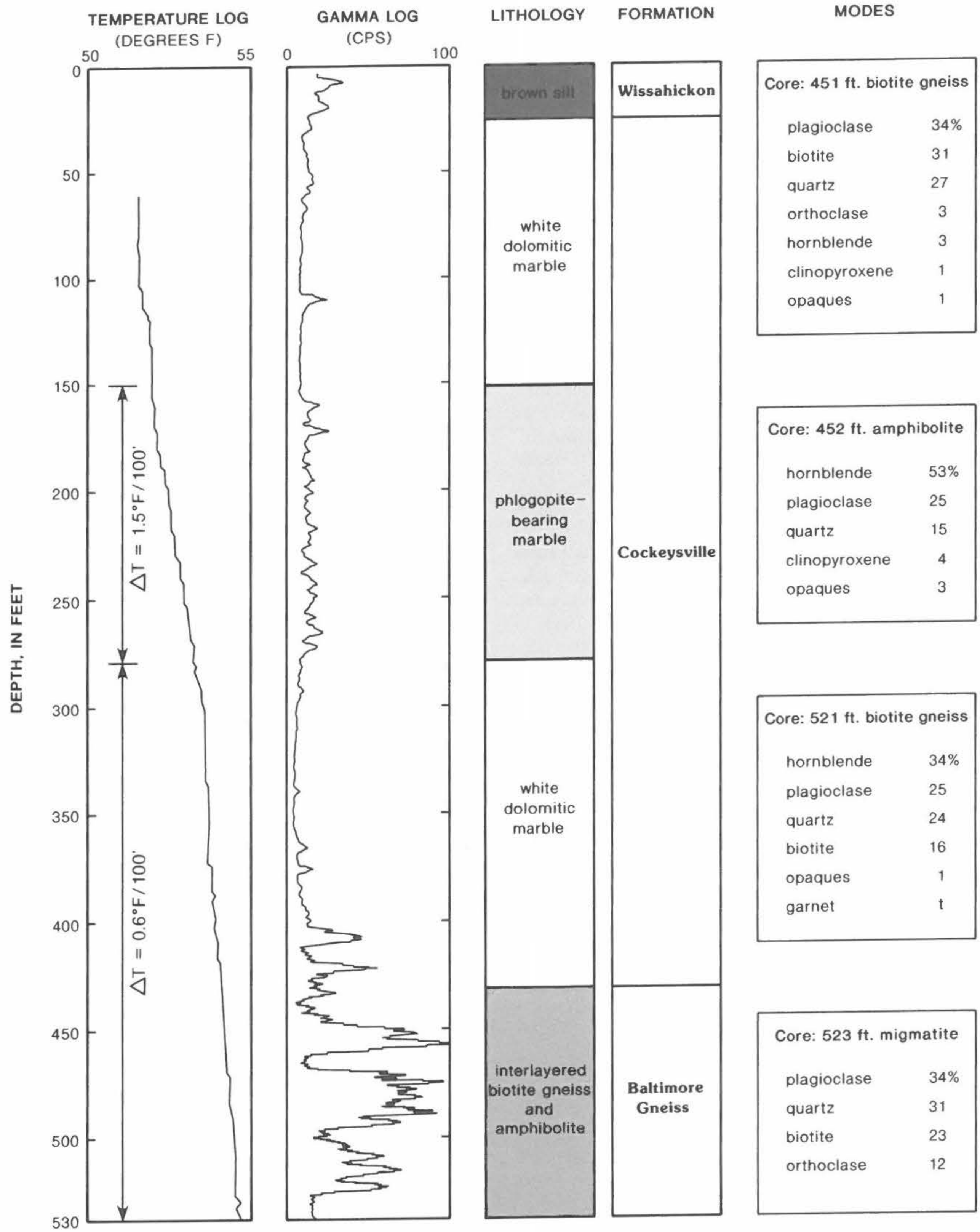


Figure 6. Selected geophysical logs and lithology from test hole Bb35-16.

gopite may show higher than normal temperature gradients because of low thermal conductivity. In hole Bb35-16, a gradient of about 1.5°F/100 ft was recorded between depths of about 100 and 290 ft, which corresponds to a zone of gamma-ray response slightly higher than might be expected from pure dolomite (Fig. 6). This is probably due to phlogopite-rich carbonate rock. The massive marble has a much lower gradient of only about 0.6°F/100 ft. The average gradient in the Delaware Piedmont as determined from unpublished log data in DGS files is about 0.9 to 1.0°F/100 ft.

Unusually pure deposits of kaolin associated with the Cockeysville were mined, most intensively during the 1860s and 1870s, but some mining apparently continued into the 1930s (Lake, 1976). These workings and numerous old test pits with exposures of kaolin are located throughout the Hockessin-Yorklyn valley. Other workings, no longer visible, were located in Pleasant Hill valley.

Kaolin forms by the hydrothermal alteration of feldspars by acidic ground water. Because feldspar is not a constituent of marble but of pegmatites, the kaolin probably formed by the alteration of pegmatites that were intruded into the marble. The veins of kaolin have no topographic expression, and their distribution and exact location are difficult to determine except by drilling or by the presence of the abandoned pits.

Petrography

The dolomite marble consists of 94 to 100 percent dolomite with calcite, phlogopite, and opaques (graphite) as additional phases (Table 5). The calcite marble consists of 80 to 100 percent calcite and dolomite with phlogopite, diopside, olivine, and graphite as additional phases. The calc-schists consist of calcite and more than 50 percent silicate minerals, mainly phlogopite, microcline, and diopside with and without tremolite. Quartz, plagioclase, scapolite, and clinozoisite occur in some samples as minor phases, and the accessory minerals are sphene, apatite, and opaques (graphite, pyrrhotite). Dolomite is generally absent (Table 5). The variety of phases and their distribution within calc-schists probably reflect the varying amounts of clay and other impurities in the parent sediments and the effects of metasomatism (Choquette, 1960). Alcock (1989) suggested that during metamorphism fluids were channelized through zones rich in silica and were responsible for additional reactions and the generation of new silicate minerals.

The marbles are thoroughly recrystallized, and, in general, the mineral assemblages appear to be in equilibrium. However, in some rocks there is evidence for retrogression; tremolite has replaced diopside; serpentine, with minor talc, has replaced diopside and olivine. The serpentine occurs in patches that mimic the size and, in some cases, the shape of olivine or diopside grains.

Brief investigation of the mineral phases in the Cockeysville Formation in Delaware show assemblages typical of orogenic marbles and calc silicate rocks metamorphosed at high temperatures (550 to 800°C) and medium pressures (4-8 kilobars). More accurate estimation of metamorphic conditions depends upon knowing the composition of the binary H_2O-CO_2 fluid phase (Alcock, 1989; Blucher and Frey, 1994).

The modes listed in Table 5 show the presence of the index minerals tremolite, diopside, and olivine (forsterite) which indicate middle or upper amphibolite facies of metamorphism. These minerals, absent in most dolomite marbles, are present in the thinly interlayered calcite marbles and in the calc-schists. Their distribution is significant; however, any attempt to estimate more accurately the metamorphic conditions or the effects of a fluid phase is beyond the scope of this report.

Fractures and Solution Cavities

Large openings or solution cavities within the formation have been verified by drill holes and, as indicated earli-

TABLE 5

Modal analyses of the Cockeysville Formation

	Dolomite Marble				Calcite Marble (retrograded)			Calc Schist				Phlogopite-rich layer	
Minerals	Bb33-25	Bb34-39	Bb34-44	Cb12-8	Bb43-13	Bb25-23	Cb12-10 H-15	Cb12-6	Cb12-18	Bb34-34 B	Cb12-10 H-6	Bb34-34 A	Bb34-42
Dolomite	98.8	100.0	94.0	99.0	18.1	37.0	51.6	x			0.5	1.5	8.7
Calcite	0.7	x	2.6	0.4	42.5	27.6	24.0	31.2	44.0	12.1	27.8	14.9	28.0
Phlogopite	0.5	x	3.2	0.6	19.4	0.5	10.0	20.0	15.5	30.5	52.5	81.3	61.3
Diopside			0.2		5.0		0.7	10.8	5.3	18.3	13.5		
Olivine							0.3						
Tremolite								10.0	5.3	0.8			
Microcline								17.6	23.0	36.0	4.0		
Plagioclase								4.0	3.0	x	0.5		0.5
Quartz								1.9	1.3				
Scapolite								2.5					
Opaques				x	0.5	x	2.8	1.5	1.6	2.3	1.2	2.3	1.5
Sphene								0.5	1.0				
Apatite									x				
Serpentine minerals			x		14.5	34.9	10.6						
Points Counted	500	500	1000	500	600	1000	1000	1000	1000	1000	1000	450	1000

DGS Well Number	Sample Number	Location (see Appendix 2 for map coordinates) x: traces
Bb33-25	24858	Test well southwest of Hockessin, core from 27 to 32 feet, layering dipping 30°
Bb34-39	24748-17	Test well Bicentennial Park, Hockessin, core from 72.7 to 82.7 feet
Bb34-44	24811	Well, Hockessin, core from 51.8 to 52 feet
Cb12-8	26233	Well, Pleasant Hill Valley, Pleasant Hill Road, core from 120 feet
Bb43-13	80575	Well, south of Valley road, Hockessin, cuttings from 210 to 215 feet
Bb25-23	25396	Well, east of Yorklyn, cores from 26.5 to 38.5 feet
Cb12-10	H-6	Test well from center of Pleasant Hill Valley, core from 408 to 419 feet
Cb12-10	H-15	Test well from center of Pleasant Hill Valley, core from 408 to 419 feet
Cb12-6	23312	Well, Pleasant Hill Valley, North Star Road, core from 45-46.5 feet
Cb12-18	81187	Well, Pleasant Hill Valley, southeast of Route 72, core from 148 to 150 feet
Bb34-34	80517	Well, Hockessin-Yorklyn Road south side, A from 200 feet and B from 215 to 200 feet
Bb34-42	24804	Test well from Bicentennial Park, Hockessin, core from 65 to 67 feet

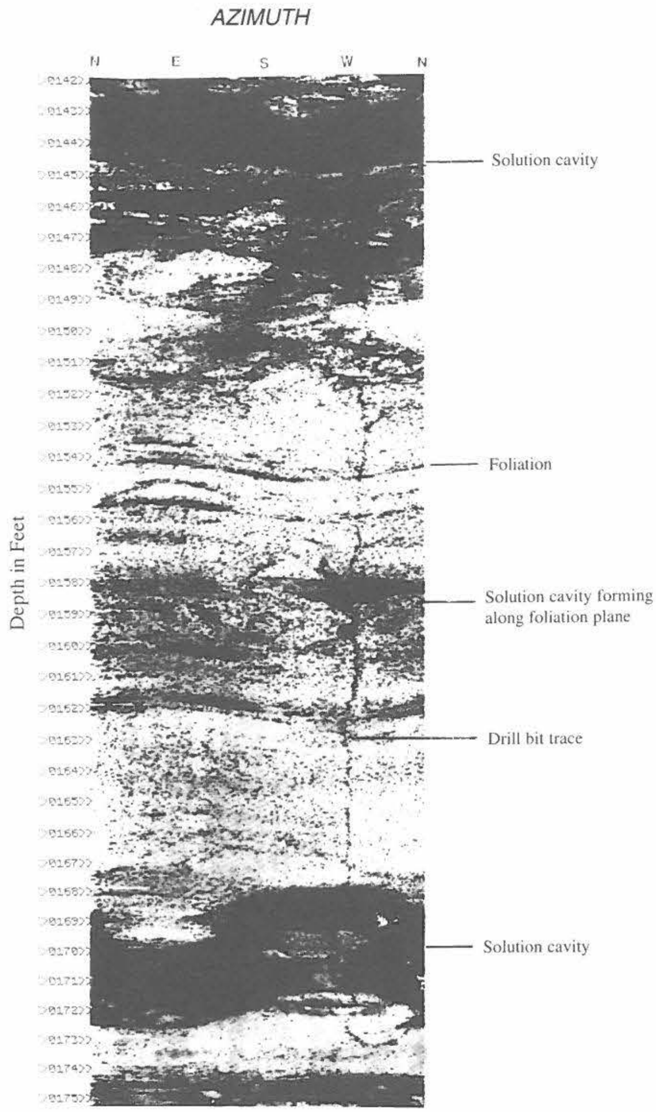


Figure 7. Acoustic televiewer log of a portion of well Bb33-26.

er, by geophysical logs. Figures 7 and 8 show portions of acoustic televiewer logs on which solution cavities in test wells Bb33-26 and Bb34-35 are particularly visible. One of the openings in Bb34-35 is about 16 ft in height. In nearly all cases, drillers' reports indicate that these openings yield large amounts of water. The televiewer log from Bb33-26 shows solution cavities in various stages of evolution and suggests that they may originate parallel to fractures or to foliation. For comparison, Figure 9 shows a partial log from the relatively unfractured Cockeysville in well Bb44-22.

Specific recharge paths to openings in the unweathered Cockeysville are difficult to determine, but in some cases recharge to deeper parts of the formation must be fairly rapid. Temperature logs (Fig. 10) from well Bb33-28, located near the central portion of the Hockessin-Yorklyn Valley, suggest that surface water is entering through one of two main fracture zones enlarged by solution in the well and probably leaving through the other. On caliper logs, fracturing is evident directly beneath the surface casing and at about 218 and 300 ft. The temperature log for April 16, 1990, shows a large, cold water temperature anomaly with the top at about 220 ft. The lowest temperature measured was about 47°F. The second run, made two days later, shows a downward shift of the anomaly. Run three, made two weeks later on May 1, 1990, indicates a decay of the cold water slug, and the fourth run, on July 31, 1990, indicates that the anomaly had completely disappeared. The recharge source apparently originated perhaps one to three months earlier during the winter. The July 31 run should have shown a high temperature anomaly if the source was constant. It was not possible to attribute the anomaly to any discreet precipitation or streamflow event although rainfalls ranging from 0.75 to 0.94 in. occurred on January 30, February 10, and March 17. Local water-level gradients (Werkheiser, this report, Fig. 30) indicate a source to the west or southwest, possibly a small stream about 900 ft to the southwest. Seepage runs indicate that all of the surface water entering the valley in this stream from the Wissahickon is lost through streambed infiltration. Mill Creek, the same distance to the south, might possibly be a source of recharge although this is not supported by ground-water level data.

Weathered Zone

The depth of weathering is highly variable but tends to be deepest in the immediate vicinity of Hockessin where it

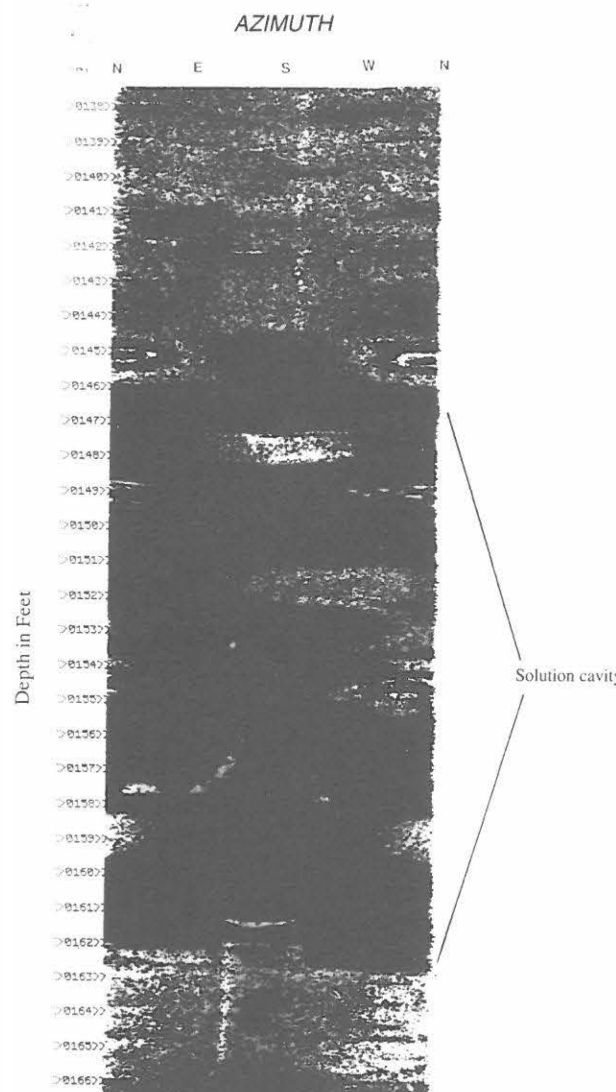


Figure 8. Acoustic televiewer log of a portion of well Bb34-35.

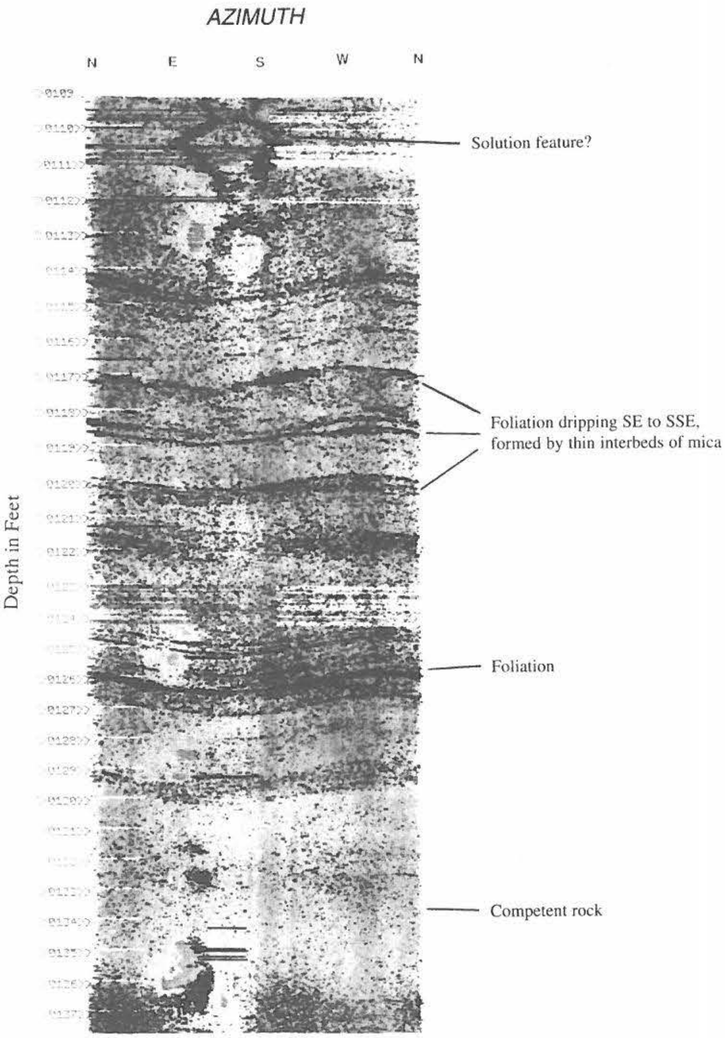


Figure 9. Acoustic televiewer log of a portion of well Bb44-22.

exceeds 150 ft (Fig. 11). In the Pleasant Hill area depth of weathering may exceed 150 ft at the southwestern end. The top 20 to 30 ft of the weathered zone usually consists of a clayey silt which grades downward into an angular, medium-to-coarse-grained, poorly sorted, calcareous, quartz sand. The sand represents the insoluble portion of the weathered marble. The silt is recognizable on gamma-ray logs (Fig. 5), but the

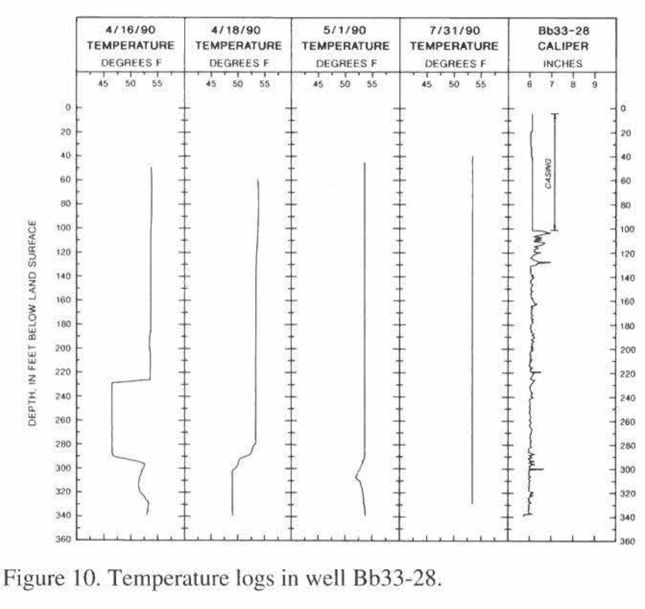


Figure 10. Temperature logs in well Bb33-28.

transition from the carbonate sand to unweathered marble is generally not discernible. Drillers' reports indicate that weathered and unweathered zones may be interbedded, although it is probable that some of the zones described may be solution channels filled with weathered or fine-grained material. Before the onset of heavy ground-water pumping in Hockessin, the weathered zone was the main source of water for domestic wells. Sections of the weathered zone in the central portion of the Hockessin area have since been dewatered, although isolated thin, perched, water-bearing zones are still present. The weathered zone is a source of recharge to fractures and solution channels in the unweathered marble. Its importance as a ground-water storage reservoir is discussed by Werkheiser (this report).

The Cockeysville is highly weathered only where it occurs at the surface. Where it occurs beneath the Wissahickon, it is fresh to only slightly weathered. There may be stratigraphic continuity with Cockeysville localities in Pennsylvania, but there is probably no direct hydrologic continuity. Fresh marble exposed in quarries in Maryland appears massive and impermeable except for local jointing or fracturing.

STRUCTURAL GEOLOGY

Most geologists agree that the major structural relations in the Delaware-Pennsylvania Piedmont are of ductile origin and early Paleozoic age (Hopson, 1964; Higgins, 1972; Crowley, 1976; Thompson, 1976; and others). Recent work suggests that much of the Piedmont is allochthonous and has been assembled by tectonic stacking of crustal slices (Alcock, 1989; Drake et al., 1989; Higgins, 1990; Wagner et al., 1991; Gates et al., 1991). Yet evidence for faulting is sparse, and low-angle thrusts that separate the slices are hard to locate.

Thompson (1981) was the first in Delaware to recognize intense Taconic-age northwest directed compressional events that generated the northeast-trending thrusts, uplifted the Mill Creek anticline, and produced, mainly in the Wissahickon, isoclinal similar flow folds with steep axial planes.

Hockessin-Yorklyn Area

The test holes and field data show the marble in the Hockessin-Yorklyn area overlies the Baltimore Gneiss and underlies the Wissahickon in a normal stratigraphic sequence. Foliations in all units strike N40-45°E, parallel to the regional strike, and dip to the southeast. In the Wissahickon immediately south of the Mill Creek Dome, foliations dip southeast between 40° and 60°, and then steepen to between 70° and 90°. North of the dome, the Wissahickon foliations dip southeast under the Baltimore Gneiss at a shallow angle, 35° southeast. The structures and map pattern suggest that the Mill Creek Dome is a nappe overturned to the northwest. The absence of the Cockeysville and Setters along the north side of the dome may be due to shearing or thinning out of these units on the overturned limb of a nappe, or to removal by faulting.

The structural relations suggest Mackin's (1962) model for the Pennsylvania Piedmont in which basement gneisses represent the cores of nappes with gently dipping south limbs and north limbs that have been cut by a low angle thrust. The basic scheme for his model is illustrated in Figure 12. The same scheme is used here for drawing cross

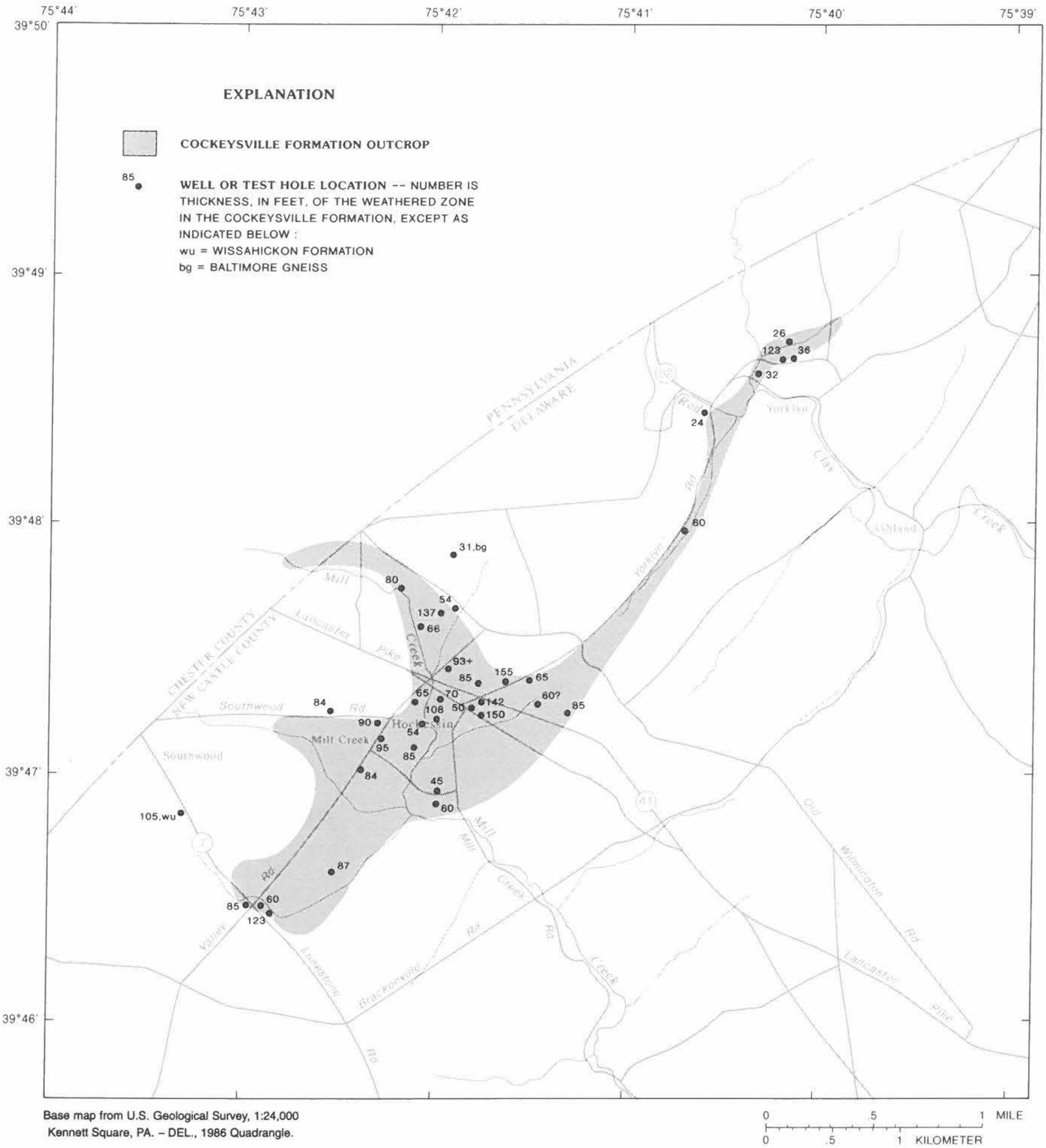


Figure 11. Thickness of weathered zone in the Cockeysville Formation.

sections A-A′, B-B′, and C-C′ (Fig. 14). Locations of cross-sections are shown on Figure 13.

Borehole Data

Drill hole results from hole Bb35-16 (Fig. 3), southwest of Yorklyn, indicate a normal stratigraphic sequence except for the absence of the Setters Formation. Weathered Wissahickon rocks are underlain at about 25 ft below land surface by moderately weathered Cockeysville which grades downward into massive, unweathered marble extending to a depth of 445 ft. The marble is underlain by fine-grained amphibolite and biotite gneiss to a depth of at least 530 ft below land surface (total hole depth). Contact depths were confirmed by geophysical logs (Fig. 6). Megascopic appearance plus petrographic analyses indicate typical Baltimore Gneiss lithologies comprising pyroxene-bearing amphibolite, hornblende biotite gneiss, and migmatite biotite gneiss (Fig. 6 and Table 2). The dip of the foliation in all cores is fairly consistent, about 30° to 45°. Cores were not oriented, but it was assumed that directions of dip are to the southeast, the same as that observed in nearby outcrops of both Wissahickon and Baltimore Gneiss.

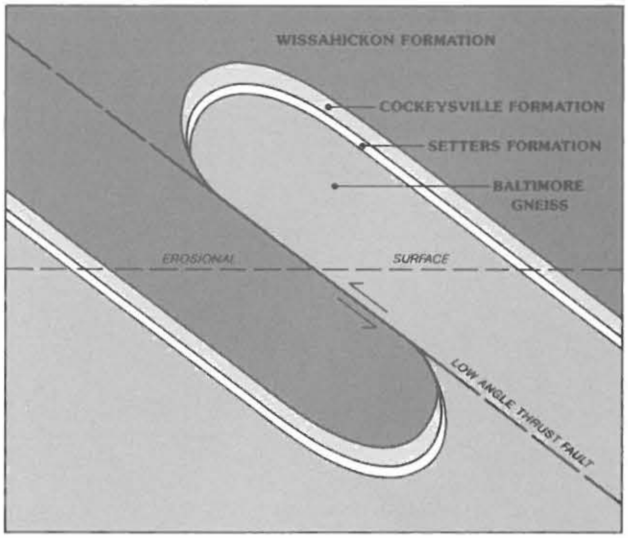


Figure 12. Basic scheme for structural relations in the Delaware-Pennsylvania Piedmont.

In the valley of Mill Creek, south of the outcrop area, the Cockeysville is overlain by a thin cover of Wissahickon. Drill hole data indicate that the Cockeysville occurs in well Bb44-9, 900 ft south of the outcrop area (Fig. 21), at a depth of 88 ft below land surface (152 ft above sea level). In well Bb44-22, which is located about 1,500 ft south of the Cockeysville outcrop in Hockessin, carbonate rock was tentatively identified from geophysical logs at about 80 ft below land surface (152 ft above sea level). The 100-ft deep core hole (Bb44-30) was drilled immediately adjacent to Bb44-22 as part of this study and confirmed that the top of the marble is 82 ft below land surface (150 ft above sea level) (Fig. 15). Geophysical logs also indicate that the marble is about 58 ft thick (82-140 ft below land surface). A single bottom-hole core in Bb44-22 from 291-297 ft indicates that the Cockeysville is underlain by the Wissahickon. The top Wissahickon-Cockeysville contact at 82 ft appears to be locally fault bounded and is marked by a thin mylonite zone, slickensides, and clay gouge. The boundary between calcareous and non-calcareous rocks is abrupt and occurs about one foot below the gouge. The bottom contact was not cored.

Field Observations

The Wissahickon underlies an area northwest of Hockessin on either side of Lancaster Pike (Plate 1). Outcrops can be observed along McGovern Road, in Wellington Hills, and on the north side of the development of Holly Knoll. The interpretation of this occurrence as a broad minor fold implies that Cockeysville underlies the Wissahickon in a normal sequence. Carbonate rocks crop out immediately to the east in the narrow north-south trending valley extending into Pennsylvania and may extend west beneath the Wissahickon cover as well. The nature of the western contact in this small area of Wissahickon is unclear as no outcrops were found along the presumed location of the contact.

Just north of the Delaware-Pennsylvania line at the intersection of Chandler Mill and Kaolin roads, the Wissahickon is exposed in a hillside and dips southeast beneath the Baltimore Gneiss with no evidence of any intervening Cockeysville (cross-section A-A′). In other nearby exposures, pegmatites and quartz veins are abundant between the contact of the Wissahickon Formation and Baltimore Gneiss and serve to delineate the northern boundary of the Baltimore Gneiss. This suggests that a thrust exists along the northwest side or leading edge of the nappe structure.

Gravity and Magnetics

Because of the short station spacing, the Bouguer gravity map of the area (Fig. 16) is strongly influenced by local structure and density changes at shallow depths. Several interpretations of the gravity data were made with the aid of a two-dimensional modeling program written for a personal computer. The interpretation shown for gravity cross-section GC-GC′ (Fig. 17) is generally typical of other modeled sections. Cross-section GC-GC′ is coincident with geologic cross-section B-B' (Fig. 14). Rock density values were compiled from the literature (Chapin, 1981; Muller and Chapin, 1984; Eisner, 1986) and from unpublished data. Density measurements from borehole gamma density logs run during this study were too variable to be useful for gravity modeling.

Any number of structural interpretations is possible based on the gravity data alone, but the interpretations shown are those that best seem to fit the borehole and outcrop observations.

An exception to the magnetic pattern that defines the Mill Creek Dome is the deep magnetic low centered about 2,500 ft southeast of the southwestern edge of the Cockeysville outcrop area near Hockessin (Fig. 18). The anomaly is thought to be due mainly to Baltimore Gneiss with thin overlying Cockeysville and Wissahickon rocks (cross-sections B-B′ and C-C′, Fig. 14). If the anomaly is caused only by the presence of Cockeysville, the Bouguer gravity values would show a significant increase over the area of the magnetic low, but they do not.

Pleasant Hill Area

The structure is more complicated in the Pleasant Hill valley where interpretations must account for the "upside-down" sequence in which the Setters overlies the Cockeysville and the Wissahickon overlies the Setters. The marble terminates sharply against the Wissahickon on the northwestern side of the valley. Our interpretation, presented in section D-D′ (Fig. 14), shows the Wissahickon faulted over the Setters and Cockeysville.

Borehole Data

About 1,300 ft south of the southern edge of the Cockeysville in Pleasant Hill valley, carbonate rocks were penetrated in test well Cb13-11 (Fig. 14) from 434 ft to about 448 ft below land surface. The driller's log indicates it is both overlain and underlain by "schist." From the information available it is not possible to determine if the underlying schist is part of the Wissahickon Formation or is the calc-schist facies of the Cockeysville.

An exploratory test well for water, well Cb13-16, was drilled to a depth of 580 ft near the southern contact of the Cockeysville Formation (Figure 14). Marble, calc-schists, and pegmatites belonging to the Cockeysville Formation were encountered from near land surface to 490 ft. Rocks encountered between 490 ft and 550 ft were identified pertrographically as a feldspathic gneiss typical of the Setters Formation. Rocks resembling lithologies in the Baltimore Gneiss were encountered between 550 ft and 580 ft.

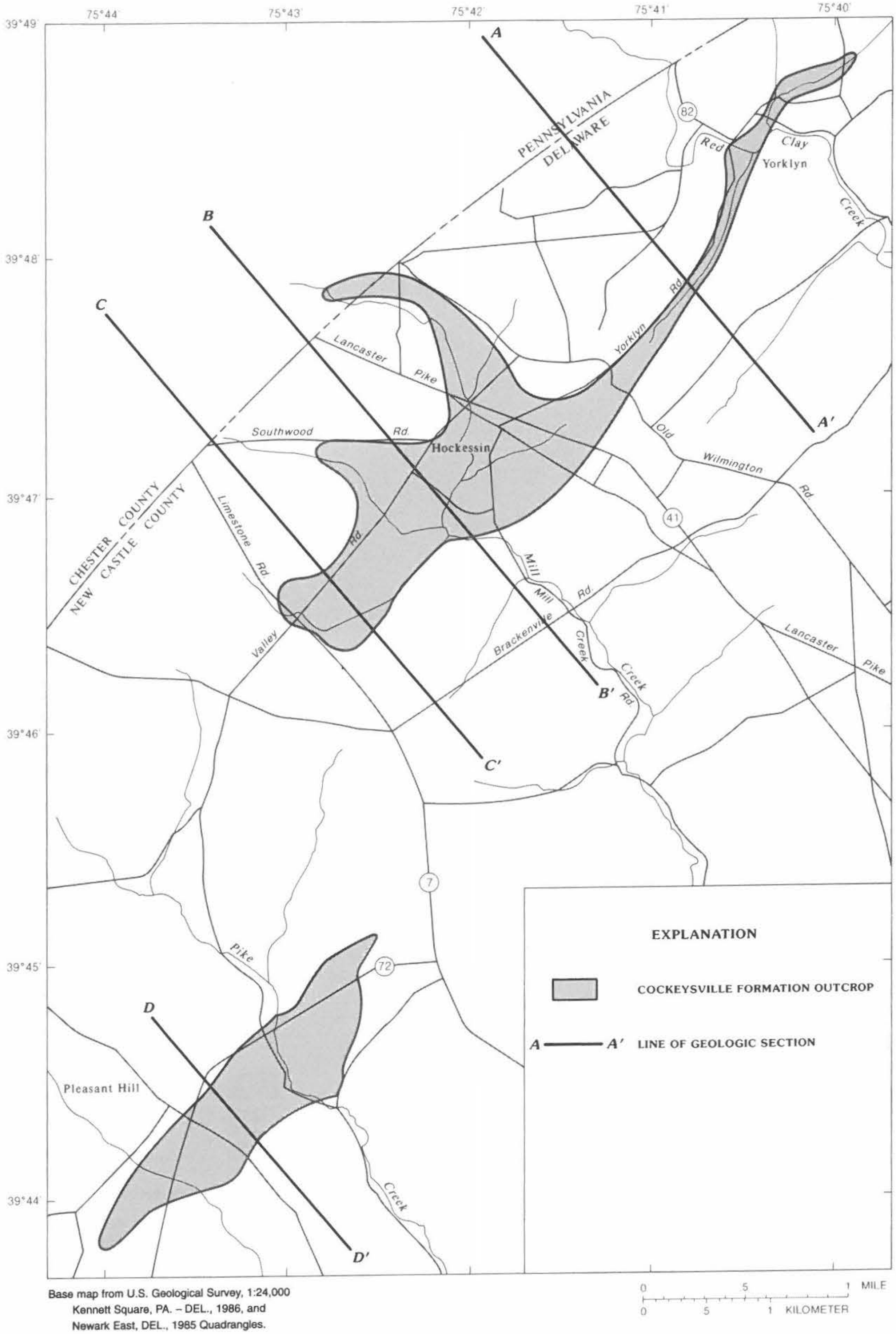


Figure 13. Map showing locations of cross-sections.

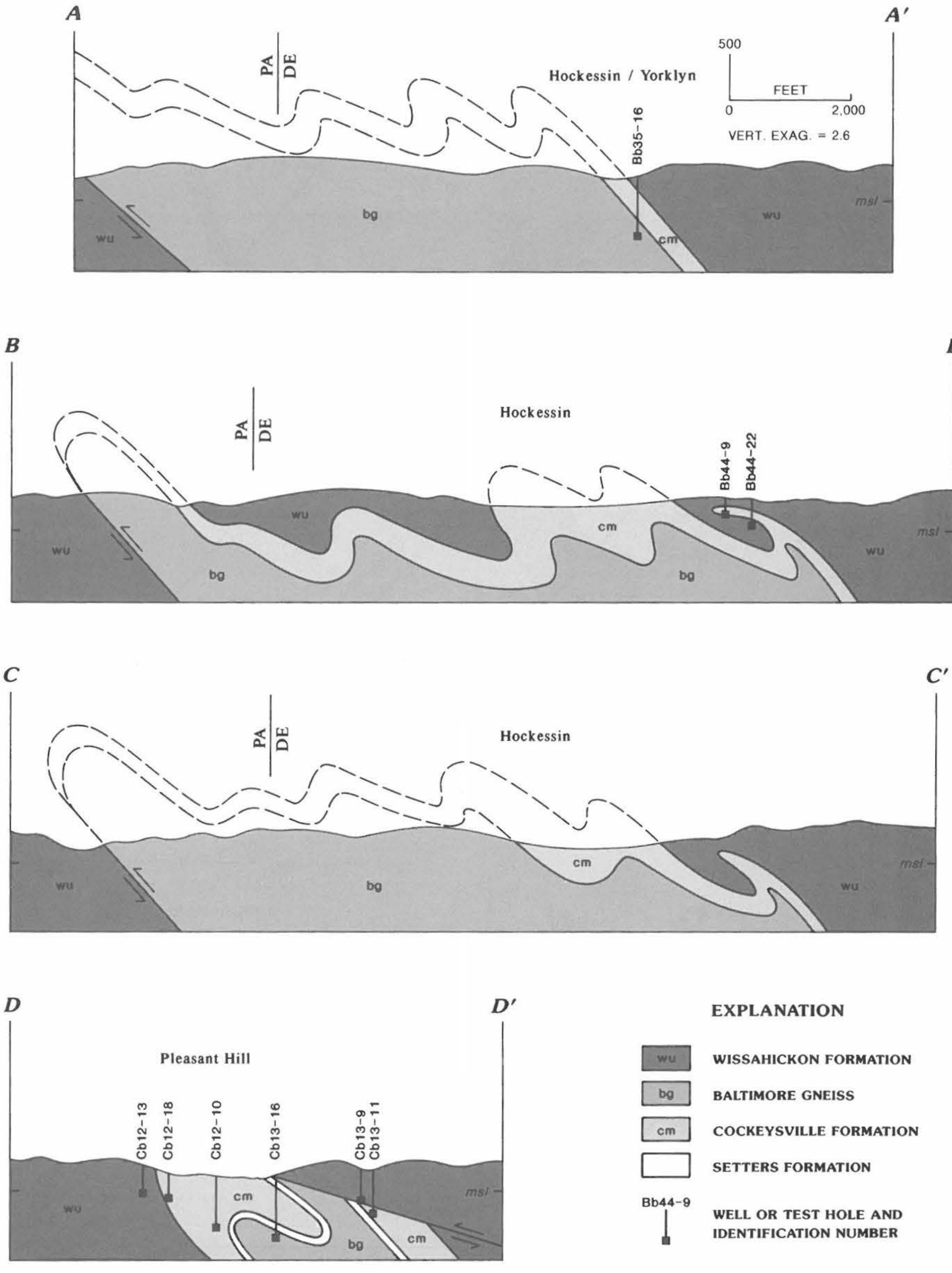


Figure 14. Cross-sections A-A′, B-B′, C-C′, and D-D′ in the Hockessin and Pleasant Hill areas. Locations are shown on Figure 13.

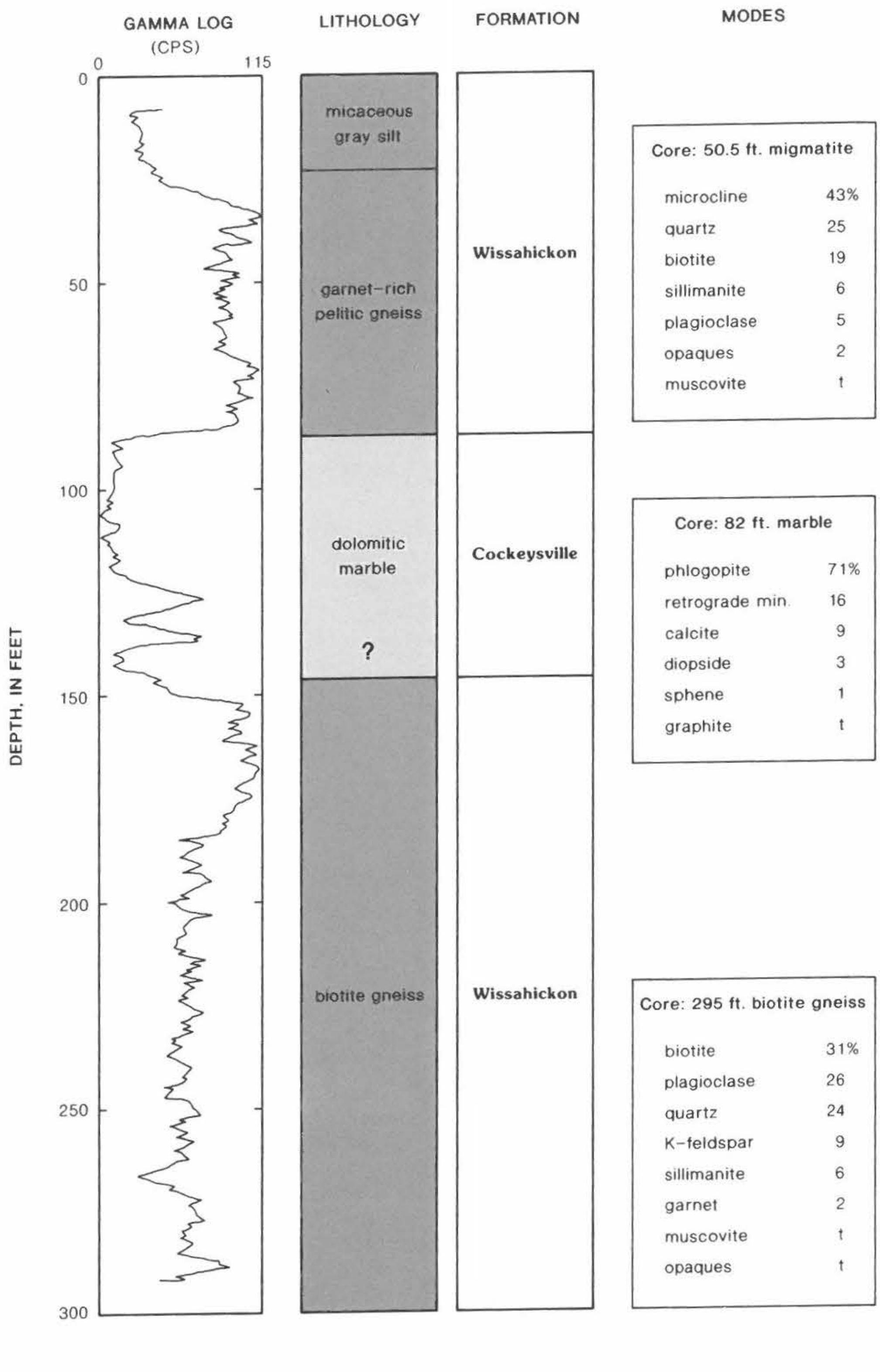


Figure 15. Descriptive and gamma-ray logs, composite for test holes Bb44-22 and Bb44-30.

Figure 16. Bouguer gravity map of the Hockessin area (gravity values in milligals).

Gravity and Magnetics

Data were not sufficient to construct a gravity model of Pleasant Hill valley. A residual gravity map was not attempted because of the uncertainties imposed by large scale differences between regional gravity maps and the map of the study area.

A magnetic low, approximately coincident with the Cockeysville outcrop in Pleasant Hill valley, indicates that the bulk of the carbonate rocks and any underlying Baltimore Gneiss is centered beneath the valley (Fig. 18). Porter (1976), using aeromagnetic data, modeled the valley as a symmetric anticline with Cockeysville resting directly on Baltimore Gneiss. The general configuration and distribution of rock types shown in section D-D′ (Fig. 14) is compatible with that shown in Porter's model although they differ in detail. The Baltimore Gneiss does not crop out in the Pleasant Hill area, but is inferred to be present at depth.

Structural Relations in the Mill Creek Dome

In outcrop, the Mill Creek Dome consists of three separate structures, the Hockessin-Yorklyn anticline, the Pleasant Hill anticline, and the Landenberg anticline (Fig. 19). Modeling suggests that Hockessin-Yorklyn and Landenberg uplifts were originally one continuous anticline

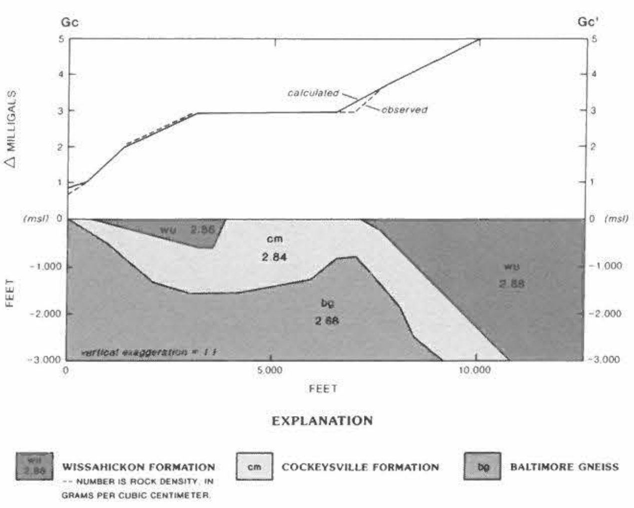


Figure 17. Gravity model across the Hockessin-Yorklyn area.

that was separated from the Pleasant Hill anticline by a syncline. Both anticlines trend northeast, parallel to the regional strike which is approximately N40°E, and are overturned to the northwest. They are probably nappes with northern limbs cut off by thrusts (Wagner and Srogi, 1987).

Thompson (1981) recognized that the map pattern of the marble in Pleasant Hill valley indicates a doubly plunging anticline probably caused by warping of the original anticline. Orientation of the second anticlinal axis is approximately normal to the regional trend. The outcrop patterns of the Hockessin-Yorklyn-Landenberg anticline suggest they are warped around similar anticlinal axes. The accompanying second order synclines occur between the Landenberg and Hockessin-Yorklyn uplifts and where the Wissahickon is exposed north of Hockessin. A strike-slip fault, with an unknown component of dip slip, offsets the west end of the Hockessin-Yorklyn structure. A thick weathered zone occurs along this fault.

The Landenberg area of the Mill Creek Dome has not been recently mapped or studied. The data used for the map (Fig. 19) is from Bascom and Stose (1932), Kuhlman (1975), and brief reconnaissance field work.

SUMMARY AND CONCLUSIONS

Field investigation accompanied by test drilling in the Cockeysville Formation resulted in slight boundary changes to the Woodruff and Thompson (1972) geologic map. In the Hockessin-Yorklyn area, the Cockeysville Formation boundary was moved to include the area along Southwood Road and contracted slightly along Limestone Road. Rocks underlying the ridge north of the Hockessin-Yorklyn valley have been correlated with the Baltimore Gneiss in Maryland and mapped as Grenville basement. In addition, the Setters Formation, the basal unit of the Glenarm Series, has been identified for the first time in the Delaware Piedmont. It is mapped as a thin layer overlying the marble along the southeastern margin of the Pleasant Hill valley.

The dominant lithologies within the Cockeysville Formation are coarsely crystalline dolomite marble, calcite marble, and micaceous calc-schist. The dolomite marbles are usually pure, being composed of 85 to 100 percent dolomite. The calc-schists contain calcite and over 50 percent silicate minerals. The index minerals tremolite, olivine, and diopside occur in the calcite marble and calc-schist, and indicate high temperature metamorphism.

The thickness of the Cockeysville in both the Hockessin-Yorklyn Valley and Pleasant Hill Valley is estimated to be between 400 and 800 ft. Where it is exposed at the surface it is weathered, sometimes to depths of more than 150 ft. Geophysical logs show that beneath the weathered zone the marble contains large solution cavities. These cavities act as important storage reservoirs for ground water. The weathered zone is an important aquifer and a source of recharge to the solution cavities in the unweathered marble beneath. The marble lying beneath the Baltimore Gneiss and the Wissahickon is primarily massive and impermeable, and, except for local fractures, stores little ground water.

Structurally, the Hockessin-Yorklyn valley lies on the upper limb of a large anticline or nappe that is cored by Baltimore Gneiss and overturned to the northwest. Test wells drilled on the southeast side of the valley found Baltimore Gneiss, Cockeysville, and Wissahickon dipping moderately to the southeast in a normal stratigraphic sequence. Southwest of Hockessin the Cockeysville marble ends abruptly against a dextral strike-slip fault. There is no evidence to suggest that the Cockeysville in the Hockessin-Yorklyn area is hydrologically connected to the Cockeysville in the Pleasant Hill area.

In the Pleasant Hill valley an inverted sequence of Setters and Cockeysville is overlain by the Wissahickon Formation. This inverted sequence is modeled as the overturned limb of a basement-cored anticline or nappe that is overthrust by Wissahickon rocks. This model requires a faulted contact between the lower Glenarm units and the Wissahickon.

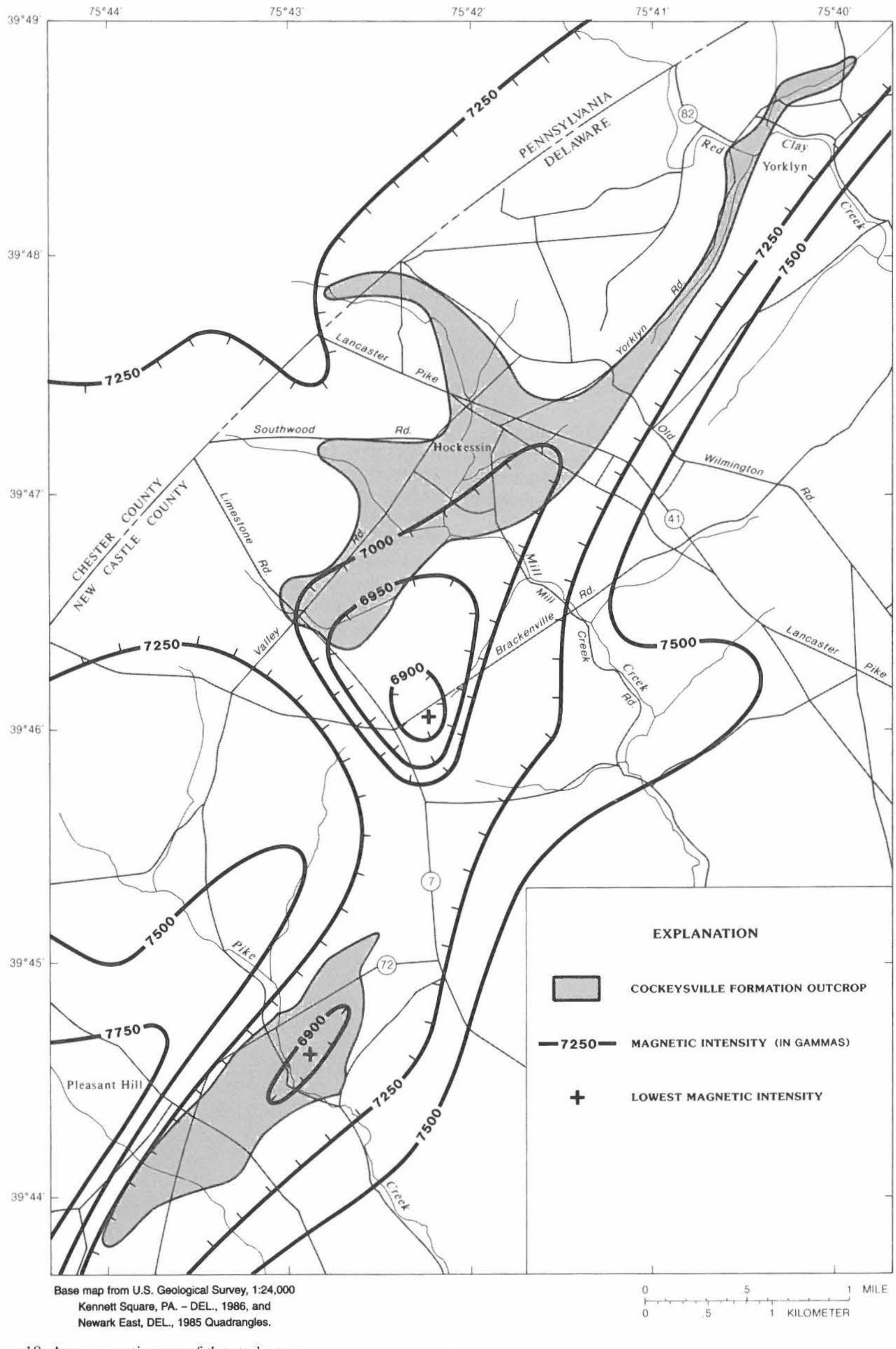


Figure 18. Aeromagnetic map of the study area.

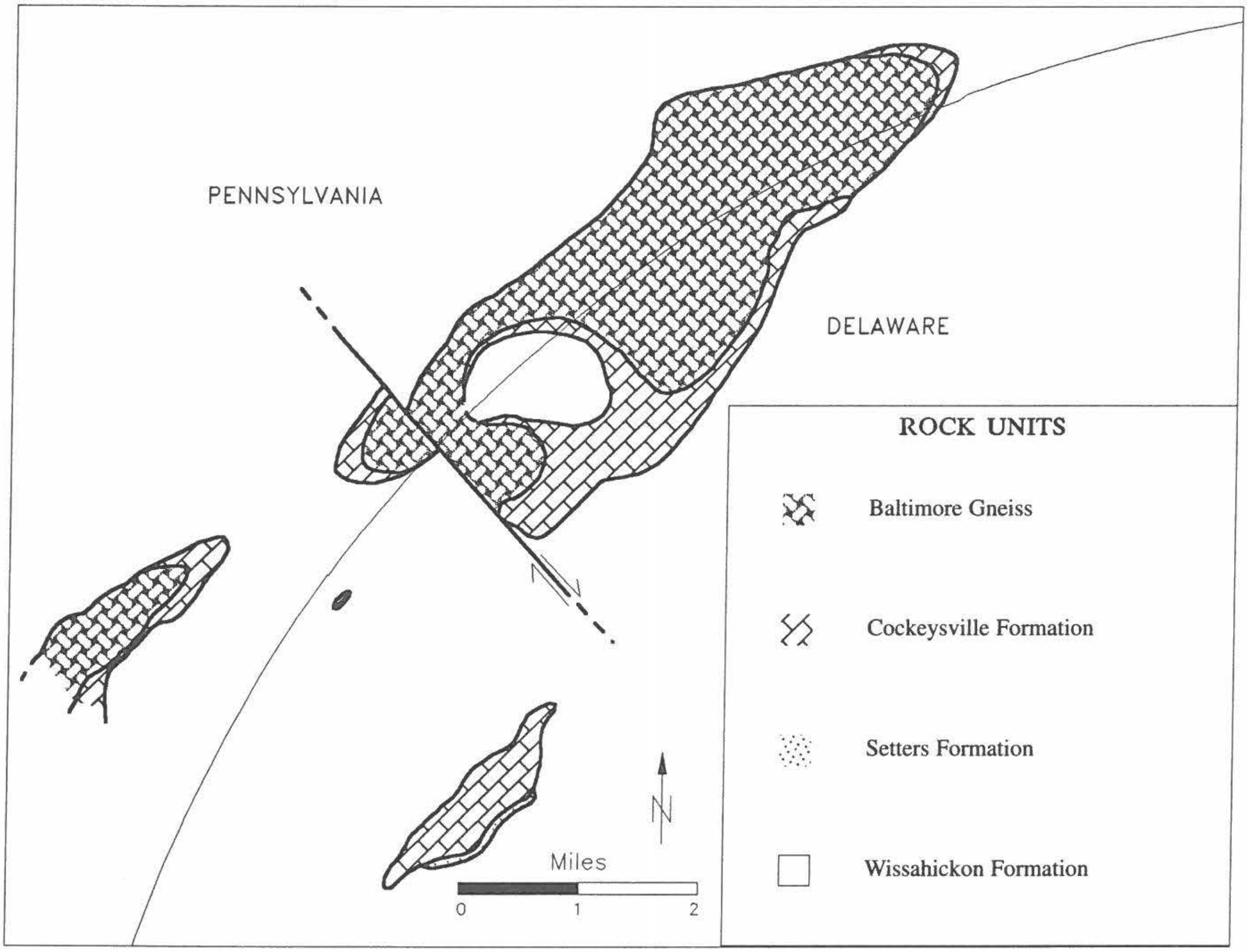


Figure 19. Generalized geologic map of the Mill Creek dome.

GEOHYDROLOGY OF THE HOCKESSIN AREA WITH EMPHASIS ON THE COCKEYSVILLE AQUIFER

William H. Werkheiser

with records of wells and water-quality tables by Deborah A. Bringman

INTRODUCTION

The area of investigation was limited to the outcrop area of the Cockeysville Formation in the Hockessin-Yorklyn area and the drainage areas of the streams that flow across the formation – Mill Creek and two unnamed tributaries to Red Clay Creek (Fig. 2). This area comprises 5.6 mi^2, of which 3.7 mi^2 is in the Mill Creek Basin and 1.9 mi^2 is in the Red Clay Creek Basin.

Land use in the study area is predominantly residential on the basis of interpretation of 1989 aerial photographs. Forty-two percent of the land is used for residential purposes, 31 percent for pasture or crops, 25 percent is covered by forest, and about 2 percent of the study area is urban land.

Topographic relief in the area is about 230 ft; elevations are between 170 ft to 400 ft above sea level. The topography strongly reflects the underlying geology; carbonate rocks of the Cockeysville Formation underlie the valleys and noncarbonate metamorphic and igneous rocks comprise the ridges.

Precipitation in the area is moderate, averaging 46.07 in. per year at Porter Reservoir near Wilmington, Delaware (located 8 mi east of Hockessin), from 1961-90. For any given year, precipitation can vary significantly from the average (Fig. 20); annual precipitation for the period ranged from 33.60 in. in 1968 to 60.35 in. in 1983. For one half of the years, annual precipitation ranged from 40.47 to 53.55 in. Overall, precipitation amounts were greater in the 1970s than the 1960s or the 1980s.

The predominant use of water in the study area is for public supply, with ground water being the only source. Ground-water withdrawals in this portion of the Piedmont are in the Mill Creek Basin, where all of the public-supply wells in the study area are located (Fig. 21). Most of the area is served by public sewers and water. Ninety percent of the residences are served by public water and 10 percent are supplied by individual wells (R. P. Hansen, Water Resources Agency for New Castle County, oral comm., 1992). The amount of ground water withdrawn from the study area is not directly related to water use because the water-distribution network in this region is capable of importing water to or exporting water from the study area. Average daily ground-water withdrawals for public water

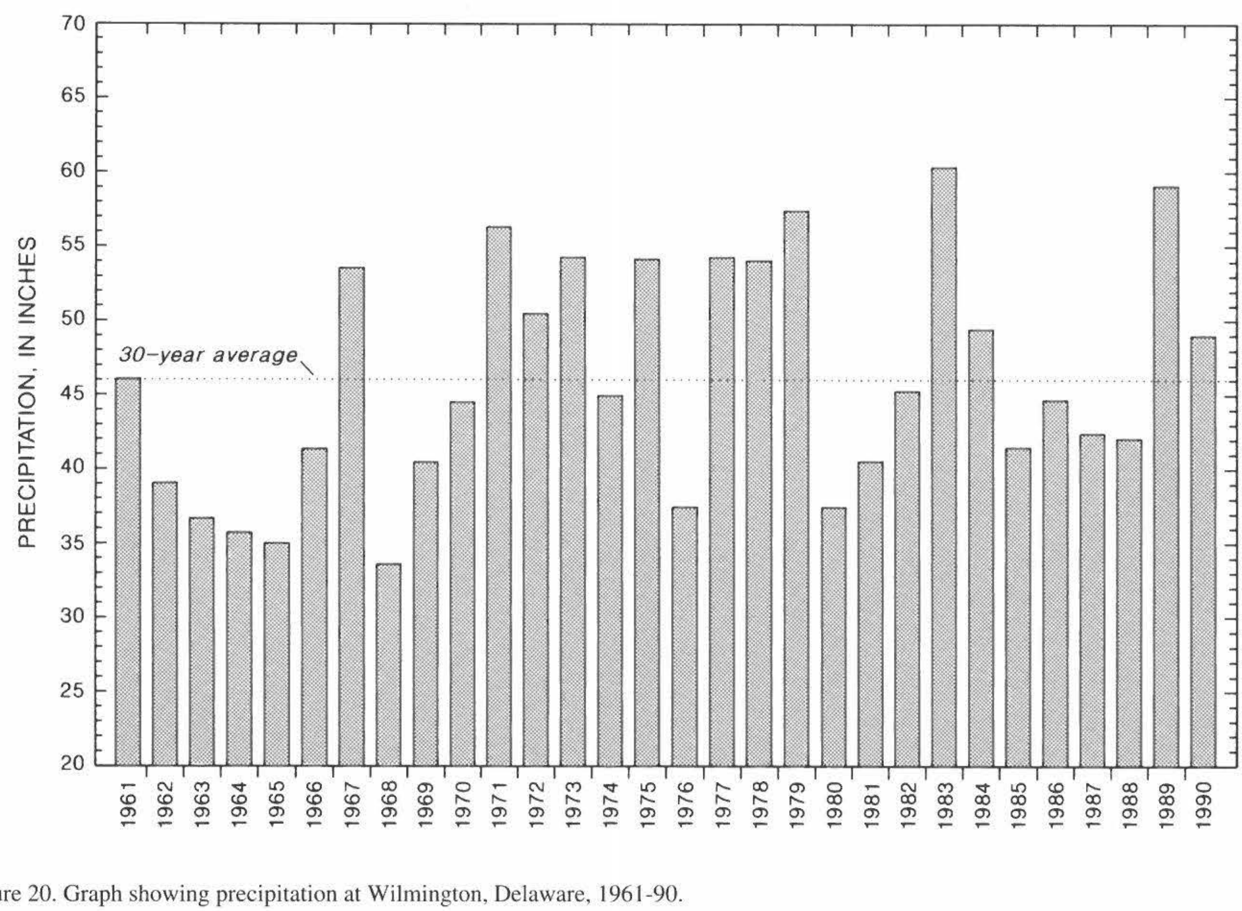


Figure 20. Graph showing precipitation at Wilmington, Delaware, 1961-90.

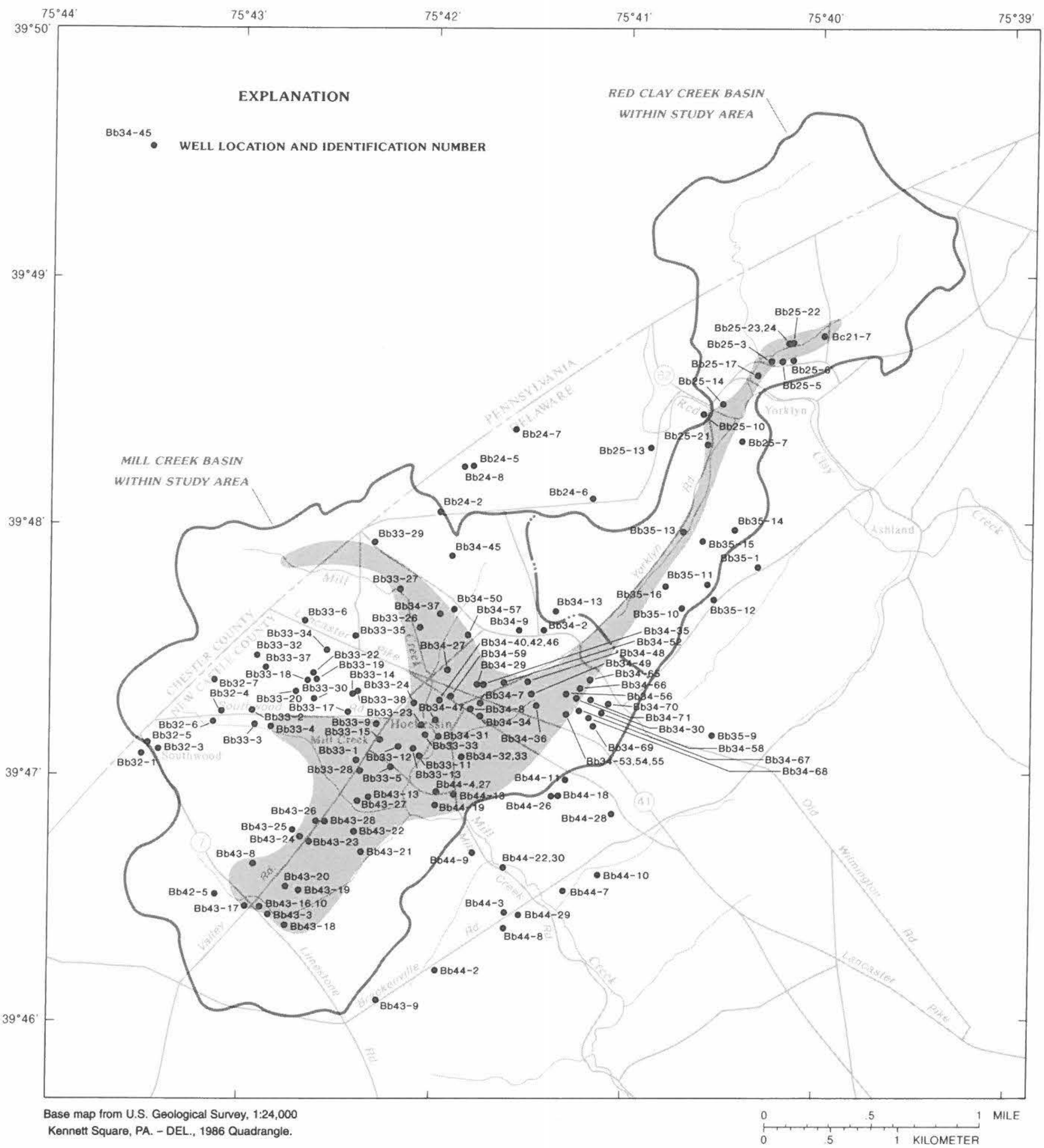


Figure 21. Map showing well locations in the Hockessin area.

supply are shown in Figure 22. Overall, withdrawals declined during 1975-90, with the largest average daily withdrawal occurring in 1977 and the smallest in 1988. The downward trend does not reflect declining water demand in the area, but more likely reflects the effects of withdrawal and drawdown limits on public supply wells resulting from management of the resource.

Locations of streamflow, precipitation, ground-water level, and water-quality data-collection sites are shown on Figure 23. Streamflow data were collected continuously at a gage constructed on Mill Creek, near the contact of the Cockeysville and Wissahickon formations. In addition to continuous monitoring of streamflow, base flow was periodically measured at 30 sites upstream of the gage. Precipitation was measured at seven sites in the study area. Precipitation gages were located to provide uniform areal distribution within the limits of site availability and accessibility. Ground-water levels in 56 wells were measured and water samples from 29 of these wells were collected for chemical analysis. Stream water from six sites was also chemically analyzed. As was done with the precipitation network, sites for the ground-water level and water-quality

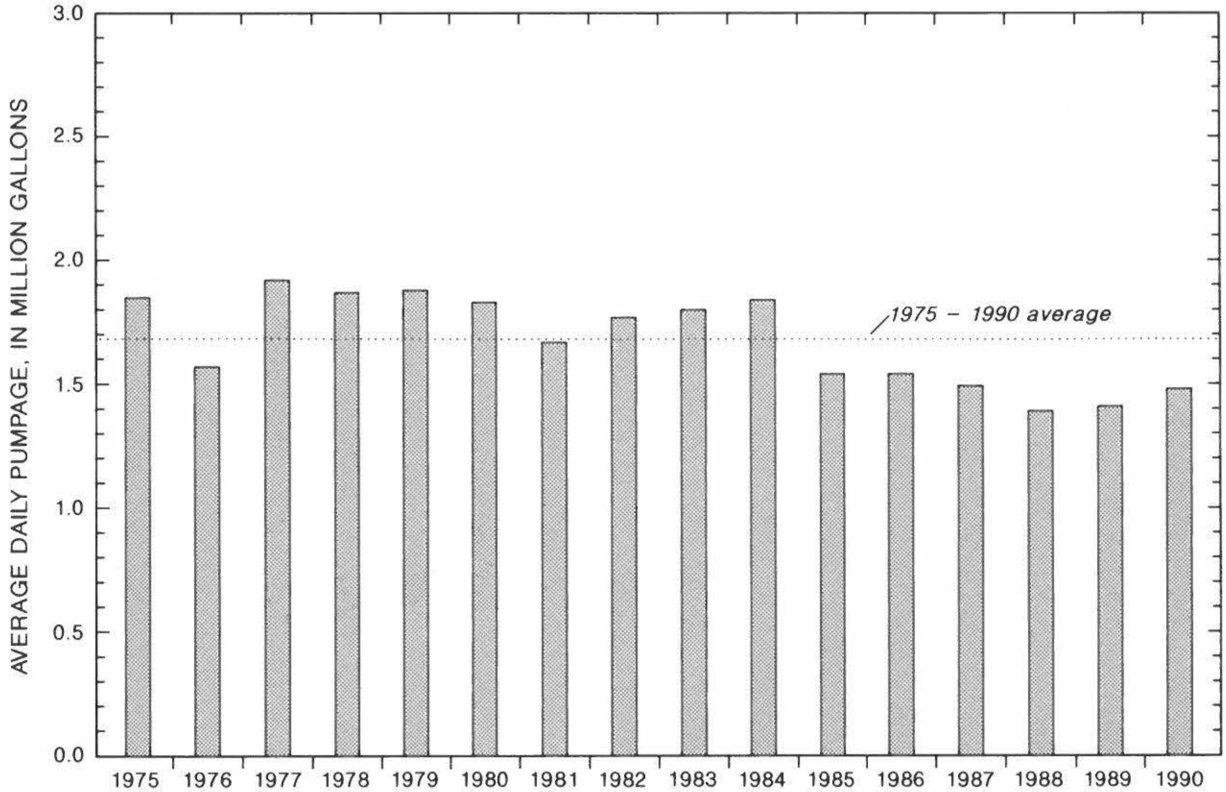


Figure 22. Graph showing ground-water withdrawals in the Hockessin area, 1975-90.

network were selected to provide uniform areal distribution within the limits of site availability and accessibility.

GEOHYDROLOGY

The geohydrology of the Hockessin area comprises the three-dimensional geometry of aquifers in the area, the water-transmitting and water-storing properties of the aquifers, ground-water-flow characteristics, and ground-water quality. Ground-water flow in the area is described in terms of boundaries of the flow system, recharge, discharge, and direction of flow as inferred from ground-water levels.

Geohydrologic Framework and Ground-Water Occurrence

Woodruff and Plank (this volume) describe the geologic units and the associated geologic framework. The geologic units underlying the study area are, from oldest to youngest, Baltimore Gneiss, Cockeysville Formation, and Wissahickon Formation. The Setters Formation, which generally occurs stratigraphically between the Baltimore Gneiss and the Cockeysville Formation, has not been found in the Hockessin area, but has been identified in Pleasant Hill valley to the west (Woodruff and Plank, this volume). Pegmatites are found throughout the study area, and could be continuous locally to inhibit lateral and vertical ground-water flow.

The Baltimore Gneiss and the Wissahickon Formation are noncarbonate rocks that have similar water-yielding characteristics (McGreevy and Sloto, 1976). In this report, therefore, these two units are treated as one geohydrologic unit and referred to as the noncarbonate aquifer (Table 6). The Cockeysville aquifer is that part of the Cockeysville Formation that can transmit significant quantities of water through fractures and solution openings in the rock. Woodruff and Plank (this volume) report that the Cockeysville Formation is relatively unfractured where it is overlain by Baltimore Gneiss or Wissahickon Formation. For this report, therefore, the areal extent of the Cockeysville aquifer corresponds to the mapped outcrop area of the Cockeysville Formation (Plate 1).

The noncarbonate and Cockeysville aquifers consist of both regolith and fractured bedrock. Regolith is a general term for the layer or mantle of unconsolidated, weathered material that overlies bedrock. Although regolith typically has different hydrologic characteristics from fractured rocks, the regolith and underlying rock are considered part of the same aquifer because they respond to stresses as a single unconfined aquifer. In the Cockeysville aquifer, the regolith is composed of interbedded silt and clay, and of

TABLE 6

Geologic and geohydrologic units in the Hockessin area.

Lithostratigraphic Unit	Geohydrologic Unit
Wissahickon Formation	Noncarbonate aquifer
Cockeysville Formation	Cockeysville aquifer
Baltimore Gneiss	Noncarbonate aquifer

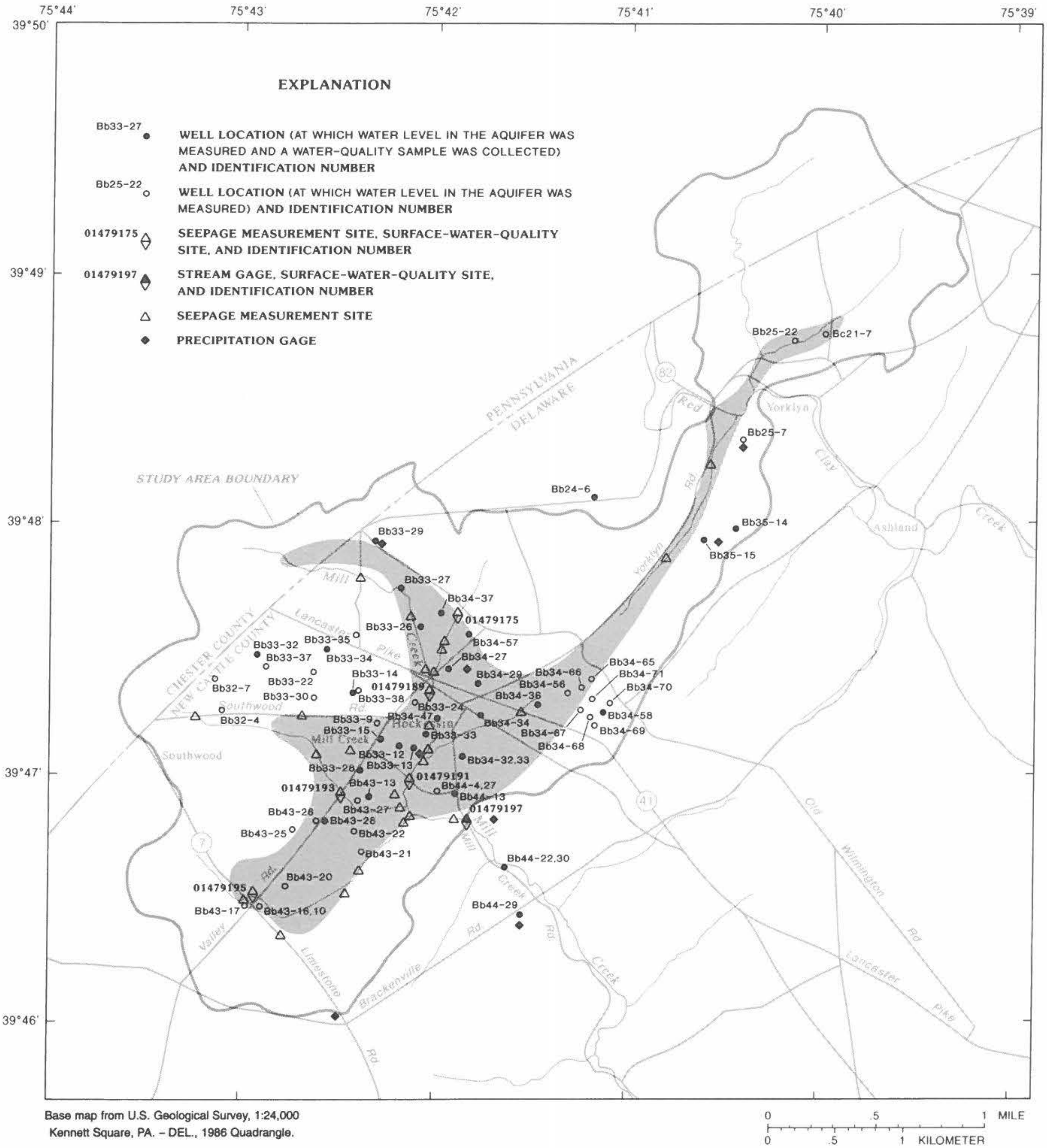


Figure 23. Map showing data-collection sites in the Hockessin area.

angular, calcareous sand which is formed by weathering and separation of dolomite cleavage twins in the marble (Leis, 1975). Typically, silty clay in the upper part of the regolith grades into angular, poorly sorted, coarse-to-medium grained sand in the lower part (Woodruff and Plank, this volume). The contact between regolith and competent rock is transitional; driller's reports often list alternating zones of weathered and unweathered marble. Reported thickness of regolith ranges from 0 to 155 ft and is highly variable over short distances. The regolith functions as a storage reservoir that receives recharge and slowly releases water to fractures in the underlying rock. Storage capacity in the regolith is greater than in fractured rock because water occupies interstices between individual mineral grains rather than fractures in the rock matrix (Heath, 1983, p. 46).

In unweathered parts of the aquifers, ground water is stored in and flows through discrete fractures and solution openings in the rock. Dissolution is predominately associated with fractures. The location, density, continuity, attitude, and size of the fractures are the primary controls on the presence of ground water in the unweathered parts of the aquifers. Dissolution also occurs along bedding in the for-

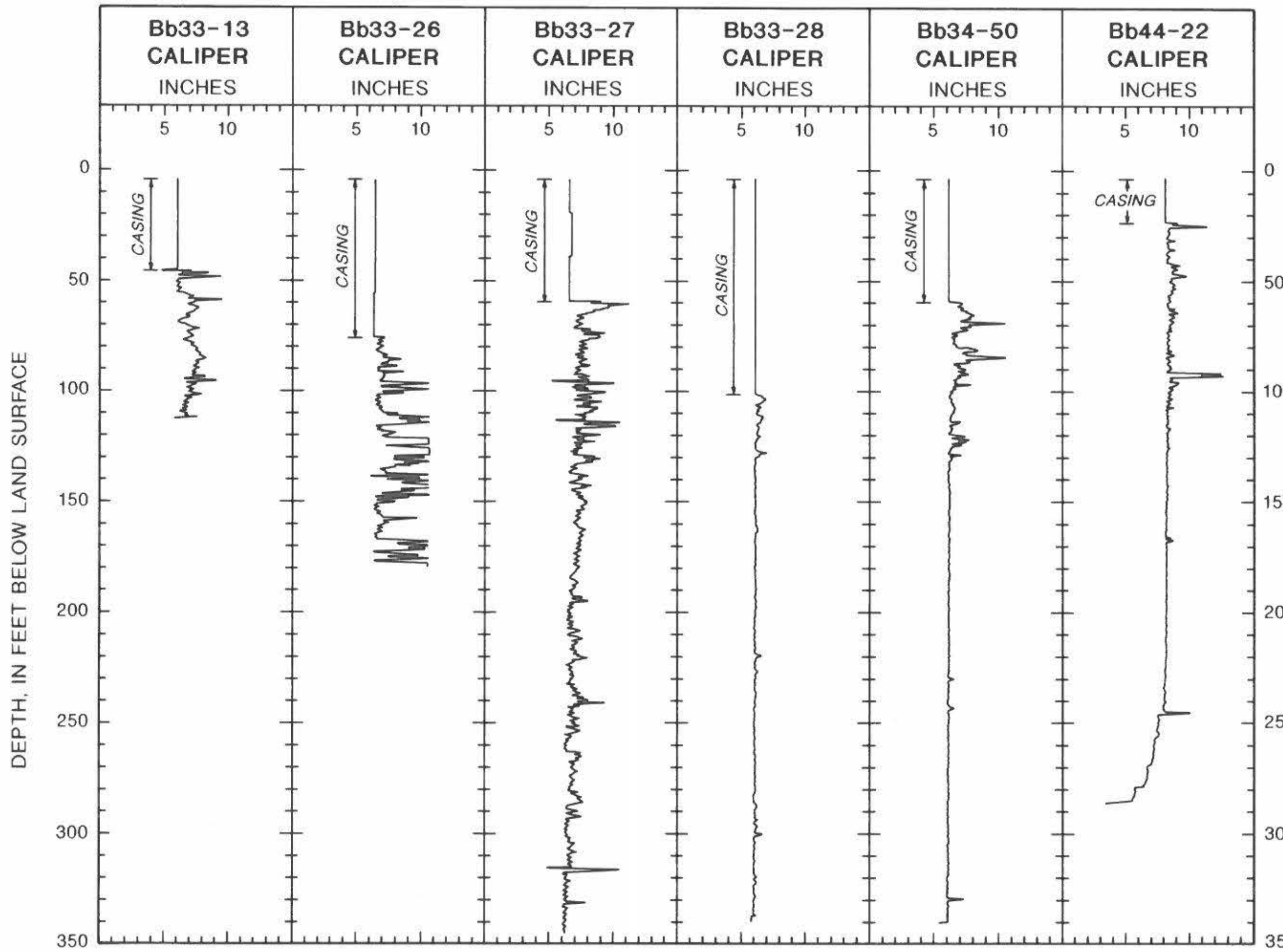


Figure 24. Caliper logs for wells in the Cockeysville aquifer.

mation. Caliper logs showing borehole diameter for wells drilled into the Cockeysville aquifer are shown in Figure 24. Deviations on the caliper log indicate where the well bore intersects fractures or solution openings. Below this zone, the character of fracturing differs. In some wells (Bb33-13, Bb33-26, and Bb33-27) the entire thickness of the aquifer that has been penetrated is highly fractured, whereas in other wells (Bb33-28, Bb34-50, and Bb44-22) only a few fractures are encountered below the transition zone. Fractures in the aquifer are commonly enlarged by dissolution of carbonate rocks, forming highly permeable conduits that can store and transmit large quantities of water. Because ground-water flow in fractured rocks is greatly affected by fracture characteristics, determining directions of ground-water flow is more difficult in fractured-rock aquifers than in unconsolidated aquifers.

Ground water usually can flow more rapidly through fractured rock aquifers than through unconsolidated aquifers because resistance to flow along fracture walls is usually lower than resistance to flow around individual mineral grains. A series of temperature logs recorded from April through July 1990 in well Bb33-28 is shown in Figure 10. The logs from April indicate strong temperature deviations in the depth range of 225-330 ft. The water temperature in this section of the well is colder than the ambient ground-water temperature. This suggests that recharge to the aquifer is relatively rapid and may be coming from streambed seepage from a nearby stream or from sinkholes in the area. The nearest possible surface-water source is about 1,500 ft from the well. If this is the source, water from the stream would have to travel this distance rapidly enough to maintain the observed temperature difference. Also, the temperature deviation is short-lived (approximately 3 weeks), indicating that water is flowing rapidly through the aquifer.

A generalized hydrogeologic section through the study area is shown in Figure 25. The Cockeysville aquifer occupies the valley and is bordered by the noncarbonate aquifer. Several investigators have noted the presence of pegmatites near the contact of the Cockeysville and noncarbonate aquifers (Leis, 1975; Yancheski, 1985). Although pegmatites were not encountered in the two wells that penetrate both the Cockeysville and noncarbonate aquifers (Bb35-16, Bb44-22), one is included on Figure 25 because of the potential effect on the ground-water-flow system. Where present, the clay weathering products associated with pegmatite could substantially inhibit the amount of ground-water flow from the noncarbonate aquifer to the Cockeysville aquifer.

The water-producing capabilities of aquifers are described in terms of well yield, specific capacity, and hydraulic properties. Well yield is usually determined at the time a well is drilled and is reported in units of gallons per minute. Information on well yield alone usually does not adequately characterize the water-producing capacity of an aquifer. Yields given in well-completion reports depend on

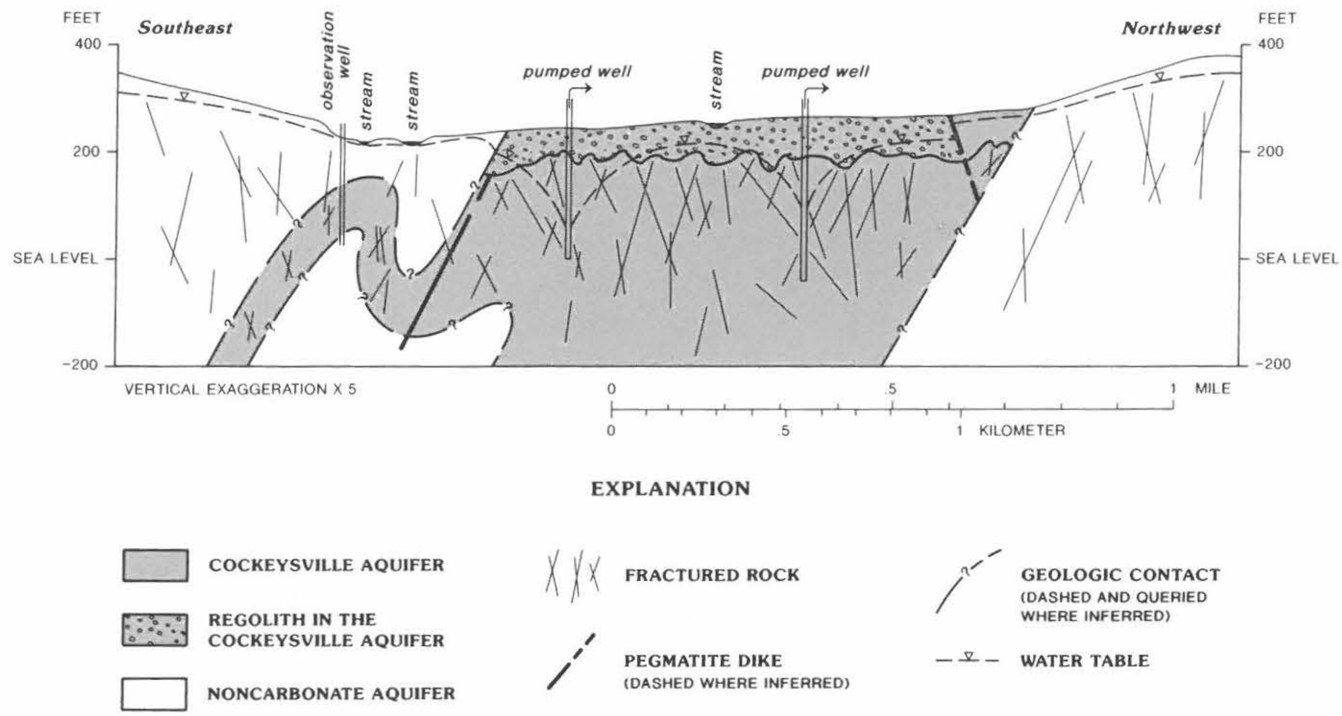


Figure 25. Generalized hydrogeologic section of the Hockessin area.

the method of well construction, type of pump used, the well yield required, duration of pumping period, and drawdown allowed during the yield test. A better means for comparing the water-producing characteristics of wells is specific capacity, which is calculated by the well discharge divided by the water-level drawdown in the well at the end of the yield test. Specific capacity more accurately reflects the hydraulic characteristics of the aquifer, but is strongly affected by well construction. Two properties that are better than specific capacity for describing the hydraulic characteristics of an aquifer are transmissivity and coefficient of storage. Transmissivity is defined as the rate that water is transmitted through a unit width of the aquifer under a unit hydraulic gradient. The storage coefficient of an aquifer is defined as the volume of water the aquifer releases from or takes into storage per unit surface area per unit change in head. In an unconfined aquifer, the storage coefficient is approximately equal to specific yield, which is defined as the ratio of the volume of water an aquifer will yield by gravity drainage to the total volume of the aquifer (Lohman, 1972). Because aquifer-test data are sparse for the study area, well yield and specific capacity are the primary indicators of water-producing capability of aquifers in the Hockessin area.

The noncarbonate aquifer has low water-yielding capability in comparison to the Cockeysville aquifer and is used only as a source for domestic supply. The reported yield of 38 wells in the aquifer ranges from 1 to 30 gal/min, with a median of 8 gal/min. Specific capacity of 28 wells ranges from 0.01 to 1.25 (gal/min)/ft of drawdown, with a median of 0.18 (gal/min)/ft of drawdown. No aquifer-test data are available for this aquifer in the study area.

The Cockeysville aquifer is the most productive aquifer in the Delaware Piedmont (Leis, 1975, p. 49) and supplies water to domestic, industrial, and public-supply wells. Reported well yields of domestic wells range from 3 to 40 gal/min (Appendix 3). Public-supply wells and industrial wells are designed to obtain large yields, and yields from these wells are probably more representative of maximum well yields available from the aquifer. Reported well yields for seven nondomestic wells range from 50 to 2,000 gal/min, with a median of 450 gal/min. Specific capacity of 17 wells in the Cockeysville aquifer ranges from 0.09 (gal/min)/ft of drawdown to 12.5 (gal/min)/ft of drawdown, with a median of 0.89 (gal/min)/ft of drawdown.

Hydraulic properties of the Cockeysville aquifer, as determined from aquifer-test data, are presented in Table 7. Transmissivity ranges from 940 to 6,820 ft^2/d. Storage coefficients that were calculated from observation well data range almost three orders of magnitude, from 4×10^{-2} to 8×10^{-5}, indicating the wide variability in the water-transmission and storage capabilities of the aquifer.

These aquifer values should be used with caution. Because of the analytical method used, water was assumed to flow through porous media rather than through discrete fractures even though most flow occurred in fractures. In fractured media, this assumption is valid only if the volume of aquifer affected during the test contains enough fractures for the aquifer to respond as if it were a porous medium. Furthermore, data were not available from a sufficient number of observation wells to evaluate the effect of anisotropy on the test data. The high values for the storage coefficient, in particular, could indicate that porosity of and groundwater flow in the fractured medium did not approximate that of a porous medium.

Moody and Associates (1975) and Leis (1975) report that aquifer-test data from well Bb44-13 and Bb34-29 indicate the presence of impermeable boundaries within the radius of influence of the pumped wells. The distance from Bb34-29 to the boundary, as calculated from the test data, is

TABLE 7

Transmissivites and storage coefficients for the Cockeysville aquifer, as determined from aquifer tests.
(gal/min = gallons per minute; ft^2/d = foot squared per day)

Pumped well	Date and duration of test	rate (gal/min)	Distance of observation well from pumped well, in feet	Method of analysis	Trans-missivity (ft^2/d)	Storage coefficient
Bb34-29	08/27/74 48 hours	744	622	Theis nonleaky artesian[1]	4,550	7×10^{-4}
				Cooper and Jacob semi-log[2]	5,080	6×10^{-4}
Bb34-33	04/02/74 48 hours	277	50	Cooper and Jacob semi-log[1]	1,560	8×10^{-5}
				Theis nonleaky artesian[1]	1,440	1×10^{-4}
				Cooper and Jacob semi-log[1]	1,000	5×10^{-4}
Bb34-33	04/02/74 48 hours	277	—	Cooper and Jacob semi-log[2]	1,600	—
Bb44-13	05/02/73 48 hours	400	—	Cooper and Jacob semi-log[1]	940	—
				Cooper and Jacob semi-log[2]	1,070	—
Bb44-13	05/02/73 145 hours	400	350	Hantush leaky artesian[3]	5,880	4×10^{-2}
Bb44-13	07/24/72 1680 hours	500	—	Cooper and Jacob semi-log[2]	1,700	—
Bb44-13	07/24/72 1680 hours	500	350	Hantush leaky artesian[3]	6,820	6×10^{-3}

[1]Analysis conducted by Moody and Associates, 1975.
[2]Analysis conducted by W. H. Werkheiser.
[3]Analysis conducted by W. M. Leis

similar to the distance from the pumped well to the mapped contact between the Cockeysville aquifer and adjacent noncarbonate units. The results of the analysis support the finding of Woodruff and Plank (this volume) that the Cockeysville aquifer is relatively unfractured, or at least that dissolution along fractures has not progressed to a large degree, beyond the outcrop area.

Cockeysville Aquifer

Because the Cockeysville aquifer is a major source of water supply for northern Delaware, knowledge of ground-water flow in the aquifer is required for management of the resource. The following sections describe the ground-water-flow system in terms of boundaries, recharge, discharge, and flow directions and water levels.

Boundaries

Ground-water flow in the Cockeysville aquifer is limited by lithologic and hydrologic boundaries. The areal extent of the Cockeysville Formation is shown in Plate 1. Although the Cockeysville Formation extends laterally in the shallow subsurface beyond its mapped contact with other formations (noncarbonate aquifers), the degree of fracturing and dissolution is greatest in the outcrop area (Woodruff and Plank, this volume). The lateral boundary of the Cockeysville aquifer, therefore, coincides with the formational contact shown on Plate 1.

A boundary within the Cockeysville aquifer is located in the northern extension of the aquifer in the Mill Creek Basin. In this area, there appears to be a structural feature that divides the Cockeysville aquifer. The presence of abandoned kaolin pits (kaolin is a weathering product of feldspars in pegmatite) and the large hydraulic-head differences indicate the presence of a hydrologic boundary in this area. Although some ground water probably flows across this boundary, the amount of flow is likely to be negligible.

Water levels in the northern extension of the Cockeysville aquifer and part of the aquifer in the Red Clay Creek Basin have not been affected appreciably by ground-water withdrawals (see "Flow Directions and Water Levels"). The northern extension of the Cockeysville aquifer and that part in the Red Clay Creek Basin are referred to as the unstressed part of the Cockeysville aquifer, and the remainder of the aquifer is referred to as the stressed part of the Cockeysville aquifer (Fig. 26).

The lower boundary of ground-water flow in the Cockeysville aquifer is not known. No wells are deeper than 530 ft; however, this probably reflects the practical limitations of drilling, rather than the lower limit of the flow system.

The upper boundary of ground-water flow is the water table. Its position is not static, but changes with time in response to natural events and human-induced stresses, such as recharge, ground-water withdrawals, and evapotranspiration.

Recharge

In this report, ground-water recharge refers to water that is added to the ground-water-flow system from external sources. There are three potential sources of recharge to the Cockeysville aquifer: areal recharge from infiltration of precipitation, infiltration of water from surface streams, and lateral flow of ground water from the surrounding noncarbonate aquifer.

Areal recharge from infiltration of precipitation is assumed to be uniform over the outcrop area of the aquifer, although infiltration capacity of soils and rock differ throughout the study area. For example, if precipitation falls on clayey soil that developed on pegmatites, water that did not infiltrate the soil could flow laterally until it encountered a more perme-

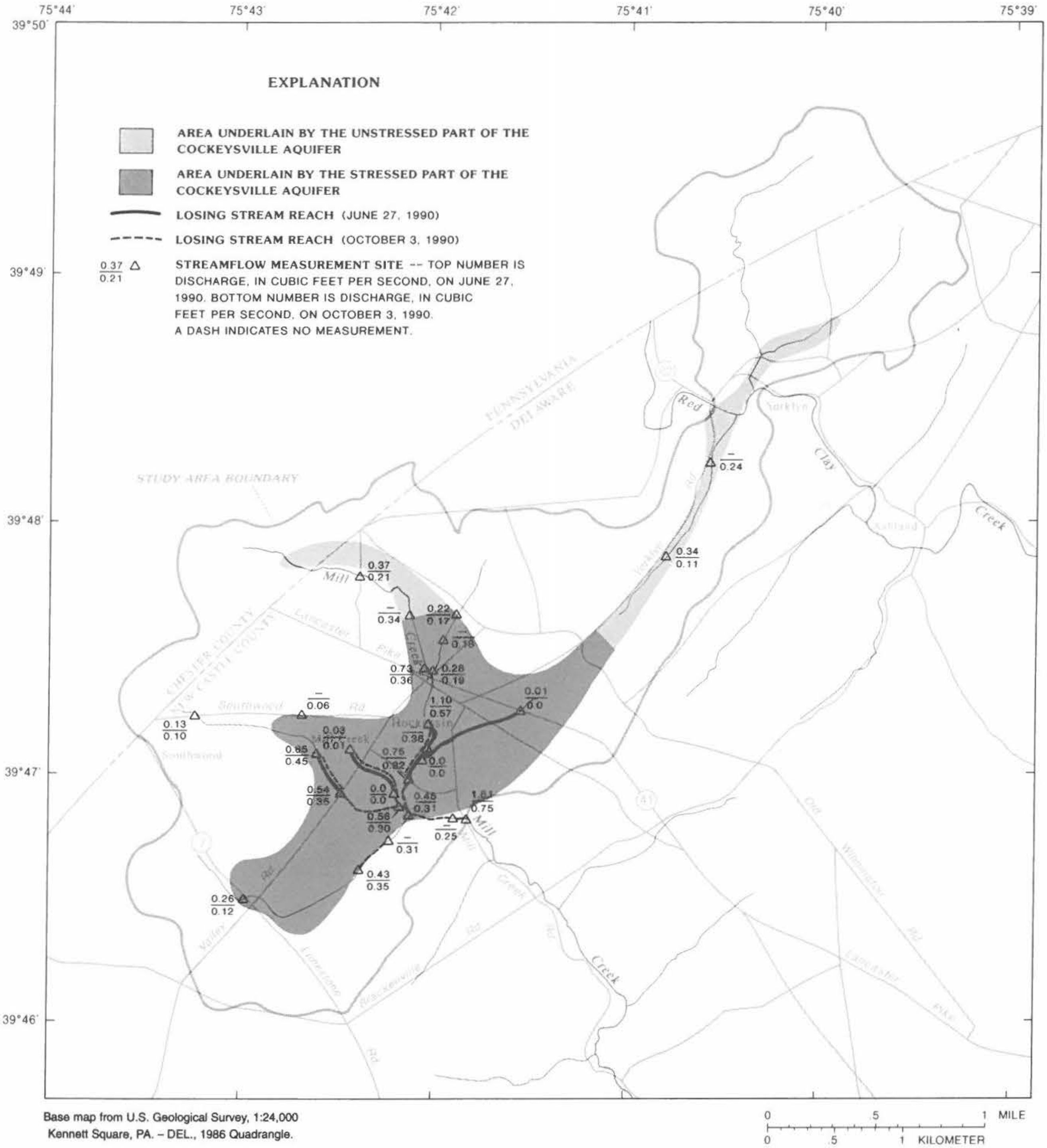


Figure 26. Map showing stream discharge on June 27, 1990, and October 3, 1990.

able soil, where the precipitation could infiltrate and recharge the system. On the other hand, if rainfall intensity exceeds the infiltration capacity of a soil some of the rain will not infiltrate but will become surface runoff.

A significant source of recharge to the stressed part of the Cockeysville aquifer is infiltration of water from surface streams. Seepage investigations were conducted in spring and fall 1990 and in spring 1991 to identify gaining and losing stream reaches and to determine seasonal variations in stream loss. The results of the spring and fall 1990 seepage investigations are shown in Figure 26. Streams flowing through the unstressed part of the Cockeysville aquifer gain water from the ground-water system (ground-water discharge), and streams flowing through the stressed part of the aquifer lose water to the ground-water system (ground-water recharge). Streamflow loss to the stressed part of the aquifer is not uniform. The greatest loss is in the center of the valley near Hockessin.

The smallest streamflow loss is along the tributary to Mill Creek that flows through the western part of the study area. The differences in streamflow measured along this tributary are not large enough to determine if the stream is

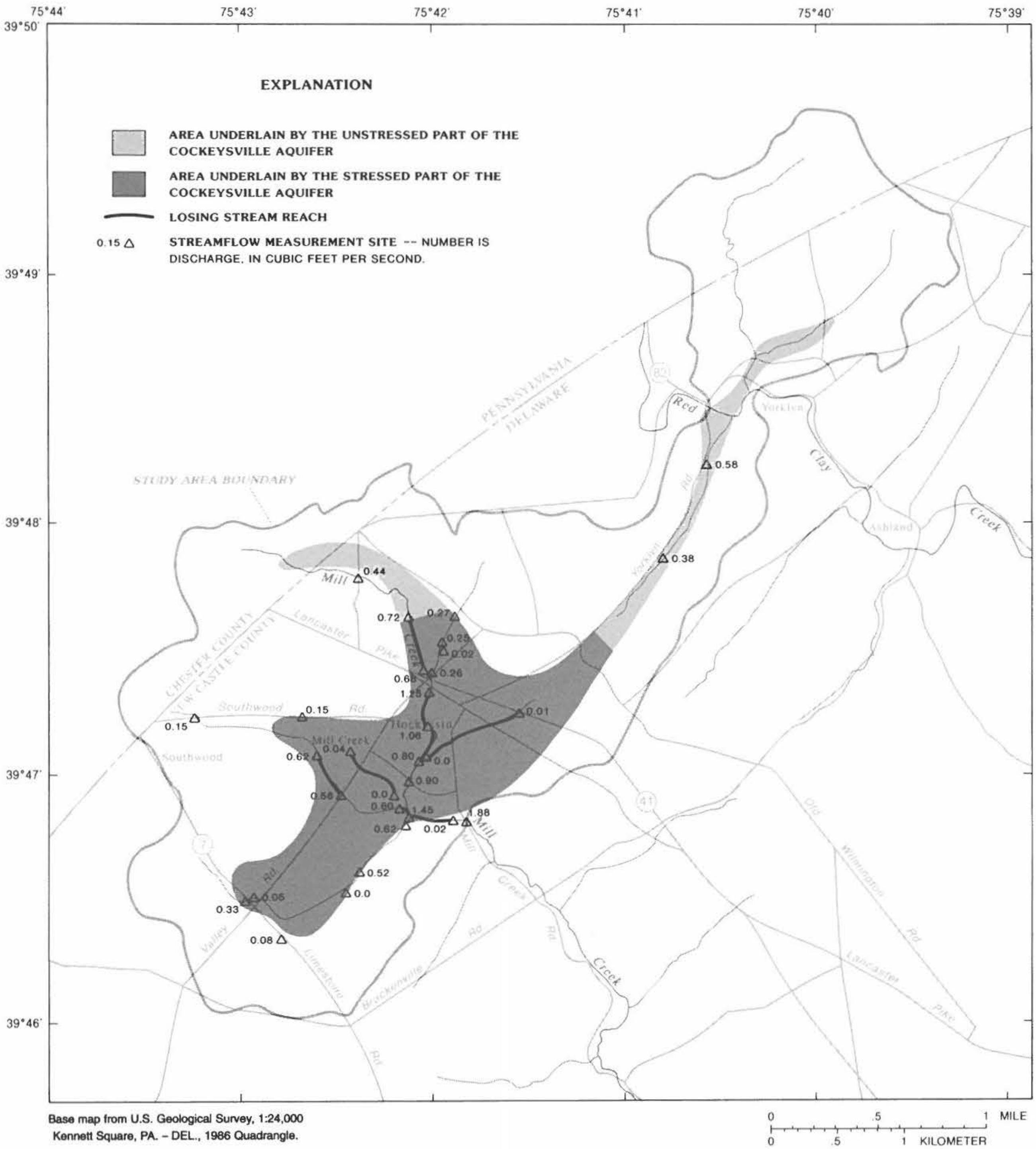


Figure 27. Map showing stream discharge on April 4, 1991.

gaining or losing water. Much of the tributary is located near the contact between the Cockeysville and Wissahickon formations and the water could be flowing on clayey weathering products of carbonate, gneiss, schist, or pegmatite. The fine-grained nature of the weathering products probably inhibits flow into or out of the stream, resulting in small differences in measured flow along the stream length.

Total streamflow was greater in the spring than during the fall, but total streamflow loss for the two measurements differed by less than 10 percent. The accuracy of the discharge measurements was about ±5 percent, so it is likely that there was little seasonal change in stream loss in 1990. This small seasonal change probably occurs because ground-water levels are below streambed elevation and the rate of infiltration through the streambed will not vary with changing ground-water level (Marsily, 1986), but only with changing stream stage and streambed area. In 1990, the daily mean stream stage fluctuated less than 2 ft and streams flowed in well-defined channels, so that the temporal variation in streamflow loss was small in comparison to total streamflow loss. The results of a more detailed seepage investigation in April 1991 (Fig. 27) indicate that total streamflow loss to the ground-water system was about 0.85 ft^3/s (0.55 Mgal/d) in the outcrop area. This streamflow loss was considered to approximate daily streamflow loss to the ground-water system in 1990.

Streamflow in the noncarbonate aquifer can significantly affect recharge to the Cockeysville aquifer. All but one of the streams that lose water to the Cockeysville aquifer originate in noncarbonate aquifers. Ground water in the noncarbonate aquifers discharges to these streams and provides most of the streamflow during dry periods. The streams then flow over the Cockeysville aquifer and lose water to it. During the study period, none of the streams that originate in noncarbonate rocks was dry. If base flow in streams in the noncarbonate part of the study area is reduced to less than the infiltration capacity of the material beneath the streams in the Cockeysville outcrop area, the streams will become dry and recharge to the Cockeysville aquifer will be greatly reduced.

Because streams lose water over the stressed part of the Cockeysville aquifer and gain water over the unstressed part, the proportion of areal recharge available to wells differs in the two parts of the aquifer. In the unstressed part, ground water discharges to local streams so that, as recharge increases, base flow to streams also increases. Therefore, although recharge adds water to the system, the increased ground-water discharge to streams increases the rate of flow from the ground-water system. In contrast, in the stressed part of the aquifer, ground-water levels are lower than stream-bottom altitudes and ground water does not discharge to streams. Recharge adds water to the system, therefore, but does not increase the rate of outflow from the system through discharge to streams.

A third source of recharge to the Cockeysville aquifer is ground-water flow from the surrounding noncarbonate aquifer. Some residents of the White Briar development (Fig. 28), located over the Wissahickon Formation, reported that water levels in their wells were lowered in response to ground-water withdrawals in the Cockeysville aquifer. This indicates that, in this area, ground water flows from the noncarbonate rocks to the Cockeysville aquifer. The zone of affected water levels is about 300 ft wide. Beyond this zone, water levels in the noncarbonate aquifer do not appear to be affected. Other geologic units in the noncarbonate aquifer do not appear to be affected by ground-water withdrawals in the Cockeysville aquifer.

Water levels in wells in the unstressed part of the aquifer near the contact with the stressed part of the Cockeysville aquifer are as much as 50 ft higher than water levels in the stressed part of the aquifer. Given the narrow width and restricted location of the affected zone, the amount of ground water flowing from the noncarbonate aquifer to recharge the Cockeysville aquifer is small, in comparison to other sources of recharge.

Of the three sources of recharge to the stressed part of the Cockeysville aquifer, only recharge from areal infiltration of precipitation can vary significantly from year to year. Except in wet years, when streambed area may substantially increase, infiltration of stream water is relatively constant. Lateral ground-water flow from the noncarbonate aquifer is small, and gradients in the noncarbonate aquifer will not increase substantially if water levels in the stressed portion of the carbonate aquifer are further lowered. Therefore, if recharge from infiltration of precipitation is less than that needed to meet water demand by natural and human-induced means, no other sources of recharge can be increased to make up the deficit. The actual rates of recharge in 1990 from each source are addressed in the "Water Budgets" section.

Discharge

In the Cockeysville aquifer, ground water discharges primarily to streams and wells. In the unstressed part of the aquifer, ground water discharges primarily to nearby streams, and the rates of discharge fluctuate because of changes in recharge and evapotranspiration. In the stressed part of the aquifer, ground water discharges primarily to pumped wells; therefore, the rate of ground-water discharge from the flow system is determined by the pumping rate of wells. The largest water withdrawals are from public supply wells. In 1990, the rate of withdrawal by these wells averaged 1.48 Mgal/d. Withdrawal rates for 1975-90 ranged from 1.39 Mgal/d in 1988 to 1.92 Mgal/d in 1979 (Fig. 22). The average withdrawal for the period of record is 1.68 Mgal/d.

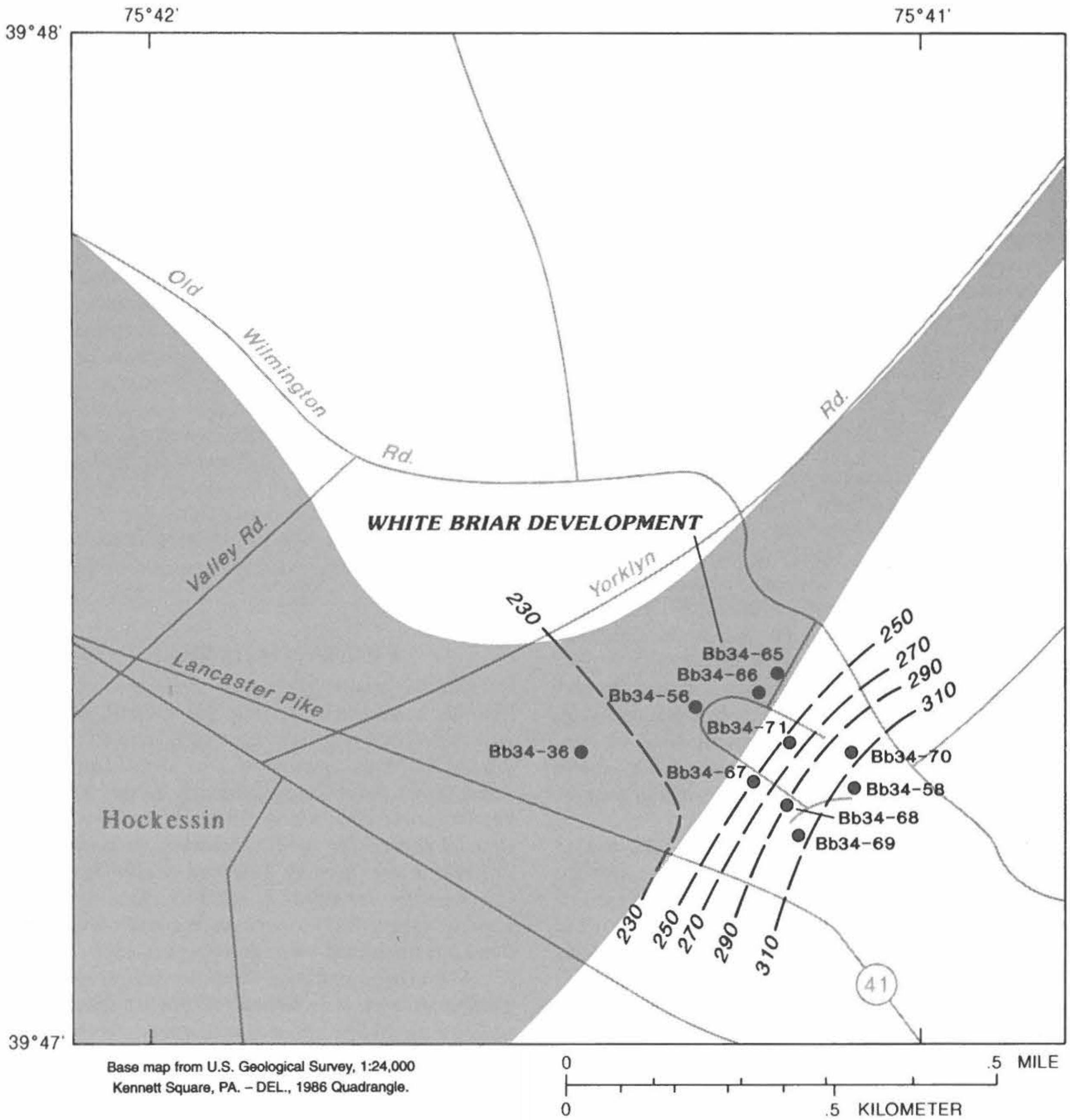
Flow Directions and Water Levels

General ground-water-flow directions can be inferred from the water-level map (Fig. 29). Overall, ground-water-flow direction is perpendicular to the contour lines shown in Figure 29. In the unstressed part of the aquifer, ground water flows from topographically higher areas toward streams located in topographically lower areas. In the stressed part of the aquifer, however, ground-water withdrawals have greatly lowered water levels in the Cockeysville and regolith aquifers. As a result, ground water no longer flows toward surface-water bodies, but now flows toward ground-water pumping centers.

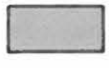
Although ground water flows toward pumped wells and gaining streams, it is difficult to predict specific ground-water-flow paths and ground-water velocities in the Cockeysville aquifer. In the regolith, ground water flows through interstices between individual grains, and the assumption that ground water flows perpendicular to water-level contours is probably valid. In the unweathered part of the aquifer, however, ground water flows through fractures and solution openings, and ground-water-flow directions are affected by the orientation of fractures. At a particular site, therefore, directions of ground-water flow could be considerably different from that inferred from the water-level map.

Prior to heavy ground-water development during the 1950s, water levels in the aquifer in the Mill Creek Basin were adjusted to the stages in the streams that flowed over the aquifer and ranged from about 230 ft above sea level, where Mill Creek exits the study area, to about 270 ft near the western and northern borders of the aquifer (Fig. 30). In the part of the aquifer that is in the Red Clay Creek Basin, water levels ranged from about 165 ft above sea level near Red Clay Creek to about 260 ft near the basin boundary.

In 1990, water levels in the unstressed part of the aquifer were similar to those in the 1950s (Figs. 29 and 30). In contrast, water levels in the stressed part of the aquifer



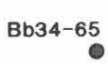
EXPLANATION



AREA UNDERLAIN BY THE COCKEYSVILLE AQUIFER

AREA UNDERLAIN BY NONCARBONATE AQUIFERS

WATER-LEVEL CONTOUR -- SHOWS APPROXIMATE WATER-LEVEL ALTITUDE IN AQUIFERS UNDERLYING THE WHITE BRIAR DEVELOPMENT. CONTOUR INTERVAL IS 20 FEET. DATUM IS SEA LEVEL.



WELL LOCATION AND IDENTIFICATION NUMBER

Figure 28. Map showing water-level altitudes in aquifers underlying White Briar.

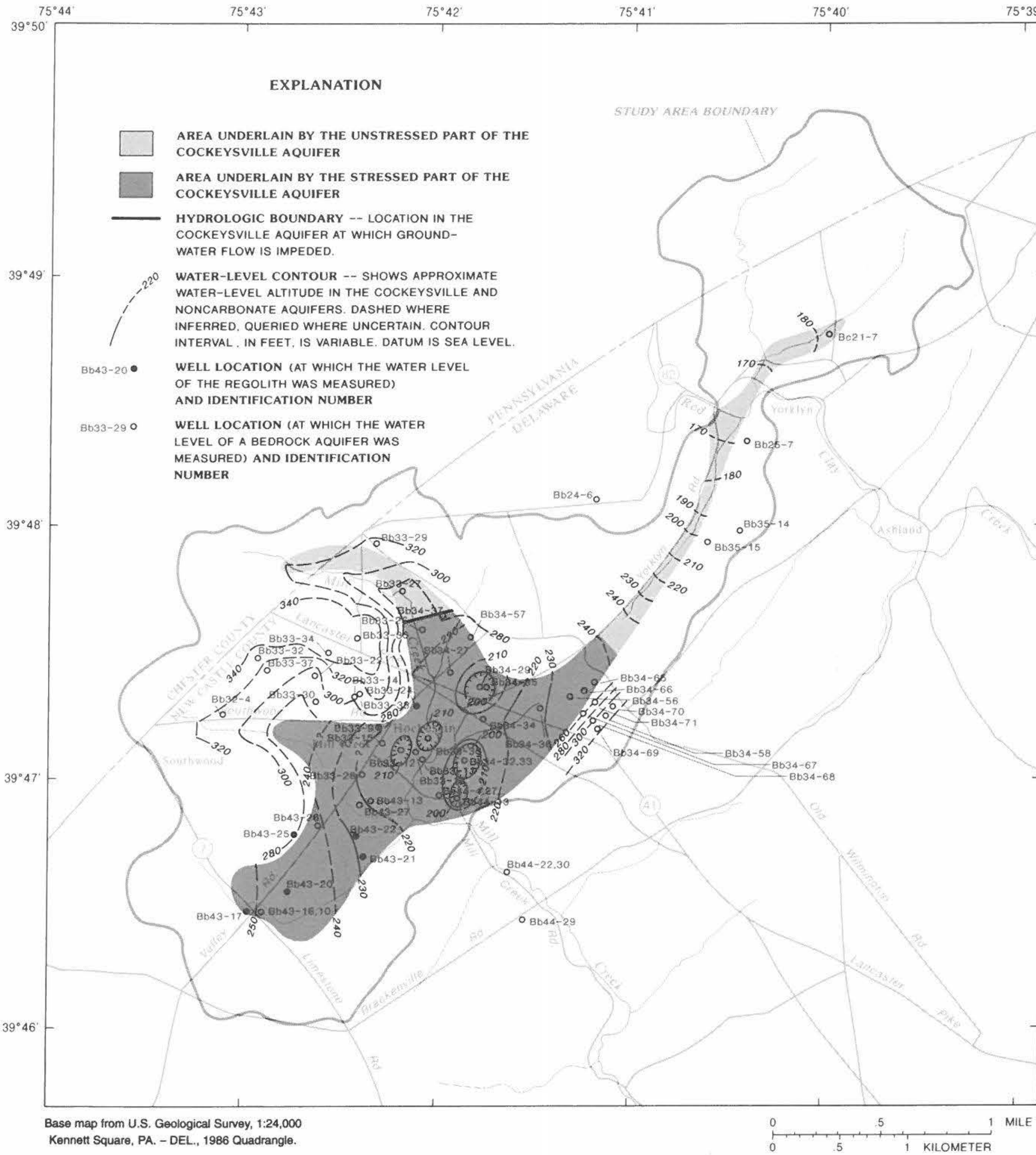


Figure 29. Map showing water-level altitudes in aquifers in the Hockessin area, November 14-16, 1990.

have declined substantially since the 1950s. In November 1990, water levels ranged from about 175 ft above sea level near pumped wells to about 250 ft above sea level near the western border of the aquifer — an average decline of 30 ft since the 1950s. The decline in water levels has resulted in significant changes in the ground-water flow system. Throughout the stressed part of the aquifer, water levels are tens of feet below streambeds, causing streams to lose water to the aquifer. In some areas, the combination of water-level declines and thin regolith has resulted in the regolith being completely dewatered periodically.

Long-term water-level response to ground-water withdrawals reveals differences in hydraulic properties within the Cockeysville aquifer and between the Cockeysville aquifer and the noncarbonate aquifer. In the noncarbonate aquifer and in the northern extension of the Cockeysville aquifer, hydraulic head is much higher than it is in the stressed part of the Cockeysville aquifer (Fig. 29), indicating that ground water does not flow readily from these areas to the stressed part of the aquifer. The resistance to flow could be caused either by lower transmissivity in the surrounding units, or by lower transmissivity in structures and

Figure 30. Map showing water-level altitudes in the Cockeysville aquifer, 1955.

rocks that are found between the stressed part of the Cockeysville aquifer and the adjacent units.

Water levels are highest in late spring or early summer and begin to decline during the growing season, when evapotranspiration is high and most infiltrating water is intercepted by plants before it reaches the ground-water system (Fig. 31). The lowest ground-water levels are at the end of the growing season, usually in late fall or early winter. After plants die or become dormant and temperatures decrease, evapotranspiration is reduced and more infiltrating water can reach the ground-water system, and water levels begin to rise until the next growing season. In 1990, water levels in the stressed portion of the aquifer generally rose from January through June and declined from July through December. These seasonal variations mask any long-term trends that might otherwise be evident in the record (Fig. 32).

Seasonal variation of water levels in the unstressed part of the aquifer are different from seasonal variations in the stressed part of the aquifer. During the period when little recharge reaches the aquifer, water-level response is similar in both parts of the aquifer. During the recharge period,

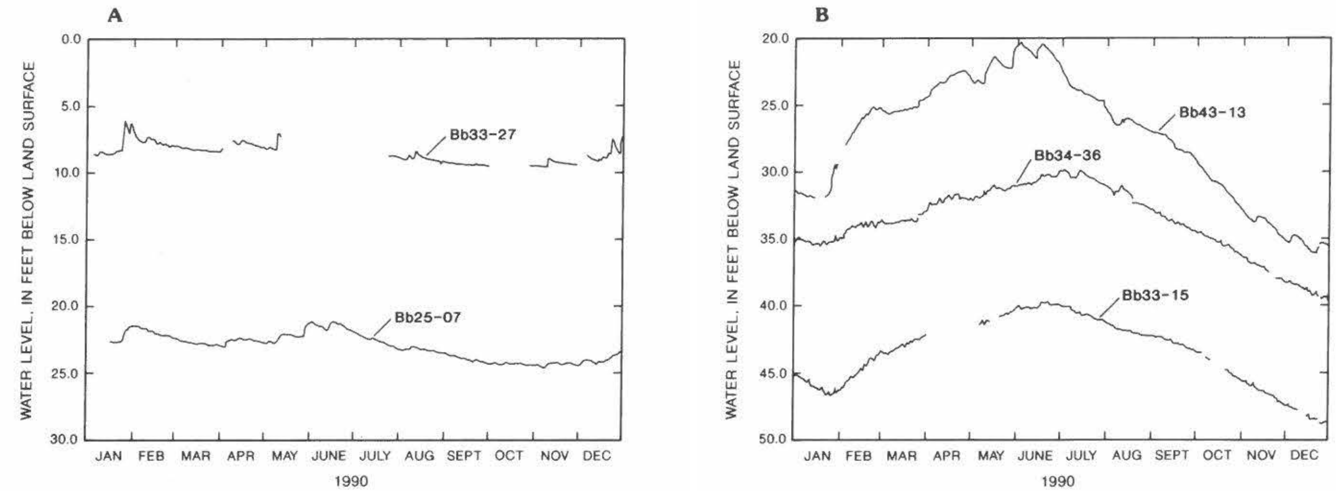


Figure 31. Graph showing water levels in observation wells; (A) in the unstressed part of the Cockeysville aquifer; (B) in the stressed part of the Cockeysville aquifer.

however, water levels in the unstressed part of the aquifer respond to individual recharge events, and water levels in the stressed part indicate a dampened response. This is probably because the thinner unsaturated zone in the unstressed part of the aquifer allows recharge from individual events to reach the water table more quickly than in the stressed part of the aquifer where water levels are depressed.

The amplitudes of seasonal fluctuations differ because of variations in precipitation magnitude and intensity, ground-water withdrawals, and evapotranspiration. From 1979-90, water levels were higher during 1979-80, 1983-84, and 1989-90 than during other years. There are also periods when parts of the regolith are completely dewatered. Periods when well Bb34-40 was dry are shown in Figure 33. This well is screened at the base of the regolith (about 60 ft below land surface), so the periods when well Bb34-40 is dry corresponds to periods when the regolith in the vicinity of the observation well is completely dewatered. During 1979-90, the aquifer in this area has been completely dewatered four times: October 1982 through March 1983, October 1986 through December 1986, November 1987 through June 1988, and October 1988 through December 1988. Because the storage capacity of the regolith is much greater than that of fractured rock, rates of water-level declines could increase if the regolith becomes unsaturated over large areas.

Water levels in observation wells respond differently to pumping of supply wells, also (Fig. 34). Some wells (Bb34-32 and Bb34-35) respond almost immediately to pumping of supply wells. Well Bb33-13 shows no immediate response to pumping of individual wells, but responds to system-wide stresses. This is probably because those wells that respond immediately intersect the same fractures as nearby pumping wells, whereas those wells that do not respond immediately intersect fractures that connect to the regolith aquifer and not to individual pumped wells.

Water Quality

Forty-two water-quality samples were collected in 1990 and 1991 from wells in the Cockeysville and noncarbonate aquifers, and from streams over the Cockeysville aquifer (Fig. 23). Twenty-nine water samples from wells were analyzed for concentrations of major ions, nutrients, trace metals, and radon (Appendix 4). Six of these wells were resampled and the water was analyzed for concentrations of

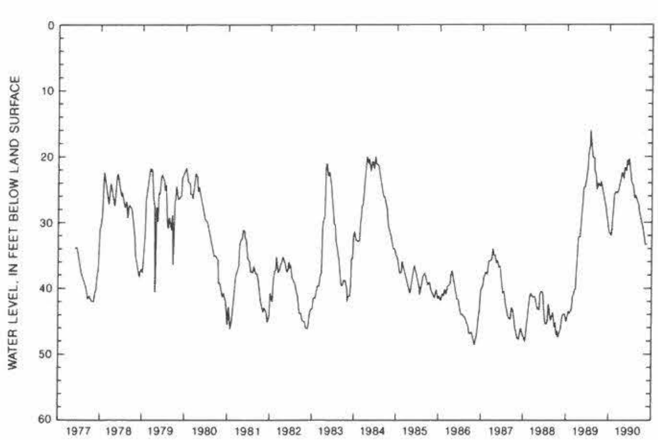


Figure 32. Graph showing water levels in observation well Bb43-13, 1977-90.

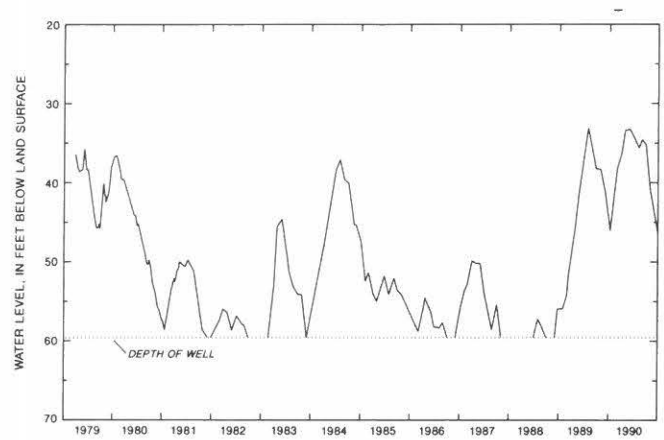


Figure 33. Graph showing water levels in observation well Bb34-40, 1979-90.

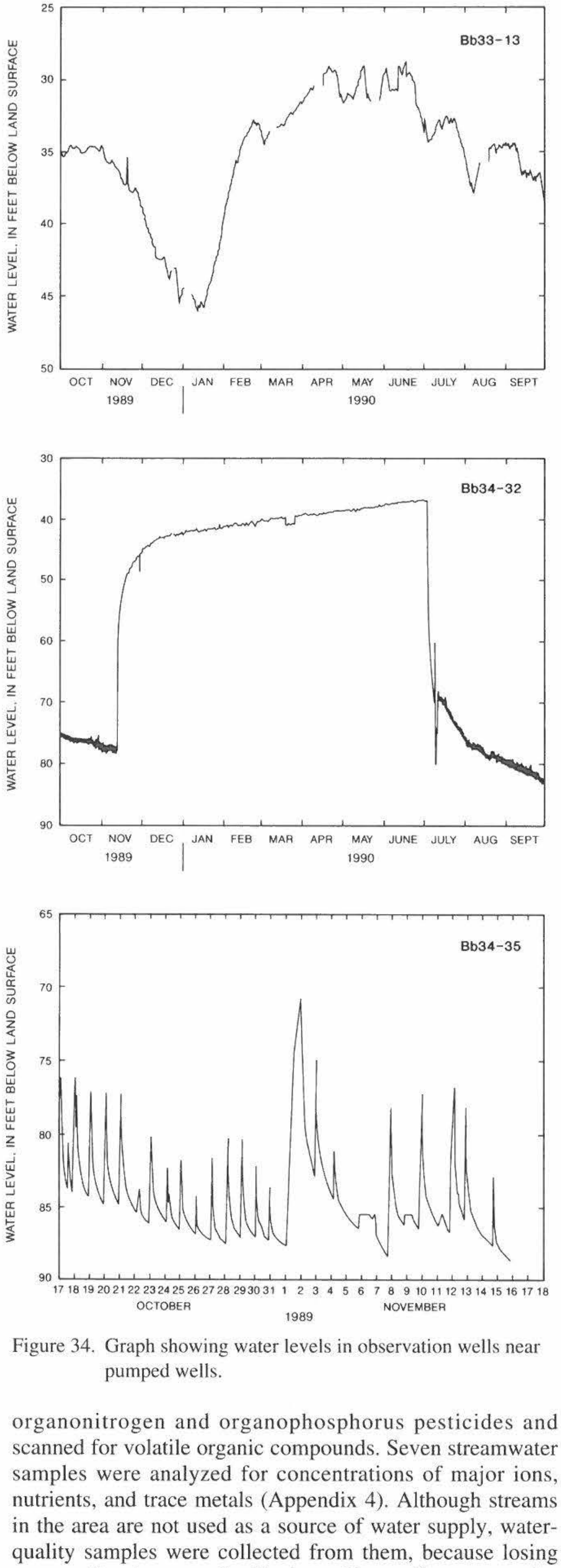


Figure 34. Graph showing water levels in observation wells near pumped wells.

organonitrogen and organophosphorus pesticides and scanned for volatile organic compounds. Seven streamwater samples were analyzed for concentrations of major ions, nutrients, and trace metals (Appendix 4). Although streams in the area are not used as a source of water supply, water-quality samples were collected from them, because losing streams flowing over the Cockeysville aquifer are a major source of recharge to the aquifer.

Occurrence of Chemical Constituents

Six streamwater-quality samples were collected during base-flow conditions and one (01479195b) was collected during stormflow. The water quality of a stream is affected by chemical reactions between the stream and the rock it flows over and by the chemistry of the base-flow water. As streams flow over the Cockeysville aquifer, major ion chemistry should be increasingly affected by ground water from the Cockeysville aquifer if the stream receives large quantities of water from the aquifer. This was not observed in the analytical results, however. All major-ion content of the water samples is similar. Calcium comprises about 50 percent of the cations, followed by magnesium and sodium, respectively (Fig. 35). Relative proportions of anions in the samples are evenly distributed. Bicarbonate concentration is slightly greater than chloride or sulfate concentration. The chemical composition of the water is consistent with the findings of the seepage investigation, that is, base flow for streams in the Mill Creek Basin originates in the noncarbonate part of the basin, and little base flow originates in the part of the basin underlain by carbonate rocks.

Strontium concentrations in streamwater samples also support the findings of the seepage investigation. Strontium is chemically similar to calcium and replaces calcium in minor amounts in rock minerals (Hem, 1985, p. 135). During metamorphism of limestone and dolomite to marble, however, strontium is lost. The result is that the Cockeysville Formation contains significantly less strontium than do the surrounding rocks. Ground water in the area typifies this relation (Appendix 4). Ground water from carbonate rocks contains less strontium than ground water from noncarbonate rocks. If ground water from the Cockeysville Formation was discharging to streams in the area, there would be decreasing strontium concentrations in water samples collected progressively downstream. The strontium concentration in the sample from Mill Creek at the streamflow gage, the most downstream point in the area, is similar to that in the upstream samples, indicating that streams in the area receive little base flow from the Cockeysville aquifer.

None of the constituent concentrations exceeds U.S. Environmental Protection Agency (USEPA) drinking-water Maximum Contaminant Levels (MCLs) (Table 8). Three samples exceed the Secondary Maximum Contaminant Levels (SMCLs) and concentrations of most trace metals, with the exception of strontium, were below reporting levels for the analytical method used (U.S. Environmental Protection Agency, 1986a, b). Although none of the water samples contains nitrate levels higher than the MCL of 10 mg/L, the water sample collected during stormflow contained higher concentrations of organic nitrogen and orthophosphorus than the base-flow samples. The high concentration of organic nitrogen indicates that upstream from the sampling point, streamflow receives overland runoff from anthropogenic sources.

The chemistry of water from wells in the Cockeysville aquifer strongly reflects the carbonate composition of the aquifer matrix. The dominant cations in 17 water samples from the aquifer are calcium and magnesium and the dominant anion is bicarbonate (Fig. 35). Because of the dissolution of carbonate rocks, alkalinity, hardness, and dissolved-solids concentrations are higher in water samples from the

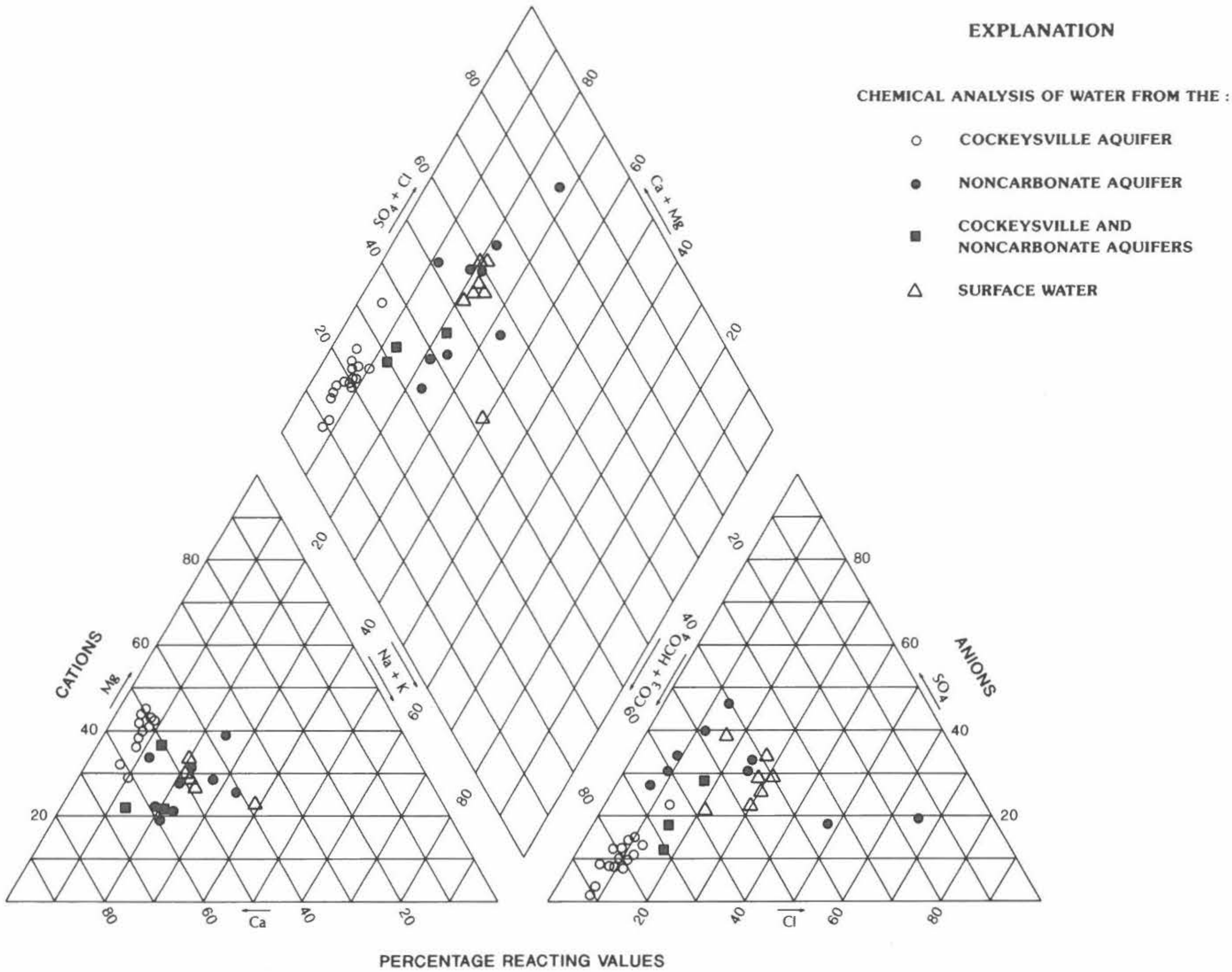


Figure 35. Graph showing trilinear diagram for ground water from the Hockessin area.

TABLE 8

Maximum contaminant levels and secondary maximum contaminant levels for selected inorganic constituents in drinking water.
(mg/L = milligrams per liter; MCL = maximum contaminant level; SMCL = secondary maximum contaminant level)

Constituent	Maximum Contaminant Level[1] (mg/L)	Secondary Maximum Contaminant Level[2]
Barium	5.00	—
Beryllium	1.00	—
Cadmium	0.005	—
Chromium	0.01	—
Chloride	—	250
Copper	—	1
Dissolved solids (total residue)	—	500
Fluoride	4.00	2
Iron	—	0.3
Lead	0.005	—
Nickel	0.01	—
Manganese	—	0.05
Nitrate (as N)	10.00	—
Sulfate	—	250

[1]MCLs are enforceable health-based standards. (U.S. Environmental Protection Agency, 1986a.)
[2]SMCLs are non-enforceable aesthetically-based standards. (U.S. Environmental Protection Agency, 1986b.)

Cockeysville aquifer than in water samples from the noncarbonate aquifer (Fig. 36).

None of the water samples contains concentrations in excess of USEPA MCLs for constituents analyzed. However, nitrate concentrations range from 1.0 to 5.7 mg/L with 16 of 17 samples having concentrations higher than 2.0 mg/L. Hamilton and others (U.S. Geological Survey, written comm., 1992), in a study of ground water on the Delmarva Peninsula, found nitrate concentrations in water unaffected by human activity to be less than 1 mg/L. The elevated concentrations of nitrate indicate that the quality of water in the aquifer is affected by human activities. Water from six wells in the Cockeysville aquifer was sampled and analyzed for volatile organic compounds and organochlorine and organophosphorus pesticides used in the mushroom industry to address further the effect of human activity on ground-water quality in the area. The results of this limited effort indicate that the samples do not contain measurable concentrations of volatile organic compounds or pesticides. Better areal and vertical coverage of the aquifer is needed to adequately evaluate if ground water in the Hockessin area is contaminated from these organic compounds.

Nine ground-water samples were collected from wells in the noncarbonate aquifers (Appendix 4). Water quality of the

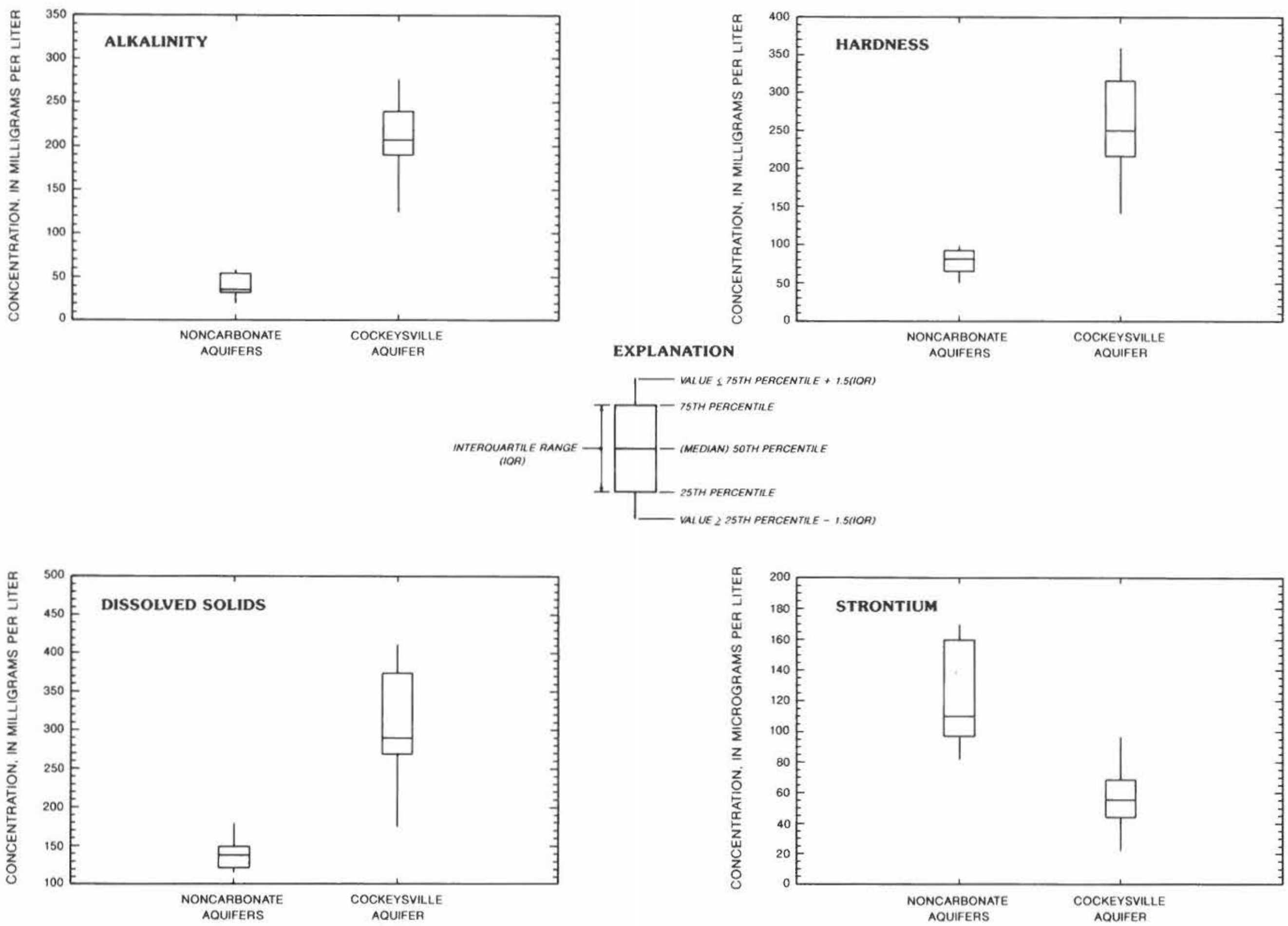


Figure 36. Box plots showing alkalinity, hardness, dissolved solids, and strontium concentrations in water from aquifers in the Hockessin area.

noncarbonate aquifers is markedly different from water quality in the Cockeysville aquifer. Chemical analyses indicate that water from the noncarbonate aquifer contains greater percentages of sodium (relative to other cations) and sulfate (relative to other anions) than water from the Cockeysville aquifer (Fig. 35). Also, the chemical analyses do not group as tightly as the analyses of water from the Cockeysville aquifer, which probably indicates varied mineralogy in the noncarbonate aquifers.

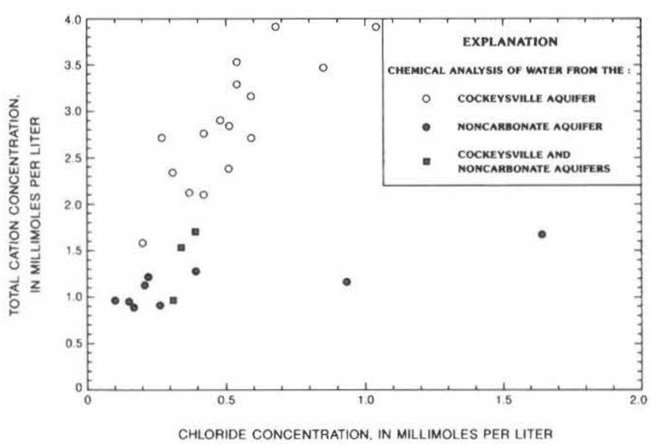


Figure 37. Graph showing relation of sum of cation concentrations to chloride concentrations.

None of the water samples contains concentrations in excess of USEPA MCLs for those constituents analyzed (Appendix 4). As in waters from the Cockeysville aquifer, however, nitrate concentrations in the water samples indicate that ground-water quality in the noncarbonate aquifer has been affected by human activity. Nitrate concentrations in samples range from less than 0.1 mg/L to 7.7 mg/L. Six of nine samples contain nitrate concentration in excess of 1 mg/L. Chloride concentrations in water samples also indicate that some ground water has been affected by human activity, such as road salting and waste disposal. Chloride concentration in water samples range from 3.7 to 58 mg/L (Appendix 4). In general, as total cation concentration increases, chloride concentration increases indicating dissolution of chloride-bearing minerals in the rocks (Fig. 37). Chloride concentrations in water samples from two wells in the noncarbonate aquifer, however, are higher, relative to total cation concentration, than chloride concentrations in water from other wells in the study area. This indicates that a source of chloride unrelated to mineral dissolution affects the quality of water in these two wells.

Evidence for Ground-Water Flow Between Aquifers

Chemical analyses of ground-water samples indicate that the stressed part of the Cockeysville aquifer does not receive large quantities of water from the noncarbonate

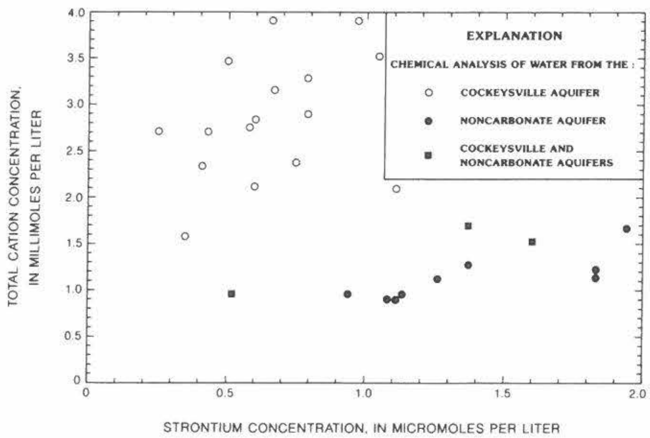


Figure 38. Graph showing relation of sum of cation concentrations to strontium concentrations.

aquifer. If the noncarbonate aquifer were contributing substantial amounts of water to the Cockeysville aquifer, chemical analyses from wells near the contact of the two aquifers would have a chemical composition similar to that of the noncarbonate aquifer, and water would become more affected by carbonate minerals as it flows through the Cockeysville aquifer. The water-quality data do not support this. Although a number of water samples from the Cockeysville aquifer are from wells that are less than 0.1 mi from the contact with noncarbonate rocks (Bb33-15, Bb33-26, Bb33-27, Bb34-29, Bb43-28, and Bb44-13), the data from the chemical analyses of the water samples plot in a close group on Figure 35, indicating that the Cockeysville aquifer is not receiving significant quantities of water from the noncarbonate aquifers. The single exception is the analysis of the water sample from well Bb34-34. The data from this analysis plot outside the grouping because the proportion of sulfate to total anions is greater in the sample from this well than in other water samples from the Cockeysville aquifer. Possible explanations for the difference are that the sampled water is influenced by water from other aquifers, or that the water is being affected by land-surface activities. The concentration of strontium in the two types of aquifers is additional evidence that the Cockeysville aquifer does not receive large quantities of water from other noncarbonate aquifers. As stated previously, strontium concentrations in water from the carbonate aquifer are lower than strontium concentrations in the noncarbonate aquifers (Fig. 36). The sum of the concentrations of all cations in a water sample is plotted against the concentration of strontium on Figure 38.

Plotted in this manner, water from the two types of aquifers fall into distinct groups. If significant quantities of water were flowing to the Cockeysville aquifer from noncarbonate aquifers, the total cation concentration of water samples from wells near the contact would be lower, and the strontium concentration would be higher than they would be in samples from other wells in the Cockeysville aquifer. With the exception of the sample from well Bb33-26, the separation of the two groups indicates that this does not occur.

Water Budgets

A water budget is a statement of water gains and losses in a region for a specified period of time. Water entering the region is equated with water leaving the region, plus any changes in the amount of water stored during the time period. The water budget can be expressed by the equation:

Water in = water out ± change in water stored.

Water budgets were formulated for the Mill Creek Basin and for the stressed part of the Cockeysville aquifer for 1990 to approximate the disposition and flux of water in the basin, and to estimate rates of ground-water recharge to the stressed part of the Cockeysville aquifer.

Mill Creek Basin

Sources of water for the Mill Creek Basin include precipitation, ground-water inflow, and water released from ground-water storage. Potential sinks of water include streamflow leaving the basin, evapotranspiration, water exported from the basin, ground-water outflow, and water taken into ground-water storage. Most of these sinks are probably insignificant factors in the Mill Creek Basin water budget. The amount of ground-water inflow and outflow is probably negligible because the noncarbonate aquifer that underlies the basin boundaries is unstressed and of low permeability. The possibility of a subsurface connection between the Cockeysville aquifer in the Mill Creek Basin and the Cockeysville Formation in the Pleasant Hill area has been postulated (Moody and Associates, 1975), but Woodruff and Plank (this volume) conclude that there is no evidence to suggest that a geologic or hydrologic connection exists between these two aquifers.

The net amount of water imported from outside the basin is also assumed to be negligible. The primary source of imported water is by public-water-supply lines. If the same amount of water leaves the basin by public sewers, however, there would be no net addition of water to the basin. Holzinger (1979) reported there were about the same number of homes served by public sewers as there were homes served by public water. Because most homes built after 1979 were connected to both public sewer and water (R. P. Hansen, Water Resources Agency for New Castle County, oral commun., 1990), the number of sewer and public-water-supply connections are assumed to be nearly equal.

Assuming that the quantity of imported water, ground-water inflow, and ground-water outflow are negligible in the Mill Creek Basin, the water budget for the basin is

Precipitation = streamflow + water exported +
evapotranspiration ± change in water stored.

The water budget for 1990 is given in Table 9. Results of other basinwide budgets also are provided so that comparisons can be made. Although there are differences in instrumentation, period of study, natural variation in weather, and purpose of the budget, the water budgets are fairly consistent. The water budget by Moody and Associates (1975) was only for part of a year, which accounts for the poor comparison with the other budgets. Another commonly used unit in water budgets is inches, which is the depth of water for 1 year distributed uniformly over the basin area. For the Mill Creek Basin, which has an area of 3.66 mi^2, 1 Mgal/d is equivalent to 5.74 in.

Precipitation, the major source of water for Mill Creek Basin, was 8.20 Mgal/d (47.04 in.) in 1990. Precipitation

TABLE 9

Water budgets for the Mill Creek Basin.

(Data in million gallons per day; precipitation = streamflow + exported water + evapotranspiration ± change in amount of water stored)

Water budget	Input precipitation	Outflow			Change in amount of water stored
		Streamflow	Exported water	Evapotranspiration	
Werkheiser (Jan-Dec 1990)	8.20	2.48	1.48	4.76	-0.52
Williams (1981) (May 1974-April 1978)	8.69 (avg. annual)	2.33	1.691	4.88	-0.10
Holzinger (1979) (May 1977-April 1978)	9.92	2.82	2.28	4.96	-0.14
Moody and Assoc. (1975) (April 14-Dec. 31, 1974)	8.77	1.38	1.80	6.79	-1.19

was measured continuously at two sites in the basin using weighing-bucket-type precipitation gages. In addition, daily observations of precipitation were recorded by volunteer observers at two sites within the basin and at three sites just outside the basin (Fig. 23). Not all of the precipitation gages were operational throughout 1990. Monthly precipitation for those sites operational for a given month were averaged to determine monthly precipitation for the basin (Table 10). The monthly averages were summed to provide the annual precipitation for the basin.

To determine the amount of surface water exiting the Mill Creek Basin, a stream gage was installed on Mill Creek, at the contact of the Cockeysville and Wissahickon Formations. Data from the gage also were used to estimate the proportion of overland flow and base flow in total streamflow, and to establish base-line conditions against which future conditions can be measured and compared.

In 1990, streamflow past the gage totaled 905 Mgal and averaged 2.48 Mgal/d (14.24 in.) (Table 9). The maximum daily streamflow was 58 Mgal on May 29 and the minimum daily streamflow was 0.4 Mgal on October 7 (Fig. 39). Automated hydrograph separation techniques, as described by R. A. Sloto (U.S. Geological Survey, written commun., 1988), were used to estimate the overland flow and base-flow components of total streamflow. Of the total streamflow leaving the basin in 1990, about 44 percent (398 Mgal (1.09 Mgal/d)) was base flow; the average base flow per square mile was about 0.30 Mgal/d.

Total streamflow and the amount of base flow during 1990 were similar to other studies conducted in the Mill Creek Basin (Holzinger, 1979; Williams, 1981). These values, when adjusted for drainage-area differences, are considerably lower than average values for other parts of the Piedmont in Delaware and Pennsylvania (Olmsted and Hely, 1962; McGreevy and Sloto, 1977). Hydrograph separation was also applied to streamflow data from a nearby gage (Red Clay Creek at Wooddale) for comparison, because base-flow estimates for Red Clay Creek are similar to long-term estimates of base flow reported for other basins in the region (Olmsted and Hely, 1962; McGreevy and Sloto, 1977). Of the total streamflow at Wooddale in 1990, about 70 percent was base flow, and the average base flow per square mile was 0.62 Mgal/d.

Ground-water withdrawals constitute a larger portion of the water budget in the Mill Creek Basin than in other nearby basins in the region (Olmsted and Hely, 1962; McGreevy and Sloto, 1977). If the amount of ground water withdrawn by public supply wells in 1990 (1.48 Mgal/d) is added to the base-flow component of Mill Creek streamflow, base flow comprises about 65 percent of streamflow, and the average base flow per square mile is about 0.70

TABLE 10

Monthly precipitation in the Hockessin area, 1990, in inches.

Month	Number of gages operational	Average amount of precipitation
January	2	3.56
February	2	1.60
March	3	1.88
April	3	3.67
May	4	8.51
June	7	4.75
July	7	3.25
August	7	6.14
September	7	2.12
October	7	2.96
November	7	2.69
December	7	5.91
Total		47.04

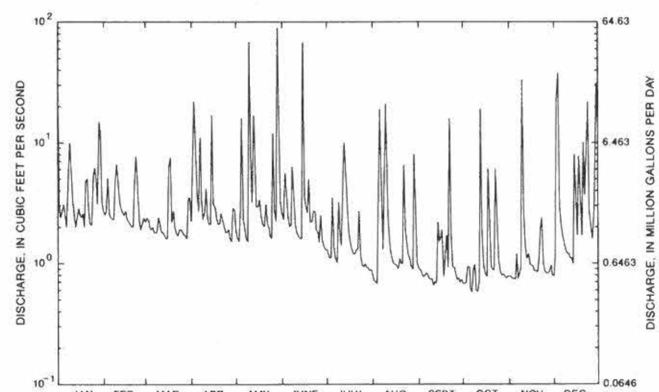


Figure 39. Graph showing discharge of Mill Creek at Mill Creek Road at Hockessin, 1990.

TABLE 11

Change in stored ground water in the Mill Creek Basin, 1990.
(Change in amount of water stored = average change in water level x gravity yield x percentage of basin underlain by aquifer)

Location	Water level (inches)	Specific yield	Underlain by aquifer	Change in amount of water stored (inches)	(Mgal/d)
Noncarbonate aquifers	-30.6	0.08	71	1.74	0.30
Unstressed part of the Cockeysville aquifer	-19.0	0.09	2	0.03	0.01
Stressed part of the Cockeysville aquifer	-49.6	0.09	27	1.21	0.21
			Total change	2.98	0.52

Mgal/d. These values compare favorably with those of similar basins, which indicates that ground-water withdrawals in the Mill Creek Basin affect the hydrologic system.

The amount of water exported from Mill Creek Basin in 1990 was equal to the amount of ground water withdrawn by wells, 1.48 Mgal/d (8.49 in.) (Table 9). Water is exported from the basin by public sewers and water-distribution systems. All public water withdrawn from the basin is ground water, and although much of the water is probably used by residents and businesses within the basin, public sewers transport most of the water from the basin. It is assumed, therefore, that exported water equals withdrawals of water from public water-supply wells.

The primary change in the amount of water stored in the basin is in the ground-water system. If basinwide ground-water levels are higher at the end of the year than at the beginning of the year, then the amount of water in storage increased over the year. Conversely, if ground-water levels are lower, then water in storage decreased over the year. The change in volume of ground water stored can be calculated as:

$$\Delta S = \Delta V \times Sy, \qquad (1)$$

where

ΔS = change in volume of water stored,
ΔV = change in volume of saturated aquifer material, and
Sy = specific yield of the aquifer in the zone of water-table fluctuation.

In this study, the change of the volume of saturated aquifer material is approximated as:

$$\Delta V = \Delta WL \times A, \qquad (2)$$

where

ΔWL = change in water level in the aquifer, and
A = surface area of the aquifer,

so that the change in volume of ground water stored is calculated as:

$$\Delta S = \Delta WL \times A \times Sy \qquad (3)$$

The discharge of ground water from basin storage in 1990 averaged 0.52 Mgal/d (2.98 in.) (Table 11). Because the noncarbonate aquifer, the stressed part of the Cockeysville aquifer, and the unstressed part of the Cockeysville aquifer probably have different hydrologic properties, equation 3 was solved for each individually.

The discharge of ground water from storage in the noncarbonate aquifer was estimated to be 0.30 Mgal/d (1.74 in.) in 1990 (Table 11). Water levels in observation wells Bb33-14 and Bb33-29 were used to approximate water-level changes in the aquifer. Specific yield of the noncarbonate aquifer is not known, but Olmsted and Hely (1962) calculated the specific yield of rocks in the Brandywine Creek Basin in Pennsylvania to be about 0.08. The rocks in the Brandywine Creek Basin are similar to the noncarbonate rocks in the Mill Creek Basin, so a value of 0.08 was used for this area.

The discharge of ground water from storage in the stressed part of the Cockeysville aquifer was 0.21 Mgal/d (1.21 in.) in 1990 (Table 11). The average water-level change in five observation wells (Bb33-15, Bb34-34, Bb34-36, Bb34-40, and Bb43-13) was 49.6 in. for 1990.

Equation 3 can be rearranged as:

$$Sy = \Delta S / (\Delta WL \times A), \qquad (4)$$

where

ΔS = change in volume of water stored in the carbonate aquifer,
ΔWL = change in ground-water level in the aquifers, and
A = surface area of the aquifers.

Because the Cockeysville aquifer does not discharge ground water to surface streams, the volume of water removed from storage during periods of no recharge nearly equals the volume of water removed from the aquifer by production wells, minus the amount of recharge from streams and the adjacent aquifer. In this analysis, the rate of recharge from streams and the adjacent aquifer was assumed to remain constant. Using water-level records for 1977-90, periods of water-level declines that lasted longer than two months were identified as periods of no recharge. For each period of no recharge, the amount of water pumped during the period, adjusted for water derived from streams and the adjacent aquifer, was divided by the amount of water-level change in the observation well during the period. This value was then divided by the area of the stressed part of the aquifer (0.99 mi^2 – 27 percent of the basin) to obtain an initial estimate of specific yield. Specific yield of the Cockeysville aquifer was estimated to be 0.09, using long-term ground-water records and equation 4. The specific-yield estimates for all periods of no recharge were then averaged to obtain a well value. This procedure was repeated for each of the five observation wells. The five well values were averaged to obtain the aquifer-wide specific-yield estimate of 0.09.

The discharge of ground water from storage in the unstressed part of the Cockeysville aquifer was 0.01 Mgal/d

(0.03 in.) in 1990 (Table 11). The average water-level change in observation wells Bb34-50 and Bb33-27 was 19.0 in., and the area of this part of the aquifer is 0.07 mi^2 (2 percent of the basin). Specific yield was assumed to be the same as in the stressed part of the aquifer, 0.09.

Evapotranspiration is defined as water removed from the basin by evaporation from water surfaces and by transpiration of plants. Calculated as a residual of the budget equation, evapotranspiration was 4.76 Mgal/d (27.33 in.) during 1990 (Table 9). As a check on this value, an empirical method for estimating evapotranspiration was used that relates evapotranspiration to soil and vegetation type, precipitation, temperature, and length of daylight (Thornthwaite and Mather, 1957). This method was modified slightly in this investigation. In the method, it is assumed that, during the months that soil moisture is less than the water-holding capacity of the soil, precipitation makes up the soil-moisture deficit before running off to streams. During several months in 1990, however, soil moisture was less than field capacity, but streams still received storm runoff. To improve the estimate of evapotranspiration, the amount of this storm runoff, 0.31 Mgal/d (1.78 in.), was subtracted from the precipitation value. The evapotranspiration estimate for 1990 by use of this modification was 4.75 Mgal/d (27.28 in.), which is nearly identical to the calculated value of 4.76 Mgal/d (27.33 in.).

The amount of base flow to streams, ground-water withdrawals, and changes in the amount of stored ground water was summed to calculate the amount of water that recharges the basinwide ground-water system. In equation form, the amount of basinwide ground-water recharge is calculated as:

Recharge =

base flow (1.09 Mgal/d) + withdrawals (1.48 Mgal/d) + water stored (-0.52 Mgal/d)

Ground-water recharge to the Mill Creek Basin in 1990 was 2.05 Mgal/d (11.77 in.).

Not all of the 2.05 Mgal/d is available for use by pumped wells in the Cockeysville aquifer. Because ground-water levels are below stream-bottom altitudes, the amount of recharge from stream leakage at any given time is at a maximum. Any base flow derived from the noncarbonate area in excess of the infiltration capacity of the stream bed leaves the area as streamflow. For example, in 1990, 1.09 Mgal/d (6.26 in.) of recharge was not available to pumped wells and left the basin as streamflow. The amount of recharge available to production wells in the Cockeysville aquifer, therefore, is significantly less than the basinwide recharge. For water-supply management, recharge to the Cockeysville aquifer is probably more important than basinwide recharge, because not all of the basinwide recharge is available for use.

Ground-Water Budget for the Stressed Part of the Cockeysville Aquifer

The ground-water budget for the stressed part of the Cockeysville aquifer can be estimated by use of the equation:

$$WP = R_s + R_p + R_a + \Delta S, \qquad (5)$$

where

WP = ground-water withdrawals,

R_s = ground-water recharge from infiltration of streamflow,

R_p = ground-water recharge from infiltration of precipitation,

R_a = ground-water recharge from adjacent aquifers, and

ΔS = change in ground-water storage.

For 1990, ΔS was -0.21 Mgal/d, R_s was 0.55 Mgal/d, and WP was about 1.48 Mgal/d.

Ground-water flow from adjacent aquifers cannot be measured directly, but under the White Briar housing development (Fig. 28) water levels in the Wissahickon Formation have been lowered in response to pumping in the Cockeysville aquifer. This effect is transmitted about 300 ft laterally into the Wissahickon Formation, but is not observed in the other rock formations that border the Cockeysville aquifer; therefore, recharge in this area will be to the Cockeysville aquifer. As a first approximation of the amount of cross-contact flow, an affected band 300 ft wide that runs the length of the contact between the Wissahickon Formation and the stressed part of the Cockeysville aquifer (10,000 ft) is assumed. Additionally, all recharge in this band is assumed to be directed to the Cockeysville aquifer (0.0027 ft/d).

The amount of ground water that flows across the contact can be calculated as:

$$10{,}000 \text{ ft} \times 300 \text{ ft} \times 0.0027 \text{ ft/d} = 8{,}100 \text{ ft}^3\text{/d} \ (0.06 \text{ Mgal/d}).$$

Rearranging the ground-water budget and solving for recharge from infiltration:

$$R_p = WP\ (1.48 \text{ Mgal/d}) - R_s\ (0.55 \text{ Mgal/d}) - R_a\ (0.06 \text{ Mgal/d}) - S\ (-0.22 \text{ Mgal/d})$$

Recharge from precipitation over the stressed part of the Cockeysville aquifer in 1990 was about 0.65 Mgal/d.

There is, however, some uncertainty in the values of recharge to the Cockeysville aquifer. For example, stream-discharge measurements are probably accurate to within ±5 percent of the stated value. Best-case and worse-case estimates of recharge from precipitation can be made by considering the uncertainty in the estimates of the other sources of recharge. Estimates of specific yield range from 0.06 to 0.12. Water-level declines in observation wells for 1990 ranged from 3.4 ft to 5.6 ft. The estimate for ground-water flow from adjacent aquifers could be in error by as much as 100 percent. Using these estimates, recharge from precipitation over the Cockeysville aquifer in 1990 could range from 0.37 to 0.86 Mgal/d (Table 12).

The 1990 ground-water budget for the stressed part of the Cockeysville aquifer illustrates that even during a wet year (average precipitation at Wilmington, Del., is 44.90 in/yr) recharge might not be sufficient to meet a demand of 1.48 Mgal/d, and some water must be removed from storage (0.22 Mgal/d in 1990).

The total amount of recharge to the Cockeysville aquifer can be estimated for previous years using water-level and ground-water withdrawal data. The annual total recharge to the aquifer can be calculated as:

$$R = WP + (\Delta WL \times Sy) \qquad (6)$$

Approximate recharge to the Cockeysville aquifer for 1978-90 is shown in Figure 40. The aquifer received the

TABLE 12

Range of estimates of areal recharge to the stressed part of the Cockeysville aquifer, 1990.
(Data in million gallons per day; Areal recharge = ground-water withdrawals – recharge from stream leakage – recharge from adjacent aquifers – change in amount of water stored)

Estimate	Ground-water withdrawals	Recharge from stream leakage	Recharge from adjacent aquifers	Change in amount of water stored	Areal recharge
Maximum	1.48	0.50	0.00	0.12	0.86
Minimum	1.48	0.60	0.12	0.39	0.37

most recharge in 1979 (2.5 Mgal/d) and the least recharge in 1980 (1.0 Mgal/d). Average annual recharge from 1978-90 was about 1.6 Mgal/d. The average withdrawal rate for this period was 1.6 Mgal/d. For the long term, therefore, ground-water withdrawals are about equal to recharge to the aquifer.

In the short term, however, recharge and withdrawals vary considerably. In years when recharge is greater than pumpage, the excess water is stored in the aquifer. Several consecutive years of less recharge than pumpage could lower the water level in the aquifer and reduce the amount of water stored. If water levels throughout the area fall below the regolith, the amount of water removed from storage per one foot drop in water level could be less than that in 1990 because of lower storage capability of the unweathered rocks of the Cockeysville aquifer. In this case, rates of water-level decline increase and it is possible that the aquifer might not meet water-supply demands. Additionally, development of the area overlying the aquifer could also increase the impervious area and decrease the amount of recharge from infiltration of precipitation.

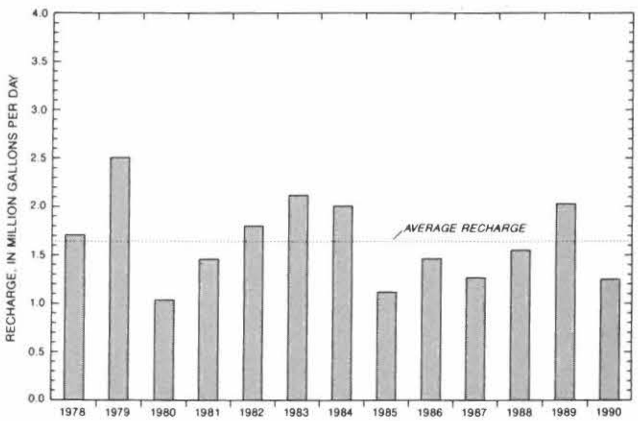


Figure 40. Annual recharge to the Cockeysville aquifer, 1978-90.

Effect of Reduced Recharge on the Ground-Water Budget for the Cockeysville Aquifer

Current land-use guidelines for New Castle County recommend that no more than 20 percent of an area being developed above the Cockeysville aquifer be impervious. Using these guidelines, an estimate was made of the decrease in recharge if the remaining undeveloped land overlying the stressed part of the Cockeysville aquifer was developed. Assumptions for the analysis were:

1. Only the remaining undeveloped portions of the area overlying the aquifer would be developed. All other land would remain as currently (1990) developed.
2. Recharge from precipitation would be at the 1990 rate of 0.65 Mgal/d. Current land use, percentage of coverage of the outcrop area, and amount of precipitation for each type of land use of the Cockeysville Formation are listed in Table 13.
3. All precipitation that falls on the impervious area is removed by storm sewers or lined ditches and is not available for recharge.
4. For each land use, recharge is uniform over the area.

TABLE 13

Land use over the stressed part of the Cockeysville aquifer, 1990.

Land use	Percentage of area used	Amount of precipitation (in million gallons per day)
Undeveloped	42.6	0.36
Parks	7.5	0.06
Suburban/residential	29.4	0.20
Urban/industrial	20.5	0.03

For these assumptions, under 1990 conditions, recharge from infiltration of precipitation would be reduced by about 0.07 Mgal/d if development of the remaining undeveloped area resulted in a loss of recharge of 20 percent.

During some years, recharge from precipitation is higher than it was in 1990, and the loss of recharge would be greater than 0.07 Mgal/d. This increased loss could be significant if a year of higher-than-normal recharge is followed by years of substantially lower recharge. During the dry period, the aquifer would be further depleted, with the result that the ability of the aquifer to sustain yields during prolonged dry periods would be significantly reduced.

SUMMARY AND CONCLUSIONS

The Hockessin area is a major source of ground water for northern Delaware. The area is underlain by the Cockeysville aquifer and a noncarbonate aquifer. The Cockeysville aquifer, which has an outcrop area of only 1.2 mi^2, supplies more water per square mile than any other fractured-rock aquifer in Delaware. Continued residential and commercial development in the area could threaten the water-supply capability of the aquifer.

Streams in the area include Mill Creek and unnamed tributaries to Red Clay Creek. Most streams originate in the noncarbonate aquifer and then flow over the Cockeysville aquifer. A streamflow-gaging station was installed on Mill Creek to monitor streamflow leaving the study area. In 1990, 905 Mgal of water left the Mill Creek Basin as streamflow, and 44 percent of the total was base flow. Minimum daily flow was 0.4 Mgal and maximum daily flow was 58 Mgal. Seepage investigations in 1990 indicated that streams in the Mill Creek Basin gained water from the noncarbonate aquifer and lost about 0.55 Mgal/d into the outcrop area of the Cockeysville aquifer. Reduction in base flow in the noncarbonate part of the study area could significantly reduce recharge to the Cockeysville aquifer.

The Cockeysville aquifer is composed of dolomite marble, calcite marble, calc-schist, and regolith (which is composed of angular, calcareous sand, and interbedded silt and clay). Regolith overlies unweathered rocks of the Cockeysville aquifer, and most areal recharge is received and stored by it and then slowly released to the underlying bedrock. In some areas, ground-water withdrawals in the Cockeysville aquifer have dewatered the regolith. The Cockeysville aquifer is used primarily as a source of public-water supply because fractures and solution channels in this carbonate aquifer can supply large amounts of water to wells. In the 1950s, water levels in the aquifer were higher than streams in the area, and the aquifer discharged ground water to local streams. Ground-water withdrawals from the aquifer have lowered water levels in the aquifer below streambed altitudes, so that in 1990 ground water in the aquifer discharged to production wells rather than to local streams. The aquifer is recharged by (1) infiltration of precipitation, (2) leakage from streams, and (3) adjacent noncarbonate aquifers. Aquifer-test and water-level data support the hypothesis that the Cockeysville aquifer has a low water-yielding potential where it is overlain by noncarbonate rocks. Water-level data indicate that the northern extension of the Cockeysville aquifer is hydrologically separated from the rest of the aquifer.

A noncarbonate aquifer surrounds the Cockeysville aquifer and is composed of metamorphosed sedimentary and igneous rocks that have much lower water-yielding potential than the carbonate aquifer. Little ground water flows from this aquifer to the Cockeysville aquifer, as determined on the basis of water-level, aquifer-test, and water-quality data. Most of the water in this aquifer discharges to streams that eventually flow across the Cockeysville outcrop area and lose water to it. Pegmatites and associated clay-weathering products are found throughout the area and can inhibit local ground-water flow.

Thirty-six ground-water and surface-water samples were analyzed for major ions, trace elements, nutrients, and radon. None of the samples contain concentrations of these constituents in excess of USEPA MCLs for drinking water. Nitrate and chloride concentrations indicate that ground water has been affected by human activity, however. Five additional water-quality samples were collected from the Cockeysville aquifer and analyzed for volatile organic compounds and organochlorine and organophosphorus pesticides. None of the samples contains detectable concentrations of these compounds.

Water budgets for the Mill Creek Basin and the stressed part of the Cockeysville aquifer were prepared to estimate fluxes of water and to estimate sources and rates of recharge to the Cockeysville aquifer. In 1990, 8.20 Mgal/d of water entered the Mill Creek Basin from precipitation and 0.52 Mgal/d was released from ground-water storage. Of the total water available, 4.76 Mgal/d left the basin through evapotranspiration, 2.48 Mgal/d through streamflow, and 1.48 Mgal/d through withdrawals from public-supply wells.

All ground water in the stressed part of the Cockeysville aquifer discharges through wells. In 1990, this amount of water totaled about 1.48 Mgal/d. Of the amount withdrawn, about 0.06 Mgal/d was from the adjacent noncarbonate aquifer, 0.55 Mgal/d was from leakage from streams, 0.65 Mgal/d was from areal recharge, and 0.22 Mgal/d was from ground-water storage. Flow from the noncarbonate aquifer and from stream leakage probably cannot increase, so that any deficit in areal recharge must be met by additional water released from ground-water storage. During 1978-90, ground-water withdrawals were about equal to total recharge to the aquifer, 1.6 Mgal/d. Assuming 1990 conditions, if recharge over the undeveloped area of the Cockeysville aquifer had been reduced by 20 percent, total recharge to the aquifer would have been reduced by 0.07 Mgal/d.

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APPENDIX 1

Conversion factors, Vertical Datum, and Abbreviated Water-Quality Units

Multiply	By	To obtain
inch (in.)	5.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
square mile (mi^2)	2.59	square kilometer
gallon per minute per foot ((gal/min)/ft)	0.2070	liter per second per meter
million gallons (Mgal)	3.78	cubic meter
foot per day (ft/d)	0.305	meter per day
foot squared per day (ft^2/d)	0.9290	meter squared per day
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
cubic foot per day (ft^3/d)	0.02832	cubic meter per day
gallon per minute (gal/min)	0.06308	liter per second
million gallons per day (Mgal/d)	0.04381	cubic meter per second
inch per year (in/yr)	25.4	millimeter per year

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929—a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929.

Abbreviated water-quality units used in this report: Chemical concentrations and water temperature are expressed in metric units. Chemical concentration is given in milligrams per liter (mg/L) or micrograms per liter (µg/L).

Temperature is given in degrees Celsius (°C), which can be converted to degrees Fahrenheit (°F) by use of the following equation:

$$F = 1.8\ (^{\circ}C) + 32$$

Specific conductance of water is expressed in microsiemens per centimeter at 25 degrees Celsius (mS/cm). This unit is equivalent to micromhos per centimeter at 25 degrees Celsius (mmho/cm), formerly used by the U.S. Geological Survey.

Radioactivity is expressed in picocuries per liter (pCi/L). A picocurie is one-trillionth (1×10^{-12}) the amount of radioactivity represented by a curie (Ci). A curie is the amount of radioactivity that yields 3.7×10^{10} radioactive disintegrations per second. A picocurie yields 2.22 disintegrations per minute.

The standard unit for transmissivity (T) is cubic foot per day per square foot times foot of aquifer thickness ($[(ft^3/d)/ft^2]ft$). This mathematical expression reduces to foot squared per day (ft^2 /d).

APPENDIX 2

Map coordinates for rock samples used for modal analyses

DGS #	Sample #	Latitude	Longitude	Quadrangle
Baltimore Gneiss				
Bb25-s	41798	39°48'31"	75°40'34"	Kennett Square
Bb34-b	41805	39°47'35"	75°41'36"	Kennett Square
Bb34-c	41967	39°47'45"	75°41'58"	Kennett Square
Bb42-b	41819	39°46'58"	75°43'03"	Kennett Square
Bb25-p	41842	39°48'40"	75°40'14"	Kennett Square
Bb25-q	41940	39°48'32"	75°40'40"	Kennett Square
Bb25-b	42363	39°48'23"	75°40'47"	Kennett Square
Bc11-b	58158	39°49'39"	75°39'22"	Kennett Square
Bb25-r	42312	39°48'10"	75°40'39"	Kennett Square
Bb35-b	41942	39°47'47"	75°40'57"	Kennett Square
Bb24-a	42362	39°48'19"	75°41'03"	Kennett Square
Bb14-a	58155	39°49'09"	75°41'26"	Kennett Square
Bb23-h	58135	39°48'22"	75°42'32"	Kennett Square
Bb34-d	42364	39°47'51"	75°41'15"	Kennett Square
Cockeysville Formation				
Bb33-25	24858	39°47'03"	75°42'18"	Kennett Square
Bb34-39	24748-15	39°47'17"	75°41'57"	Kennett Square
Bb34-44	24811	39°47'17"	75°41'57"	Kennett Square
Cb12-8	26233	39°44'18"	75°43'17"	Newark East
Bb43-13	80575	39°46'54"	75°42'18"	Kennett Square
Bb25-23	25396	39°48'43"	75°40'12"	Kennett Square
Cb12-10	H-6	39°44'27"	75°43'11"	Newark East
Cb12-10	H-15	39°44'27"	75°43'11"	Newark East
Cb12-6	23312	39°44'44"	75°43'01"	Newark East
Cb12-18	81187	39°44'42"	75°43'17"	Newark East
Bb34-34	80517	39°47'14"	75°41'43"	Kennett Square
Bb34-42	24804	39°47'17"	75°41'57"	Kennett Square
Wissahickon Formation				
Ca23a	41818	39°43'38"	75°47'22"	Newark West
Ca35b	41938	39°42'29"	75°45'37"	Newark West
Cb14b	41934	39°44'39"	75°41'44"	Newark East
Bc21r	41946	39°48'25"	75°39'06"	Kennett Square
Bc24b	42325	39°48'22"	75°36'16"	Wilmington North
Bc31b	UoD M-6	39°47'40"	75°34'39"	Newark East
Cb13-9	80160	39°44'12"	75°42'50"	Kennett Square
Bb25c	42342	39°48'29"	75°40'19"	Kennett Square
Bb33d	42332	39°47'47"	75°42'33"	Kennett Square
Bb33c	42335	39°47'36"	75°42'55"	Kennett Square
Bb33-16	60628	39°47'47"	75°42'24"	Kennett Square
Bb33b	41941	39°47'21"	75°42'23"	Kennett Square
Bc32b	UoD H130	39°47'32"	75°38'43"	Kennett Square
Bc32o	UoD H129	39°47'21"	75°38'37"	Kennett Square
Setters Formation				
Cb12a	42339	39°44'25"	75°43'03"	Newark East
Cb12a	42340	39°44'25"	75°43'03"	Newark East

APPENDIX 3

Records of wells in the Hockessin and Pleasant Hill areas by Deborah A. Bringman.

Topographic Setting:
F – Flat
H – Hilltop
K – Sink
S – Hillside
V – Valley Flat

Aquifer:
bg – Baltimore Gneiss
cm – Cockeysville
wu – Wissahickon

Water Use:
C – Commercial
D – Domestic
F – Fire
I – Industrial
M – Monitor
N – None
O – Observation
P – Public
R – Irrigation
T – Test
U – Unknown

APPENDIX 3

Records of wells in the Hockessin and Pleasant Hill areas.

DGS Well No.	Owner	Driller	Date Constructed	Altitude of Land Surface (ft.)	Topographic Setting	Depth Drilled (ft.)	Diameter of Casing (in.)	Depth of Casing (ft.)
Bb24-02	Biederman, H.	Slauch & Son	00-00-54	390	V	73	6	55
Bb24-05	McGlinchy	Auld	00-00-55	340	S	44	6	30
Bb24-06	Fraim, Donald	Walton Corp.	12-22-65	315	S	156	6	21
Bb24-07	Auburn Development	Duffy-Gastor	08-30-74	375	S	100	6	42
Bb24-08	Auburn Development	Duffy-Gastor	04-11-74	300	S	125	6	45
Bb25-03	Trimble, David	Slauch & Son	05-00-55	195	S	71	6	—
Bb25-05	Trimble, David	Slauch & Son	04-22-55	210	S	130	6	123
Bb25-06	Trimble, David	Slauch & Son	04-13-55	215	S	48.9	6	9
Bb25-07	—	—	—	200	S	—	—	—
Bb25-10	National Vul. Fibre Co.	Kennett	08-05-54	170	V	46	5.63	24
Bb25-13	National Vul. Fibre Co.	Kennett	10-21-54	270	S	100	6	10
Bb25-14	Concord Real Estate	—	00-00-00	175	V	20	144	20
Bb25-17	DGS	DGS	02-17-81	180	F	22.3	—	—
Bb25-21	Taylor, Thomas	—	12-03-85	185	S	240	6	80
Bb25-22	Uhde, George	Powell	07-11-86	190	V	355	6	105
Bb25-23	DGS	DGS	11-02-90	180	F	38.5	—	—
Bb25-24	DGS	DGS	11-02-90	190	F	32.7	—	—
Bb32-01	Thurlow, C.	—	1800's	350	S	35	3	3
Bb32-03	Artesian Water Co.	Layne-N. Y.	07-25-74	350	H	250	12	29
Bb32-04	Callough, James G.	Walton Corp.	05-23-75	330	S	180	6	105
Bb32-05	Fritze	—	00-00-40	360	S	30	—	30
Bb32-06	Carlozzi, Kathy	—	00-00-00	320	V	21	48	21
Bb32-07	Mumford, Charles	—	00-00-86	370	S	100	6	—
Bb33-01	Persoglia, Anna	Meyers	00-00-28	275	V	63	6	63
Bb33-02	Pierson, Wilson	Walton Corp.	10-01-53	320	S	58	6	40
Bb33-03	Pierson, Wilson	—	10-01-53	310	S	63	6	43
Bb33-04	Pierson, Wilson	—	10-05-53	310	S	47	6	30
Bb33-05	Gray, R.	—	00-00-10	258	V	18	48	18
Bb33-06	McGovern J.	—	00-00-20	390	H	60	4	60
Bb33-09	Higgins, George	Walton Corp.	12-00-54	300	V	92	6	27
Bb33-11	Artesian Water Co.	Artesian	01-00-70	252	F	312	18	28
Bb33-12	Artesian Water Co.	Artesian	04-00-68	260	V	332	18	52
Bb33-13	Artesian Water Co.	Artesian	08-00-68	250	S	163	6	43.6
Bb33-14	Artesian Water Co.	Weiand	02-00-77	300	S	298	5.63	45
Bb33-15	Artesian Water Co.	Weiand	02-00-77	275	S	298	6.63	62.2
Bb33-17	Green, R.	—	09-29-70	290	H	270	5	105
Bb33-18	Bates Jr., Philip K.	Duffy-Gastor	09-18-74	310	S	120	6	54
Bb33-19	Wellington Hills	Duffy-Gastor	06-10-74	362	H	80	6	48
Bb33-20	Wellington Hills	Duffy-Gastor	10-07-74	350	H	82	6	74
Bb33-22	Gardner, David	Duffy-Gastor	06-03-74	310	S	140	6	52
Bb33-23	NCC Parks & Recreation	DGS	06-24-80	251	K	58.4	-	—
Bb33-24	NCC Parks & Recreation	DGS	08-12-80	273	K	65.6	-	—
Bb33-26	Artesian Water Co.	Walton Corp.	06-15-89	280	V	340	6	74
Bb33-27	Artesian Water Co.	Walton Corp.	06-19-89	300	S	360	6	59
Bb33-28	McGrellis, John J.	Walton Corp.	03-14-90	260	V	340	6	101
Bb33-29	Mitchell, Robert	—	—	345	V	40	6	40
Bb33-31	Artesian Water Co.	—	—	254	V	—	—	—
Bb33-32	Boylan, James	Madron	04-21-88	360	S	150	6	50
Bb33-33	DGS	DGS	10-25-90	—	F	—	—	—
Bb33-34	—	—	—	280	H	—	—	—
Bb33-35	Saunders, Richard	—	00-00-00	370	S	—	—	—
Bb33-36	DGS	DGS	07-12-91	—	V	95	—	—
Bb33-37	Hunt, James	—	00-00-84	325	S	—	6	—
Bb33-39	Domanski, Peter	Walton Corp.	00-00-89	320	S	168	6	83
Bb34-02	Schultz, William	—	12-28-53	370	S	192	6	190
Bb34-07	Diamond Ice & Coal Co.	—	04-01-55	260	V	159	6	156
Bb34-08	Hockessin Fire Co.	Slauch & Son	07-01-55	260	V	54	6	54
Bb34-09	Lake, Joseph	Slauch & Son	06-20-55	375	S	161	6	24
Bb34-13	Artesian Water Co.	Artesian	02-28-72	245	F	190	24	24
Bb34-27	Chiffons, Eldridge	Slauch & Son	07-11-57	260	V	93	6	82
Bb34-29	Artesian Water Co.	Artesian	04-00-74	265	F	273	8	42
Bb34-30	Ahrens, James	Walton Corp.	01-24-75	265	V	230	6	110
Bb34-31	Artesian Water Co.	—	03-30-79	250	V	60	—	—
Bb34-32	Artesian Water Co.	Artesian	—	260	V	165	16	44
Bb34-33	Artesian Water Co.	Layne	01-28-74	255	V	305	—	—
Bb34-34	Artesian Water Co.	Weiand	02-00-77	260	F	298	6.63	145
Bb34-35	Artesian Water Co.	Weiand	02-00-77	260	F	248	6.63	104
Bb34-36	Artesian Water Co.	Weiand	02-00-77	260	V	248	6.63	61.5
Bb34-37	Bell, Gertrude	DGS	06-06-78	280	V	137	—	—
Bb34-40	NCC Parks & Recreation	DGS	03-28-79	253.1	K	70	4	44.6
Bb34-42	NCC Parks & Recreation	DGS	04-14-79	251	K	65	4	35
Bb34-45	Bell, Gertrude	DGS	03-20-80	390	S	31	—	—
Bb34-46	NCC Parks & Recreation	DGS	03-27-80	253	K	52.5	—	—

APPENDIX 3 (continued)

Records of wells in the Hockessin and Pleasant Hill areas.

Aquifer	Water level (ft.)	Date Measured	Drawdown (ft.)	Discharge (gal/min)	Hours Pumped	Specific Capacity (gal/min/ft of drawdown)	Water Use	DGS Well No.
bg	46	01-06-55	—	—	—	—	R	Bb24-02
bg	18	01-03-55	—	—	—	—	D	Bb24-05
bg	8.5m	05-22-90	98	10	4	0.10	D	Bb24-06
bg	40	08-30-74	20	10	2	0.50	P	Bb24-07
bg	20	04-11-74	60	8	2	0.13	D	Bb24-08
cm	10.5m	06-28-55	—	—	—	—	D	Bb25-03
cm	13.7m	06-28-55	—	6	1	—	D	Bb25-05
cm	11.6m	06-28-55	6	15	2	2.50	D	Bb25-06
cm	24.8	11-04-88	—	—	—	—	U	Bb25-07
bg	14	08-05-55	3	40	24	13.3	I	Bb25-10
bg	31	10-21-54	55	8	1	—	D	Bb25-13
bg	10.1m	03-12-55	—	—	—	—	U	Bb25-14
wu	3.30	02-17-81	—	—	—	—	N	Bb25-17
bg	28.0	12-03-85	—	—	—	—	D	Bb25-21
cm	40	07-15-86	18	8.5	1	0.05	D	Bb25-22
cm	—	—	—	—	—	—	N	Bb25-23
cm	—	—	—	—	—	—	N	Bb25-24
bg	29	01-00-54	—	—	—	—	D	Bb32-01
bg	23.3m	07-25-74	—	—	—	—	U	Bb32-03
bg	10.0m	11-03-89	79	15	4	0.19	D	Bb32-04
bg	—	—	—	—	—	—	D	Bb32-05
bg	16.0m	11-03-89	—	—	—	—	U	Bb32-06
wu	18.3m	05-23-90	—	—	—	—	D	Bb32-07
cm	6.19m	11-12-53	—	—	—	—	U	Bb33-01
bg	40	10-01-53	—	10	—	—	D	Bb33-02
bg	40	11-30-53	13	7	6	0.54	D	Bb33-03
bg	34	10-05-53	8.00	10	6	1.25	D	Bb33-04
cm	11.4m	01-04-55	—	—	—	—	D	Bb33-05
wu	4	01-02-55	—	—	—	—	D	Bb33-06
cm	23.7m	10-25-89	48	10	6	0.21	D	Bb33-09
cm	21.9	12-00-70	—	450	—	—	P	Bb33-11
cm	12.5	03-00-70	—	1000	—	5	P	Bb33-12
cm	—	—	—	—	—	—	O	Bb33-13
wu	6.68m	03-09-77	—	30	—	—	O	Bb33-14
cm	45.1m	03-10-77	—	100	—	—	O	Bb33-15
wu	30	09-29-70	—	—	—	—	D	Bb33-17
cm	15.0	09-18-74	45	40	1	0.89	D	Bb33-18
wu	10	06-10-74	10	10	2	1.00	D	Bb33-19
wu	20	10-07-74	20	25	2	1.25	D	Bb33-20
cm	42.9m	10-27-89	30	15	2	0.50	D	Bb33-22
cm	—	—	—	—	—	—	N	Bb33-23
wu	9.10	08-06-80	—	—	—	—	N	Bb33-24
cm	3	06-15-89	197	200	5	1.02	P	Bb33-26
cm	4.5m	08-16-89	—	300	—	—	P	Bb33-27
cm	35.7m	07-31-90	170	30	4	0.18	D	Bb33-28
wu	—	—	—	—	—	—	D	Bb33-29
cm	—	—	—	—	—	—	P	Bb33-31
wu	22	04-21-88	13	8.00	8	0.62	D	Bb33-32
cm	—	—	—	—	—	—	N	Bb33-33
wu	—	—	—	—	—	—	D	Bb33-34
wu	12.2m	11-16-90	—	—	—	—	D	Bb33-35
—	23.5	07-12-91	—	—	—	—	N	Bb33-36
wu	5.1m	05-23-90	—	—	—	—	D	Bb33-37
wu	9.4m	11-02-89	—	30	—	—	D	Bb33-38
wu	25m	12-28-53	45	8	6	0.18	D	Bb34-02
cm	12	04-29-55	—	—	—	—	U	Bb34-07
cm	13.3m	07-01-55	12	30	3	2.50	F	Bb34-08
wu	20	06-20-55	—	4	1	—	D	Bb34-09
cm	—	—	—	—	—	—	P	Bb34-13
cm	11.0	07-11-57	—	15	1	—	D	Bb34-27
cm	28.4	04-00-74	—	—	—	—	P	Bb34-29
cm	23m	01-24-75	77	8	4	0.10	D	Bb34-30
—	—	—	—	—	—	—	—	Bb34-31
cm	12	06-00-73	—	—	—	—	O	Bb34-32
cm	18.5	01-28-74	—	—	—	—	P	Bb34-33
cm	37.3m	03-07-77	—	—	—	—	O	Bb34-34
cm	47.5m	03-07-77	—	—	—	—	O	Bb34-35
cm	—	—	—	—	—	—	O	Bb34-36
cm	—	—	—	—	—	—	N	Bb34-37
cm	31.9m	03-28-79	—	—	—	—	O	Bb34-40
cm	40.2	04-20-79	—	—	—	—	O	Bb34-42
bg	—	—	—	—	—	—	N	Bb34-45
cm	41.2	03-28-80	—	—	—	—	N	Bb34-46

APPENDIX 3 (continued)

Records of wells in the Hockessin and Pleasant Hill areas.

DGS Well No.	Owner	Driller	Date Constructed	Altitude of Land Surface (ft.)	Topographic Setting	Depth Drilled (ft.)	Diameter of Casing (in.)	Depth of Casing (ft.)
Bb34-47	NCC Parks & Recreation	DGS	04-21-80	248	K	116	—	—
Bb34-48	Shoppes of Hockessin	Walton Corp.	04-07-83	260	F	64	2	55
Bb34-49	Shoppes of Hockessin	Walton Corp.	04-12-83	260	V	50.5	2	44
Bb34-50	Artesian Water Co.	Walton Corp.	06-19-89	300	V	340	6	59
Bb34-52	Barnyard Gardens	Walton Corp.	04-29-74	270	F	180	5	155
Bb34-53	DGS	DGS	07-17-90	285	S	89.2	—	—
Bb34-54	DGS	DGS	07-24-90	280	S	77.7	—	—
Bb34-55	DGS	DGS	08-27-90	290	S	61	—	—
Bb34-56	Suloff, Edward	—	00-00-82	330	S	60	6	—
Bb34-57	Fair, S.	Walton Corp.	00-00-75	275	S	60	6	—
Bb34-58	Suloff, Edward	—	00-00-60	325	S	60	6	—
Bb34-59	DGS	DGS	12-31-90	255	V	51	—	—
Bb34-65	Nardozzi, J.	Powell	00-00-00	289	S	120	6	—
Bb34-66	Nardozzi, M.	—	00-00-00	292	S	—	6	—
Bb34-67	Brandeth	—	00-00-00	300	S	—	6	—
Bb34-68	Nelson	Powell	00-00-00	320	S	—	6	—
Bb34-69	Hyrdam	Powell	00-00-00	325	S	—	6	—
Bb34-70	Giobbe	Powell	00-00-00	315	S	—	6	—
Bb34-71	—	—	00-00-00	295	S	—	6	—
Bb35-01	Hackett, R. G.	Walton Corp.	04-06-54	260	S	110	6	44
Bb35-09	Dill, George	Walton Corp.	01-19-63	360	H	245	6	70
Bb35-10	Valley View	Duffy-Gastor	10-02-74	350	H	80	6	45
Bb35-11	Valley View	Duffy-Gastor	10-18-73	320	H	105	6	45
Bb35-12	Valley View	Duffy-Gastor	12-05-73	370	H	230	6	52
Bb35-13	Swift, Kenneth	Walton Corp.	08-26-85	210	F	140	6	116
Bb35-14	Boyd, Philip S.	Walton Corp.	11-13-85	320	H	500	6	48
Bb35-15	Elliot, N.	—	—	228	V	75	6	—
Bb35-16	DGS	Walton Corp.	08-19-91	250	S	530	6	96
Bb42-05	Meco Partnership	Walton Corp.	07-19-89	287.5	S	71	2	64
Bb43-03	Hockessin Foods	Slauch & Son	00-00-49	270	V	36.6	8	—
Bb43-08	Baldassari, Frank	Slauch & Son	00-00-50	290	H	369	6	330
Bb43-09	Schaller, Leon	Walton Corp.	09-25-52	340	S	123	6	101
Bb43-10	Giacomelli, Alfred	Slauch & Son	02-07-55	270	V	125	6	123
Bb43-13	Artesian Water Co.	Weiand	02-00-77	260	F	287	6	82.7
Bb43-15	Foskey, H. T.	DGS	04-17-80	380	K	87.5	-	—
Bb43-16	Hockessin Mushroom Prod.	Walton Corp.	03-22-85	270	F	257	6	99
Bb43-16	Hockessin Mushroom Prod.	Walton Corp.	03-22-85	270	V	257	6	99
Bb43-17	Meco Partnership	Walton Corp.	07-17-89	275	V	59	2	54
Bb43-18	Lantana Square	Walton Corp.	02-24-88	260	V	55	2	49
Bb43-19	Lantana Square	Walton Corp.	02-23-88	240	V	50	2	44
Bb43-20	Lantana Square	Walton Corp.	02-23-88	270	V	50	2	44
Bb43-21	Baldini, Inc.	Walton Corp.	05-19-89	245	V	29.2	2	24
Bb43-22	Baldini, Inc.	Walton Corp.	05-19-89	240	V	34.6	2	29
Bb43-23	Foskey Jr., Horace	Mayberry	07-29-71	275	V	76	6	—
Bb43-24	Valley Road Association	Walton Corp.	05-12-89	265	V	64	2	59
Bb43-25	Valley Road Association	Walton Corp.	05-08-89	285	V	39	2	34
Bb43-26	Camoirano, Charles	Madron	08-00-87	265	V	126	6	120
Bb43-27	Kuhn Construction	—	00-00-00	254	V	—	6	—
Bb43-28	Kolcum	—	—	260	V	—	6	—
Bb44-02	Alexander, James A.	Walton Corp.	08-15-53	350	H	77	6	—
Bb44-03	Newton, James	Walton Corp.	05-21-53	280	H	82	6	40
Bb44-04	Ford, Raymond	Walton Corp.	00-00-53	248	V	57	6	48
Bb44-07	Brubaker, A. A.	Walton Corp.	09-27-54	240	V	83	6	38
Bb44-08	LeCompte	Walton Corp.	00-00-54	300	H	124	6	32
Bb44-09	Peterson, Dorset	Slauch & Son	06-24-55	240	S	112	6	97
Bb44-10	Kreibel, Norman	Walton Corp.	06-04-55	250	H	76.8	6	26
Bb44-11	Walker, R. B.	—	00-00-50	340	V	24.2	48	—
Bb44-13	Artesian Water Co.	Artesian	02-29-72	245	F	190	18	130
Bb44-18	Walker, J. B.	Walton Corp.	02-25-72	350	H	205	5	70
Bb44-19	Ogorek, Ed Jr.	—	—	230	V	63	6	63
Bb44-22	Artesian Water Co.	Layne	07-00-73	250	V	290	8	18
Bb44-26	Walker Greenhouses	Walton Corp.	08-26-77	330	H	205	6	62
Bb44-27	Ford, Raymond	Walton Corp.	10-24-53	250	V	57	6	48
Bb44-28	Brackin, Bayard	Walton Corp.	06-26-64	300	H	126	5	28
Bb44-29	Davitt, H.	—	00-00-70	265	S	300	6	—
Bb44-30	DGS	Walton Corp.	07-01-91	225	V	100	—	—
Bc21-07	Berg, James	Madron	09-14-89	205	U	150	6	—
Cb12-10	Flinn, Margaret	Walton Corp	09-25-73	175	F	410	6	103
Cb12-13	Patterson, Walter	Walton Corp	11-07-75	235	F	417	6	92
Cb12-18	Waxman, Ronald	Walton Corp	12-06-78	210	F	230	6	74
Cb13-09	Schlosser, Paul	Walton Corp	04-30-76	200	V	417	6	97.5
Cb13-11	Artesian Water Co.	—	—	150	V	—	—	—
Cb13-16	Artesian Water Co.	Walton Corp	05-31-94	200	F	580	6	79

APPENDIX 3 (continued)

Records of wells in the Hockessin and Pleasant Hill areas.

Aquifer	Water level (ft.)	Date Measured	Drawdown (ft.)	Discharge (gal/min)	Hours Pumped	Specific Capacity (gal/min/ft of drawdown)	Water Use	DGS Well No.
cm	41	04-21-80	—	—	—	—	N	Bb34-47
bg	—	04-15-83	—	—	—	—	O	Bb34-48
cm	26.1m	04-12-83	—	—	—	—	O	Bb34-49
cm	4.5m	06-30-89	—	—	—	—	O	Bb34-50
bg	33.8m	08-27-74	73	25	4	0.34	D	Bb34-52
cm	10	07-20-90	—	—	—	—	N	Bb34-53
cm	32.10	07-25-90	—	—	—	—	N	Bb34-54
cm	—	—	—	—	—	—	N	Bb34-55
cm	7.0m	03-23-90	—	—	—	—	D	Bb34-56
bg	—	—	—	—	—	—	D	Bb34-57
wu	—	—	—	—	—	—	D	Bb34-58
cm	—	—	—	—	—	—	N	Bb34-59
cm	52.7m	11-15-90	—	—	—	—	U	Bb34-65
cm	47.3m	11-15-90	—	—	—	—	U	Bb34-66
bg	48.1m	11-15-90	—	—	—	—	D	Bb34-67
bg	24.4m	11-15-90	—	—	—	—	U	Bb34-68
bg	15.3m	11-15-90	—	—	—	—	U	Bb34-69
bg	7.8m	11-15-90	—	—	—	—	D	Bb34-70
bg	29	11-15-90	—	—	—	—	D	Bb34-71
wu	18	04-06-54	72	4	6	0.06	D	Bb35-01
wu	28	01-19-63	217	4	4	0.02	D	Bb35-09
wu	50	10-02-74	—	—	—	—	D	Bb35-10
wu	20	10-18-73	23	7	2	0.30	D	Bb35-11
wu	50	12-05-73	70	6	2	0.09	D	Bb35-12
cm	25	08-26-85	55	40	4	0.73	D	Bb35-13
wu	38	11-13-85	412	2	4	0.00	D	Bb35-14
cm	—	—	—	—	—	—	D	Bb35-15
cm	34.66	03-08-77	—	—	—	—	O	Bb35-16
cm	3.2m	07-25-89	—	—	—	—	M	Bb42-05
wu	3.7m	06-27-55	—	—	—	—	I	Bb43-03
cm	11.8m	11-12-53	—	15	—	—	D	Bb43-08
cm	42.6m	11-30-53	35	3	6	0.09	R	Bb43-09
cm	18.3m	02-09-55	44	25	1	0.57	D	Bb43-10
cm	34.7m	03-08-77	—	—	—	—	O	Bb43-13
cm	18	—	—	—	—	—	N	Bb43-15
cm	20	03-22-85	—	—	—	—	I	Bb43-16
cm	16.5m	11-07-89	50	50	4	1.00	C	Bb43-16
cm	22.8	07-25-89	—	—	—	—	M	Bb43-17
cm	46	02-24-88	—	—	—	—	U	Bb43-18
cm	34	02-23-88	—	—	—	—	U	Bb43-19
cm	39	02-23-88	—	—	—	—	U	Bb43-20
cm	12.8m	05-17-90	—	—	—	—	U	Bb43-21
cm	21.6m	05-17-90	—	—	—	—	U	Bb43-22
cm	—	—	—	—	—	—	D	Bb43-23
cm	24	05-12-89	—	—	—	—	U	Bb43-24
bg	12.5	05-08-89	—	—	—	—	U	Bb43-25
cm	12	08-00-87	—	—	—	—	D	Bb43-26
cm	20.1	05-25-90	—	—	—	—	D	Bb43-27
cm	—	—	—	—	—	—	D	Bb43-28
wu	26.9m	11-30-53	20	5	6	0.17	D	Bb44-02
wu	20m	05-21-53	30	10	8	0.33	D	Bb44-03
cm	12	10-24-53	3	20	4	6.67	D	Bb44-04
wu	25	01-06-55	20	10	6	—	D	Bb44-07
wu	30	12-25-54	60	12	4	0.20	D	Bb44-08
—	24	06-24-55	—	—	—	—	D	Bb44-09
wu	22.7m	07-14-55	38.0	8	4	0.21	D	Bb44-10
wu	20.4m	01-04-55	—	—	—	—	U	Bb44-11
cm	—	—	12	150	7	<12.5	P	Bb44-13
wu	—	—	142	5	4	0.04	C	Bb44-18
—	7.55	07-25-72	—	—	—	—	—	Bb44-19
cm	.95m	08-02-90	—	—	—	—	U	Bb44-22
wu	40	08-26-77	85	15	4	0.18	D	Bb44-26
cm	12	10-24-53	3	20	4	6.67	D	Bb44-27
wu	22	06-26-54	78	3	4	0.04	D	Bb44-28
wu	—	—	—	—	—	—	D	Bb44-29
cm	—	—	—	—	—	—	O	Bb44-30
cm	19	05-24-90	—	—	—	—	D	Bc21-07
cm	9.1	01-12-78	—	—	—	—	O	Cb12-10
wu	8.25	11-07-75	—	60	—	—	-	Cb12-13
cm	32.1	12-??-78	—	—	—	—	D	Cb12-18
wu	+22.4	05-10-76	197.4	200	49.3	1.01	T	Cb13-09
—	—	—	—	—	—	—	T	Cb13-11
cm	19.1	07-13-94	274	205	24	0.7	T	Cb13-16

APPENDIX 4

Chemical analyses of ground water and surface water in the Hockessin area.

(µ/cm = microsiemens per centimeter at 25 degrees Celsius; mg/L = milligrams per liter; µg/L = micrograms per liter; pCi/L = picocuries per liter < = less than; — = no data; cm = Cockeysville aquifer; nca = noncarbonate aquifer)

Site	Aquifer	Date	Specific conduc-tance (µs/cm)	pH, field (standard units)	Oxygen, dissolved (mg/L)	Calcium, dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)	Sodium, dissolved (mg/L as Na)	Potassium, dissolved (mg/L as K	Alkalinity, total field (mg/L as CaCO3)	Sulfate, dissolved (mg/L as SO)
Bb24-06	nca	02-21-91	296	5.6	7.5	24	9.3	16	1.6	20	23
Bb33-11	cm	08-23-90	495	7.2	5.5	56	27	9.1	0	200	25
Bb33-12	cm	08-23-90	660	7.1	3.7	80	36	10	3.4	260	45
Bb33-13	cm	08-14-90	451	7.6	—	57	28	6.0	2.2	210	35
Bb33-14	nca	08-13-90	181	7.2	0.5	12	7.6	7.1	3.2	55	31
Bb33-15	cm,nca	08-14-90	409	7.5	5.0	57	18	5.1	2.5	190	17
Bb33-26	cm	09-27-90	355	7.5	3.0	49	14	7.0	2.2	130	22
Bb33-27	cm	08-30-90	273	8.0	5.7	30	16	3.9	1.6	120	1.9
Bb33-28	cm	08-23-90	603	7.3	1.8	74	32	8.5	4.0	260	35
Bb33-29	nca	09-05-90	174	5.9	8.0	12	4.6	10	2.1	23	15
Bb33-32	nca	09-25-90	230	6.0	6.3	24	8.9	4.0	3.4	45	35
Bb33-34	nca	09-26-90	215	5.9	6.4	21	6.9	8.3	2.4	34	17
Bb34-27	cm	09-24-90	645	7.0	3.1	78	40	7.3	1.8	280	36
Bb34-29	cm	09-04-90	548	7.3	2.8	61	31	8.3	2.1	230	27
Bb34-31	cm	08-29-90	560	7.6	—	66	32	7.5	2.2	240	33
Bb34-33	cm	09-04-90	480	7.6	5.8	52	29	5.0	1.6	200	28
Bb34-34	cm	08-22-90	591	7.5	3.7	68	37	5.8	0.90	210	70
Bb34-36	cm	08-29-90	445	7.2	0.4	55	27	6.3	1.0	210	19
Bb34-40	cm	09-25-90	489	7.4	3.6	58	30	6.7	2.3	—	30
Bb34-50	cm,nca	08-30-90	273	6.4	5.0	31	6.7	11	3.3	55	27
Bb34-57	nca	02-22-91	242	5.8	6.5	27	6.1	8.5	2.0	35	25
Bb34-58	nca	09-26-90	215	5.7	4.1	20	8.0	9.1	2.0	33	36
Bb35-14	nca	09-24-90	169	7.3	2.9	20	3.8	7.0	1.9	54	26
Bb35-15	cm	09-05-90	276	6.5	4.6	41	8.2	7.7	2.1	90	23
Bb43-13	cm	09-27-90	434	7.5	4.2	54	28	4.9	1.5	210	20
Bb43-28	cm	02-21-91	392	7.5	3.6	45	24	5.3	3.1	180	6.1
Bb44-13	cm	09-04-90	383	7.7	5.4	46	18	5.3	3.3	150	18
Bb44-22	cm, nca	08-21-90	216	7.2	2.3	18	7.9	4.2	1.6	61	10
Bb44-29	nca	02-22-91	166	7.8	0.2	19	4.3	7.4	2.4	57	23
01479175		04-01-91	203	6.3	13.0	17	7.3	7.1	2.1	29	20
01479189		04-01-91	300	6.9	14.2	25	9.6	9.9	4.1	44	35
01479191		04-01-91	269	8.0	15.3	25	9.4	9.9	4.0	43	36
01479193		04-05-91	232	4.9	12.3	21	7.6	9.2	2.7	9	32
01479195		04-01-91	182	6.6	8.3	16	5.4	7.0	3.5	31	18
01479195b		04-05-91	259	7.4	—	17	6.1	8.2	19	59	20
01479197		04-01-91	253	6.5	10.0	23	8.2	9.6	4.2	46	29

APPENDIX 4 (continued)

Chemical analyses of ground water and surface water in the Hockessin area.

(µ/cm = microsiemens per centimeter at 25 degrees Celsius; mg/L = milligrams per liter; µg/L = micrograms per liter; pCi/L = picocuries per liter < = less than; — = no data; cm = Cockeysville aquifer; nca = noncarbonate aquifer)

Chloride, dissolved (mg/L as Cl)	Fluoride, dissolved (mg/L as F)	Silica, dissolved (mg/L as SiO)	Solids, sum of constituents, dissolved (mg/l)	Nitrogen, nitrite dissolved (mg/L as N)	Nitrogen, NO + NO dissolved (mg/L as N)	Nitrogen, ammonia dissolved (mg/L as N)	Nitrogen, ammonia + organic, dissolved (mg/L as N)	Phosphorus, ortho, dissolved (mg/L as P)	Aluminum, dissolved (µg/L as Al)	Antimony, dissolved (µg/L as Sb)	Site
58	<0.1	25	179	<0.01	2.1	0.01	<0.20	0.04	<10	<1	Bb24-06
17	0.1	17	292	<0.01	3.9	0.01	0.50	0.02	<10	<1	Bb33-11
24	<0.1	21	402	<0.01	5.7	<0.01	0.90	0.01	<10	<1	Bb33-12
18	<0.1	16	305	<0.01	4.0	<0.01	0.60	<0.01	<10	<1	Bb33-13
5.5	<0.1	27	128	<0.01	<0.10	0.02	<0.20	<0.01	<10	<1	Bb33-14
18	0.3	24	271	<0.01	3.4	<0.01	0.40	<0.01	<10	<1	Bb33-15
15	<0.1	26	230	<0.01	3.8	0.02	0.60	0.03	<10	<1	Bb33-26
7.2	<0.1	21	175	<0.01	4.2	<0.01	0.40	0.03	<10	<1	Bb33-27
19	0.1	22	374	0.02	5.2	0.04	0.70	0.02	<10	<1	Bb33-28
9.2	<0.1	21	116	<0.01	6.4	0.02	0.50	0.02	<10	<1	Bb33-29
7.6	<0.1	14	146	<0.01	5.1	<0.01	1.0	<0.01	<10	<1	Bb33-32
33	<0.1	22	138	<0.01	1.4	0.02	<0.20	0.03	<10	<1	Bb33-34
37	<0.1	24	411	<0.01	4.7	<0.01	0.80	<0.01	<10	<1	Bb34-27
21	0.1	21	322	<0.01	2.7	0.03	0.40	0.03	<10	<1	Bb34-29
19	<0.1	18	340	<0.01	4.2	0.02	0.30	0.04	<10	<1	Bb34-31
21	0.2	17	289	<0.01	3.9	0.02	0.70	<0.01	<10	<1	Bb34-33
30	<0.1	16	376	<0.01	5.4	<0.01	0.40	<0.01	<10	<1	Bb34-34
15	<0.1	16	269	<0.01	1.0	0.01	<0.20	<0.01	<10	<1	Bb34-36
12	<0.1	19	297	<0.01	3.1	<0.01	0.50	<0.01	10	<1	Bb34-40
12	<0.1	24	176	0.08	6.1	0.01	0.40	0.02	<10	<1	Bb34-50
14	<0.1	25	163	<0.01	7.7	<0.01	<0.20	0.04	<10	<1	Bb34-57
7.7	<0.1	22	149	<0.01	5.6	0.01	0.70	0.02	<10	<1	Bb34-58
5.3	0.2	20	118	0.02	0.4	<0.01	<0.20	<0.01	<10	<1	Bb35-14
14	<0.1	26	197	<0.01	4.8	0.01	0.40	<0.01	<10	<1	Bb35-15
9.6	<0.1	16	272	<0.01	2.8	0.01	1.8	0.01	<10	<1	Bb43-13
11	<0.1	12	236	<0.01	4.9	<0.01	<0.20	0.03	<10	<1	Bb43-28
13	0.2	21	228	<0.01	2.7	0.02	0.30	0.02	<10	<1	Bb44-13
11	<0.1	21	134	<0.01	5.3	<0.01	0.40	<0.01	<10	<1	Bb44-22
3.7	<0.1	27	122	<0.01	<0.100	0.01	<0.20	0.04	20	<1	Bb44-29
16	<0.1	20	113	<0.01	1.3	<0.01	<0.20	<0.01	<10	<1	01479175
24	<0.1	13	154	0.02	1.6	0.02	<0.20	<0.01	<10	<1	01479189
21	0.1	10	145	0.01	0.84	0.02	0.20	<0.01	<10	<1	01479191
10	<0.1	16	119	0.02	3.4	0.08	0.40	0.01	20	<1	01479193
15	<0.1	15	103	<0.01	0.92	0.03	<0.20	<0.01	<10	<1	01479195
15	<0.1	13	149	0.02	2.5	1.9	5.5	0.45	20	<1	01479195b
21	<0.1	12	142	0.02	1.6	0.03	0.80	<0.01	<10	<1	01479197

APPENDIX 4 (continued)

Chemical analyses of ground water and surface water in the Hockessin area.

(µ/cm = microsiemens per centimeter at 25 degrees Celsius; mg/L = milligrams per liter; µg/L = micrograms per liter; < = less than; — = no data; cm = Cockeysville aquifer; nca = noncarbonate aquifer)

Site	Arsenic, dissolved (µg/L as As)	Barium, dissolved (µg/L as Ba)	Beryllium, dissolved (µg/L as Be)	Boron, dissolved (µg/L as B)	Cadmium, dissolved (µg/L as Cd)	Chromium, dissolved (µg/L as Cr)	Cobolt, dissolved (µg/L as Co)	Copper, dissolved (µg/L as Cu)	Iron, dissolved (µg/L as Fe	Lead, dissolved (µg/L as Pb)
Bb24-06	<1	150	<0.5	10	3.0	<5	<3	110	24	<10
Bb33-11	<1	37	<0.5	<10	<1.0	<5	<3	<10	12	<10
Bb33-12	<1	45	<0.5	<10	<1.0	<5	<3	<10	3	<10
Bb33-13	<1	32	<0.5	<10	<1.0	<5	<3	<10	3	<10
Bb33-14	<1	37	<0.5	<10	<1.0	<5	<3	<10	1000	<10
Bb33-15	<1	28	<0.5	<10	<1.0	<5	<3	<10	5	<10
Bb33-26	<1	24	<0.5	<10	<1.0	<5	<3	<10	6	<10
Bb33-27	<1	23	<0.5	<10	<1.0	<5	<3	<10	6	<10
Bb33-28	<1	48	<0.5	<10	<1.0	<5	<3	<10	190	<10
Bb33-29	<1	120	<0.5	<10	2.0	<5	<3	90	12	<10
Bb33-32	<1	90	<0.5	40	1.0	<5	<3	30	7	<10
Bb33-34	<1	49	0.6	<10	2.0	<5	<3	120	4	<10
Bb34-27	<1	170	<0.5	<10	<1.0	<5	<3	10	4	<10
Bb34-29	<1	43	<0.5	<10	<1.0	<5	<3	<10	<3	<10
Bb34-31	<1	33	<0.5	10	2.0	<5	<3	<10	3	<10
Bb34-33	<1	33	<0.5	<10	<1.0	<5	<3	<10	<3	<10
Bb34-34	<1	11	<0.5	20	<1.0	<5	<3	<10	39	<10
Bb34-36	<1	280	<0.5	<10	<1.0	<5	<3	<10	230	<10
Bb34-40	<1	26	<0.5	20	<1.0	<5	<3	<10	<3	<10
Bb34-50	<1	110	<0.5	20	2.0	<5	<3	<10	36	<10
Bb34-57	<1	130	<0.5	10	1.0	<5	<3	130	9	<10
Bb34-58	<1	39	<0.5	<10	3.0	<5	<3	100	12	<10
Bb35-14	<1	11	<0.5	<10	<1.0	<5	<3	20	<3	<10
Bb35-15	<1	23	<0.5	<10	<1.0	<5	<3	<10	<3	<10
Bb43-13	<1	33	<0.5	10	<1.0	<5	<3	<10	9	<10
Bb43-28	<1	27	<0.5	<10	<1.0	<5	<3	10	5	<10
Bb44-13	<1	31	<0.5	<10	<1.0	<5	<3	<10	4	<10
Bb44-22	<1	21	<0.5	10	<1.0	<5	<3	<10	90	<10
Bb44-29	<1	11	<0.5	20	<1.0	<5	<3	<10	160	<10
01479175	<1	82	<0.5	10	<1.0	<5	<3	<10	27	<10
01479189	<1	52	<0.5	10	<1.0	<5	<3	<10	60	<10
01479191	<1	43	<0.5	10	<1.0	<5	<3	<10	21	<10
01479193	<1	36	<0.5	<10	<1.0	<5	<3	<10	24	<10
01479195	<1	58	<0.5	<10	<1.0	<5	<3	<10	48	<10
01479195b	1	13	<0.5	<10	<1.0	<5	<3	<10	93	<10
01479197	<1	45	<0.5	10	<1.0	<5	<3	<10	26	<10

APPENDIX 4 (continued)

Chemical analyses of ground water and surface water in the Hockessin area.

(μ/cm = microsiemens per centimeter at 25 degrees Celsius; mg/L = milligrams per liter; μg/L = micrograms per liter; pCi/L = picocuries per liter < = less than; — = no data; cm = Cockeysville aquifer; nca = noncarbonate aquifer)

Lithium, dissolved (μg/L as Li)	Manganese, dissolved (μg/L as Mn)	Molybdenum, dissolved (μg/L as Mo)	Nickel, dissolved (μg/L as Ni)	Selenium, dissolved (μg/L as Se)	Silver, dissolved (μg/L as Ag	Strontium, dissolved (μg/L as Sr)	Vanadium, dissolved (μg/L as V)	Zinc, dissolved (μg/L as Zn)	Radon-222, total (pCi/L)	Site
<4	4	<10	<10	<1	<1.0	170	<6	37	1100	Bb24-06
<4	1	<10	<10	<1	<1.0	69	<6	6	380	Bb33-11
8	2	<10	<10	<1	<1.0	85	<6	18	260	Bb33-12
8	2	<10	<10	<1	<1.0	53	<6	17	410	Bb33-13
9	80	<10	<10	<1	<1.0	97	<6	12	420	Bb33-14
8	2	<10	<10	<1	<1.0	66	<6	11	89	Bb33-15
6	2	<10	<10	<1	<1.0	97	<6	10	<80	Bb33-26
<4	5	<10	<10	<1	<1.0	31	<6	<3	98	Bb33-27
8	23	<10	<10	<1	<1.0	94	<6	120	130	Bb33-28
<4	2	<10	<10	2	<1.0	95	<6	67	1800	Bb33-29
<4	8	<10	<10	2	<1.0	110	<6	30	2500	Bb33-32
<4	2	<10	<10	2	<1.0	160	<6	18	320	Bb33-34
8	2	<10	<10	<1	<1.0	58	<6	39	88	Bb34-27
7	<1	<10	<10	<1	<1.0	59	<6	15	260	Bb34-29
7	3	<10	<10	<1	<1.0	69	<6	15	270	Bb34-31
5	<1	<10	<10	<1	<1.0	22	<6	17	170	Bb34-33
9	3	<10	<10	<1	<1.0	44	<6	8	95	Bb34-34
<4	1000	<10	<10	<1	<1.0	51	<6	120	190	Bb34-36
6	6	<10	<10	<1	<1.0	47	<6	8	<80	Bb34-40
5	10	<10	<10	2	2.0	140	<6	19	1800	Bb34-50
<4	2	<10	<10	2	<1.0	120	<6	34	450	Bb34-57
<4	12	<10	<10	<1	<1.0	160	<6	22	420	Bb34-58
<4	2	<10	<10	1	<1.0	99	<6	17	310	Bb35-14
<4	<1	<10	<10	<1	<1.0	120	<6	7	530	Bb35-15
5	4	<10	<10	<1	<1.0	38	<6	16	330	Bb43-13
<4	1	<10	<10	<1	<1.0	36	<6	25	140	Bb43-28
5	<1	<10	<10	<1	1.0	53	<6	11	230	Bb44-13
5	27	<10	<10	<1	<1.0	46	<6	7	330	Bb44-22
<4	130	<10	<10	<1	<1.0	82	<6	3	250	Bb44-29
4	67	<10	<10	<1	<1.0	100	<6	10	—	01479175
<4	43	<10	<10	<1	<1.0	120	<6	4	—	01479189
<4	20	<10	<10	<1	<1.0	120	<6	<3	—	01479191
5	58	<10	<10	<1	<1.0	130	<6	11	—	01479193
15	30	<10	<10	<1	<1.0	110	<6	7	—	01479195
6	58	<10	<10	<1	<1.0	110	<6	12	—	01479195b
6	41	<10	<10	<1	<1.0	120	<6	7	—	01479197

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