# Hydrogeologic Terranes and Potential Yield of Water to Wells in the Valley and Ridge Physiographic Province in the Eastern and Southeastern United States

REGIONAL AQUIFER-SYSTEM ANALYSIS


U.S. Department of the Interior
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# Hydrogeologic Terranes and Potential Yield of Water to Wells in the Valley and Ridge Physiographic Province in the Eastern and Southeastern United States

*By* E.F. HOLLYDAY *and* G.E. HILEMAN

REGIONAL AQUIFER-SYSTEM ANALYSIS—
APPALACHIAN VALLEY AND PIEDMONT

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1422–C

**U.S. DEPARTMENT OF THE INTERIOR**

**BRUCE BABBITT, *Secretary***

**U.S. GEOLOGICAL SURVEY**

**Gordon P. Eaton, *Director***

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**Library of Congress Cataloging in Publication Data**

Hollyday, E.F.

Hydrogeologic terranes and potential yield of water to wells in the Valley and Ridge physiographic province in the eastern and southeastern United States / by E.F. Hollyday and G.E. Hileman.

p. cm. — (Regional aquifer-system analysis—Appalachian Valley and Piedmont ; C) (U.S. Geological Survey professional paper ; 1422)

Includes bibliographical references (p. - ).

1. Aquifers—Appalachian Basin. 2. Groundwater—Appalachian Basin. I. Hileman, G.E. (Gregg Edward), 1962- . II. Title. III. Series. IV. Series: U.S. Geological Survey professional paper ; 1422.

GB1199.3.A6H65 1996

553.7′9′0974—DC21

96-49996

CIP

ISBN 0-607-87064-8

For sale by U.S. Geological Survey, Information Services
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# FOREWORD

## THE REGIONAL AQUIFER-SYSTEM ANALYSIS PROGRAM

The RASA Program represents a systematic effort to study a number of the Nation's most important aquifer systems, which, in aggregate, underlie much of the country and which represent an important component of the Nation's total water supply. In general, the boundaries of these studies are identified by the hydrologic extent of each system and, accordingly, transcend the political subdivisions to which investigations have often arbitrarily been limited in the past. The broad objective for each study is to assemble geologic, hydrologic, and geochemical information, to analyze and develop an understanding of the system, and to develop predictive capabilities that will contribute to the effective management of the system. The use of computer simulation is an important element of the RASA studies to develop an understanding of the natural, undisturbed hydrologic system and the changes brought about in it by human activities and to provide a means of predicting the regional effects of future pumping or other stresses.

The final interpretive results of the RASA Program are presented in a series of U.S. Geological Survey Professional Papers that describe the geology, hydrology, and geochemistry of each regional aquifer system. Each study within the RASA Program is assigned a single Professional Paper number beginning with Professional Paper 1400.

Gordon P. Eaton
Director

# CONTENTS



# ILLUSTRATIONS

[Plates in pocket]

## CONVERSION FACTORS AND VERTICAL DATUM

| Multiply | By | To obtain |
|---|---|---|
| inch (in.) | 25.4 | millimeter |
| foot (ft) | 0.3048 | meter |
| gallon per minute (gal/min) | 0.06309 | liter per second |
| gallon per minute per foot [(gal/min)/ft] | 0.2070 | liter per second per meter |

**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.

# HYDROGEOLOGIC TERRANES AND POTENTIAL YIELD OF WATER TO WELLS IN THE VALLEY AND RIDGE PHYSIOGRAPHIC PROVINCE IN THE EASTERN AND SOUTHEASTERN UNITED STATES

By E.F. Hollyday and G.E. Hileman

ABSTRACT

The Valley and Ridge Physiographic Province is underlain by deformed sedimentary rock of Paleozoic age including dolomite, limestone, shale, and sandstone. Regolith (soil, sediment, and weathered rock) covers the Paleozoic rock throughout most of the province. Local differences in lithology, structure, and weathering can result in four orders of magnitude variation in the water-yielding properties of the geologic units that underlie the area. Selected rock types, however, can account for a substantial part of this variation because of the unique way in which these dense, consolidated sedimentary rock types deform and weather to produce secondary openings.

On the basis of relations among rock type, water-yielding openings, and water-yielding properties (as indicated by specific capacity), the regolith and consolidated rock were classified and mapped as five hydrogeologic terranes—alluvium, dolomite, limestone, argillaceous carbonate rock, and siliciclastic rock. The hydrogeologic terranes are named after the predominant outcrop lithology within them. The western toe of the Blue Ridge Mountains is classified as a subdivision of the dolomite hydrogeologic terrane that may produce yields of water in excess of 1,000 gallons per minute (gal/min) to public and industrial supply wells.

Specific-capacity data for homogeneous data sets, which consist of all wells that have the same characteristics in regard to casing diameter, primary use of the water, and topographic setting, revealed significant differences in water-yielding properties among the five hydrogeologic terranes. According to results of Tukey statistical tests at a probability (alpha level) of 0.05, 8 out of 10 pairs of hydrogeologic terranes (for example, alluvium/limestone) had significantly different median specific-capacity values. The median value for public and industrial supply wells in the western toe is three times greater than the value for comparable wells in the dolomite hydrogeologic terrane elsewhere.

Estimates of potential yields to public and industrial supply wells were calculated from specific-capacity data for most-productive wells, which have casing diameter of 7 in. or more, discharge water primarily for public or industrial supply, and are in a valley. Median constant drawdowns, calculated from reported drawdowns, were assumed to be between 10 and 90 ft for wells completed in each of the five hydrogeologic terranes, and well-entrance losses were assumed to be negligible. Estimated interquartile ranges in potential yields to 412 most-productive wells in the five hydrogeologic terranes were 170 to 580 gal/min, alluvium; 210 to 1,400 gal/min, dolomite; 80 to 720 gal/min, limestone; 65 to 850 gal/min, argillaceous carbonate rock; and 70 to 280 gal/min, siliciclastic rock.

## INTRODUCTION

The U.S. Geological Survey (USGS) started the Regional Aquifer-System Analysis (RASA) Program in 1978 in response to congressional concern about the adequacy of water supplies during drought. The purposes of the RASA Program were to define the regional hydrology and geology of the Nation's important aquifer systems and to establish a framework of background information on geology, hydrology, and water chemistry for each aquifer system. This critical information is needed to develop an understanding of regional ground-water flow systems and to support efficient ground-water resources management (Sun, 1986, p. 1–8).

In 1988 as part of the RASA Program, the USGS began a 6-year study of the ground-water resources in parts of 11 States in the Eastern and Southeastern United States (Swain and others, 1991). The study was called the Appalachian Valley and Piedmont Regional Aquifer-System Analysis (APRASA). The APRASA team investigated ground-water resources primarily in the unglaciated part of the Valley and Ridge, Blue Ridge, New England, and Piedmont Physiographic Provinces (fig. 1). The Valley and Ridge subproject team of the APRASA study focused on a regional analysis of the hydrogeology of the carbonate and siliciclastic rocks in the Valley and Ridge Physiographic Province.

### PROBLEM

A major problem in the effective development, management, and protection of the ground-water resources of the Valley and Ridge Physiographic Province is insufficient information on the regional hydrogeologic framework. Definition of the framework is made difficult by the complexity of the geology, which causes large variation in the water-yielding properties of the rocks. The

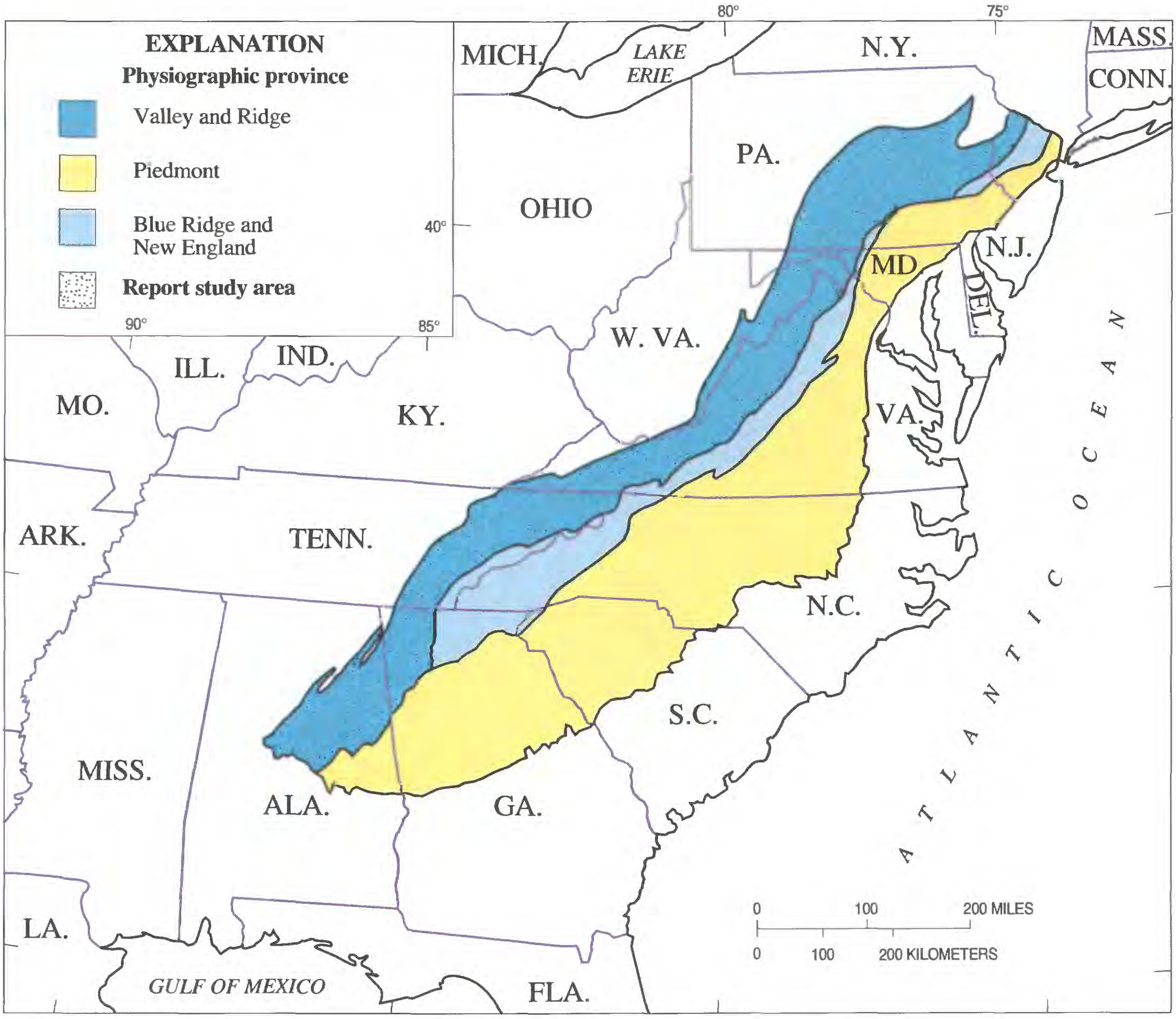



FIGURE 1.—The Appalachian Valley and Piedmont Regional Aquifer-System Analysis study area, physiographic provinces, and report study area.

range in yields of water to wells completed in any particular geologic unit can span several orders of magnitude and overlap the ranges of well yields in other units. Any analysis of this variation requires a large amount of well data to describe differences in the hydraulic characteristics within each unit and to test for significant differences in hydraulic characteristics among units.

## PURPOSE AND SCOPE

The purpose of this report is to provide background information on the regional hydrogeologic setting of the Valley and Ridge Physiographic Province in Alabama, Georgia, Maryland, New Jersey, Pennsylvania, Tennessee, Virginia, and West Virginia; to describe and map hydrogeologic terranes within this setting; to test these hydrogeologic terranes for significant differences in water-yielding properties; and to estimate the quantity of water potentially available to wells in these hydrogeologic terranes. Hydrogeologic terranes are defined in this report as regionally mappable areas characterized by similar rock type and water-yielding properties. The hydrogeologic terranes represent areas of distinct hydrologic character. They are intended to help water users locate and develop adequate water supplies and to help hydrologists interpret the regional hydrogeology.

This report is one of four chapters in U.S. Geological Survey Professional Paper 1422 that describes various aspects of the geology, hydrology, and geochemistry of ground water in the APRASA study area. These chapters include the summary (Chapter A) and descriptions of surface- and ground-water relations (Chapter B), the hydrogeologic framework of the Valley and Ridge Physiographic Province [Chapter C (this report)], and ground-water geochemistry (Chapter D).

### PREVIOUS INVESTIGATIONS

Previous investigations provide maps and descriptions of the geologic units, describe the local quantity and quality of the ground water within these units, and establish the statistical methods for comparing the water-yielding properties of these units. State geologic maps show the distribution of geologic units at a scale of 1:500,000 for Alabama (Osborne and others, 1989), Georgia (Lawton and others, 1976), and Virginia (Calver and Hobbs, 1963). State geologic maps show units at a scale of 1:250,000 for Maryland (Cleaves and others, 1968), New Jersey (Lewis and Kummel, 1912), Pennsylvania (Berg and others, 1980), Tennessee (Hardeman, 1966), and West Virginia (Cardwell and others, 1968). Descriptions of the geology of some individual topographic quadrangles, counties, parts of counties, or several counties in the area have been published. Many reports describing the ground-water resources of a county, parts of counties, multicounty areas, or river basin are listed in the Selected References section of this report.

The statistical methods used in this report are largely based on those used by Knopman (1990, p. 7–9) in her analysis of well records in the USGS Ground-Water Site Inventory (GWSI) data base. This analysis ranked factors that influence the water-yielding potential of the rocks in the Piedmont and Valley and Ridge Physiographic Provinces in Pennsylvania. In her analysis, she used values of the dependent variable that were transformed by their natural logarithm in order to work with a more symmetric distribution than for untransformed data. Nonparametric statistical methods were used because of the persistence of outliers and the occasional violation of the normality assumption when working with small subsets of the data. Statistical analysis included monotonic correlation, one-way and factorial analysis of variance, and multiple linear regression. Readers are referred to Knopman (1990) for the details regarding her statistical methods.

### ACKNOWLEDGMENTS

The authors wish to express their gratitude to Jason E. Duke and Paul A. Pearson, Student Trainees (Hydrology), who personally collected 570 records primarily of municipal and industrial wells in Alabama, Georgia, Tennessee, Virginia, and West Virginia. They exercised considerable independent judgment while adding these records to the USGS GWSI data base in each State, compiling a data base for the project, and performing statistical tests and summaries on the data. Without their unusual dedication to data collection, data verification, and statistical analysis of the data, this report would have been far less quantitative than in its present form.

## HYDROGEOLOGIC SETTING

The complexity of the geology in the Valley and Ridge Physiographic Province results in a large variation in the water-yielding properties of the carbonate and siliciclastic rocks that underlie the study area. This variation has been observed on the scale of a single county (Clark and others, 1976, figs. 17–23; Swain and others, 1991, p. 30). Within a single geologic unit (formation, group, or member) or combination of units, the effects of local differences in lithology, structure, and weathering can result in a range in water-yielding properties that spans several orders of magnitude. If specific capacity (the discharge of a well divided by the resulting drawdown) is considered to be a measure of the water-yielding properties, then the range in water-yielding properties of a single unit can span four orders of magnitude and overlap the ranges of many other units (fig. 2).

### GENERAL FEATURES

The Valley and Ridge Physiographic Province is underlain by deformed sedimentary rock of Paleozoic age that overlies metamorphic and igneous rock of Precambrian age. The metamorphic and igneous rock is not discussed in the report because it has low permeability relative to the sedimentary rock and occurs either at depths greater than 1,000 ft or in limited outcrop within the study area. The Paleozoic sedimentary rock is, in order of abundance, carbonate rock (dolomite and limestone), shale, and sandstone (Colton, 1970, p. 10). Folding and faulting of this rock, which was initially deposited in an almost horizontal position, has resulted in large structural features (anticlines, synclines, and thrust faults) that include several tens of square miles. Regolith (soil, sediment, and weathered rock) covers the consolidated rock throughout most of the study area.

Ground water in the consolidated rock of the study area resides in and flows through secondary openings (joints, fractures, bedding-plane partings, and dissolution openings). The secondary openings were formed by mechanical breakage and enlarged by chemical weathering of the consolidated rock. These openings, which were produced after the rock was lithified, contrast with the primary openings that existed between grains in the original sediment.

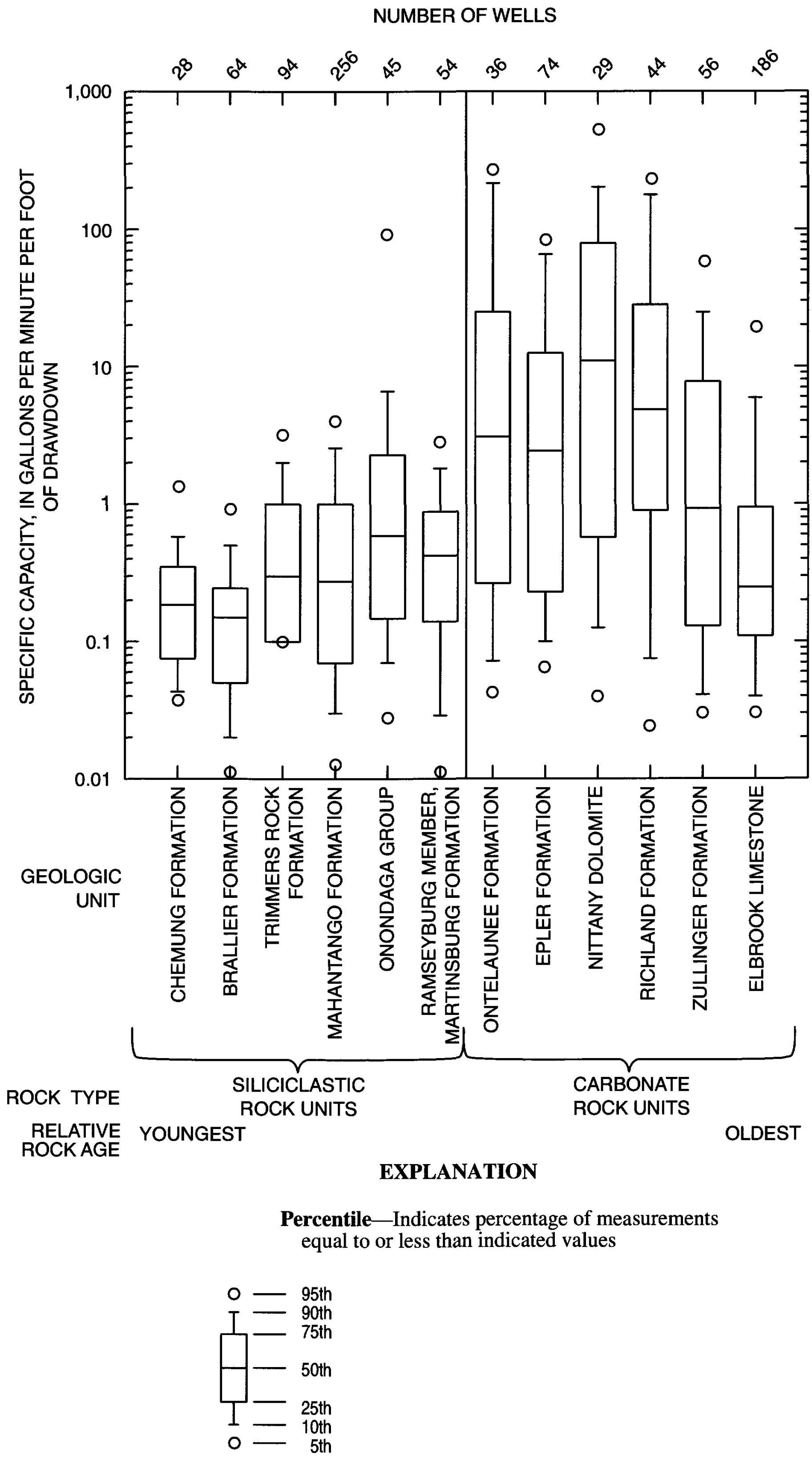



FIGURE 2.—Variation of specific-capacity values for wells grouped by a selected dozen geologic units.

Ground-water flow systems in consolidated rock tend to be restricted in depth and areal extent because of the restricted vertical extent of major weathering and the change in geologic structure over short distances. Weathering decreases with depth, thereby restricting the depth of development of the more permeable zones. Faults commonly restrict the areal extent of flow systems by cutting across geologic units and juxtaposing permeable rock and less permeable rock. Folds restrict the areal extent of flow systems by distorting the horizontal layering and exposing both permeable and less permeable rock units at the land surface. In addition, the widespread occurrence of trellis drainage networks in the Valley and Ridge Physiographic Province supplement restrictions on the areal extent of ground-water flow systems imposed by faults and folds. For these reasons, flow systems in the more permeable rock typically occupy a space of a few hundreds of feet in depth by tens or hundreds of square miles in area. For example, a map of the potentiometric surface indicates that ground-water flow in the Spring Creek basin of south-central Pennsylvania is restricted to an area of approximately 10 mi by 17.5 mi (Wood, 1980, p. 10–12 and fig. 5). A similar map indicates that flow in the Carson Spring basin of the northwestern Valley and Ridge, Tennessee, is restricted to an area of approximately 2.3 mi by 4 mi (Webster and Carmichael, 1993, p. 5–10 and fig. 15). This is in contrast to areas of extensive unconsolidated deposits such as the Atlantic and Gulf Coastal Plain where flow systems can occupy a space of many hundreds of feet in depth by thousands or tens of thousands of square miles in area.

The largest ground-water flow systems in the Valley and Ridge Physiographic Province discharge at large springs (450–45,000 gal/min) that are fed by conduits in carbonate rock. These conduits discharge at points rather than along extended lines of seeps. In the study area in Pennsylvania, 90 percent of springs that discharge 100 gal/min or more produce water from carbonate rock (Saad and Hippe, 1990, p. 8). A substantial number of wells that discharge more than 1,000 gal/min in the study area are located adjacent to large springs that drain carbonate rock.

The quality and quantity of ground water in the consolidated rock are influenced by the depth of occurrence of the water and the lithology of the rock through which it flows. Freshwater occurs in usable quantities almost everywhere in consolidated rock to depths of several hundred feet, but tends to be deeper in carbonate rock than in argillaceous siliciclastic rock. Freshwater, which is in quantities too small for economic use, and brine occur in this rock to depths of a few thousand feet. One exception is the deep, warm freshwater in the Oriskany Sandstone and stratigraphically equivalent or adjacent rock units in Virginia and West Virginia. This ground water probably circulates as deep as 1,800 ft below land surface where it is warmed by the surrounding rock before returning to land surface to discharge at hot springs (Hobba and others, 1979). Compared with siliciclastic rock, carbonate rock tends to have more variable water-yielding properties, larger maximum potential yields of water to wells, and water with less dissolved iron, but greater hardness.

## LITHOLOGY

Differences in the lithology of selected rock types can account for a substantial part of the variation in the water-yielding properties of the rock. Different unconsolidated materials have different primary porosity and permeability as a result of differences in their grain size, packing, and cementation. Different consolidated sedimentary rocks have different secondary porosity and permeability as a result of differences in the way they deform and weather. Dolomite or limestone that is mostly free of clay or shale interbeds tends to deform plastically or develop few fractures at great depth within the Earth's crust. At shallow depth during weathering, the dissolution of soluble minerals along joints, fractures, and bedding-plane partings causes widening of these planar openings and results in a honeycomb rock that has variable, but commonly high, permeability. The pure or nearly pure carbonate rock typically is covered by only a few feet of residuum. Argillaceous carbonate rock also tends to deform plastically and develop fewer fractures. During weathering, clays are likely to swell or otherwise fill the few fractures and dissolution openings, which results in a rock that has low permeability. This rock usually is covered by a few tens of feet of residuum. Argillaceous siliciclastic rock generally deforms and weathers in a manner similar to argillaceous carbonate rock but lacks any substantial development of dissolution openings and has low permeability. Sandstone that is mostly free of clay or shale interbeds develops fractures at depth, but during weathering, these fractures are not widened by dissolution. The permeability of clean sandstone is higher than that of argillaceous siliciclastic rock but lower than that of clay-free carbonate rock. Nonargillaceous sandstone typically is covered by a few feet of stony residuum. Thus, because these selected, sedimentary rock types deform and weather differently, each type tends to have unique water-yielding characteristics.

Differences in the thickness and texture of regolith (unconsolidated materials) can account for a substantial part of the variation in the water-yielding properties of geologic materials in an area. Thick, coarse-grained regolith has a high permeability and, where saturated, can form a productive aquifer above the consolidated rock. Although thick fine-grained regolith has a low permeability, where saturated, it can provide abundant recharge to the underlying aquifers in consolidated rock. The water-yielding properties of geologic materials in areas with thin regolith, which stores little water, are predominantly influenced by the properties of the underlying consolidated rock.

### CONSOLIDATED ROCK

The consolidated sedimentary rock units in the study area represent a wide variety of rock types—dolomite; magnesian limestone; limestone; argillaceous carbonate rock; shale, mudstone, and siltstone; sandstone; conglomerate; interbedded sandstone, siltstone, and shale (Patchen and others, 1985a, 1985b). The authors determined that most of these rock types could be grouped into a classification wherein each class is hydrologically unique. Under this classification, the rock types of hydrologic significance in the study area are these sedimentary rocks: dolomite, limestone, argillaceous carbonate rock, and siliciclastic rock. The distribution through time of these rock types and local geologic units comprising them and their location across the study area (fig. 3) are illustrated by 21 stratigraphic columns in plate 1. For the most part, the geologic unit names in plate 1 conform to the usage of the State Geological Surveys. The columns contain the map symbols used in the State geologic maps referenced at the top of the columns in plate 1. The symbols may be used to relate the map units to a particular geologic unit, rock type, and hydrologic significance.

For the hydrologic purpose of this report, the dolomite rock type includes: (1) units that are predominantly dolomite (such as the Shady Dolomite in the Lower Cambrian Series), (2) a combination of dolomite and sandstone or chert (Gatesburg Formation and Copper Ridge Dolomite in the Upper Cambrian Series), and (3) dolomite and limestone with as much as 70 percent limestone (Elbrook Limestone in the Middle and Upper Cambrian Series in Virginia). The limestone rock type includes units that are predominantly limestone (Lincolnshire Limestone, Middle Ordovician Series in Virginia and West Virginia) and limestone with less than 30 percent dolomite (Stonehenge Limestone, Lower Ordovician Series).

The argillaceous carbonate rock type includes units that are predominantly clay-rich dolomite or limestone (Chambersburg Limestone in the Middle Ordovician Series in Maryland and Pennsylvania) as well as shale units that contain abundant calcite or magnesium calcite (Wills Creek Formation, Upper Silurian Series). The argillaceous carbonate rock type also includes undifferentiated geologic units that may be a combination of limestone, argillaceous carbonate rock, and siliciclastic rock (Middle and Upper Ordovician Series rock, undifferentiated, in Virginia). The siliciclastic rock type includes units that are predominantly shale with little or no carbonate content (such as the Chattanooga Shale, Lower Mississippian and Upper Devonian Series), siltstone (Maccrady Shale, Lower and Upper Mississippian Series), sandstone (Clinch Sandstone, Lower Silurian Series), and conglomerate (Shawangunk Conglomerate, Lower and Middle Silurian Series in New Jersey) that consist of clay minerals, quartz grains, or siliceous rock fragments. In New Jersey and eastern Pennsylvania, the siliciclastic rock type also includes a unit that contains a substantial amount of slate (Martinsburg Shale, Middle and Upper Ordovician Series).

Different rock types characterize different rock ages (pl. 1). Substantial amounts of dolomite are only in the carbonate rock that is mostly of Lower Cambrian through Middle Ordovician Series. Limestone is common in the Cambrian and Ordovician Systems throughout the study area, the Upper Silurian and Lower Devonian Series in the northern half of the study area, and the Mississippian System in the southern half of the study area. Siliciclastic rock is particularly abundant in rock series younger than the Middle Ordovician. The argillaceous carbonate rock typically is in a stratigraphic interval between siliciclastic rock and either dolomite or limestone.

Different rock types of the same age characterize different parts of the study area (pl. 1). For example, the siliciclastic and argillaceous carbonate rocks in the Upper Silurian and Lower Devonian Series in New Jersey (column 1) grade laterally into limestone and argillaceous carbonate rocks in Pennsylvania (columns 3 and 4) and into limestone and siliciclastic rocks in Maryland, Virginia, and West Virginia (columns 5–11). Within these same two series, most geologic units are missing and the thickness of the section approaches zero in the southwestern half of the study area (columns 12–21). Different rock types of the same age may even characterize different parts of the same column area (column 9, Middle Ordovician Series) where a thrust fault has juxtaposed rock types that originally were in compositionally different and widely separated parts of the same depositional basin.

### REGOLITH

Regolith varies in thickness from 0 to 450 ft and in texture from clay to gravel. It was either formed in place by the weathering of the underlying bedrock (residuum) or deposited after being transported from the place of weathering (till, colluvium, and alluvium). Only a small part of the regolith is shown on maps in this report because of the thinness and variable texture of most of these materials.

## EXPLANATION

| Column number | Column name | Column number | Column name |
|---|---|---|---|
| 1 | Northwestern New Jersey | 16 | Northwestern Valley and Ridge, Tennessee |
| 2 | Eastern Pennsylvania | 17 | Southeastern Valley and Ridge, Tennessee |
| 3 | Southeastern Pennsylvania | 18 | Valley and Ridge and Plateau, Georgia |
| 4 | South-central Pennsylvania | 19 | Valley and Ridge, Northern Segment, Alabama |
| 5 | Washington County, Maryland | 20 | Calhoun, St. Clair, and Talladega Counties, Alabama |
| 6 | Allegany County, Maryland | 21 | Valley and Ridge, Southern Segment, Alabama |
| 7 | Northeastern West Virginia | | |
| 8 | Northwestern Virginia | | |
| 9 | Montgomery, Roanoke, Botetourt, and Rockbridge Counties, Virginia | | |
| 10 | Craig, Alleghany, Bath, and Highland Counties, Virginia | | |
| 11 | Southeastern West Virginia | | |
| 12 | Washington, Smyth, Wythe, and Pulaski Counties, Virginia | | Boundary of area of stratigraphic column—Number represents column in plate 1 |
| 13 | Scott, Russell, Tazewell, Bland, and Giles Counties, Virginia | | |
| 14 | Lee and Wise Counties, Virginia | | Boundary of study area of report |
| 15 | Northeastern Valley and Ridge, Tennessee | | |

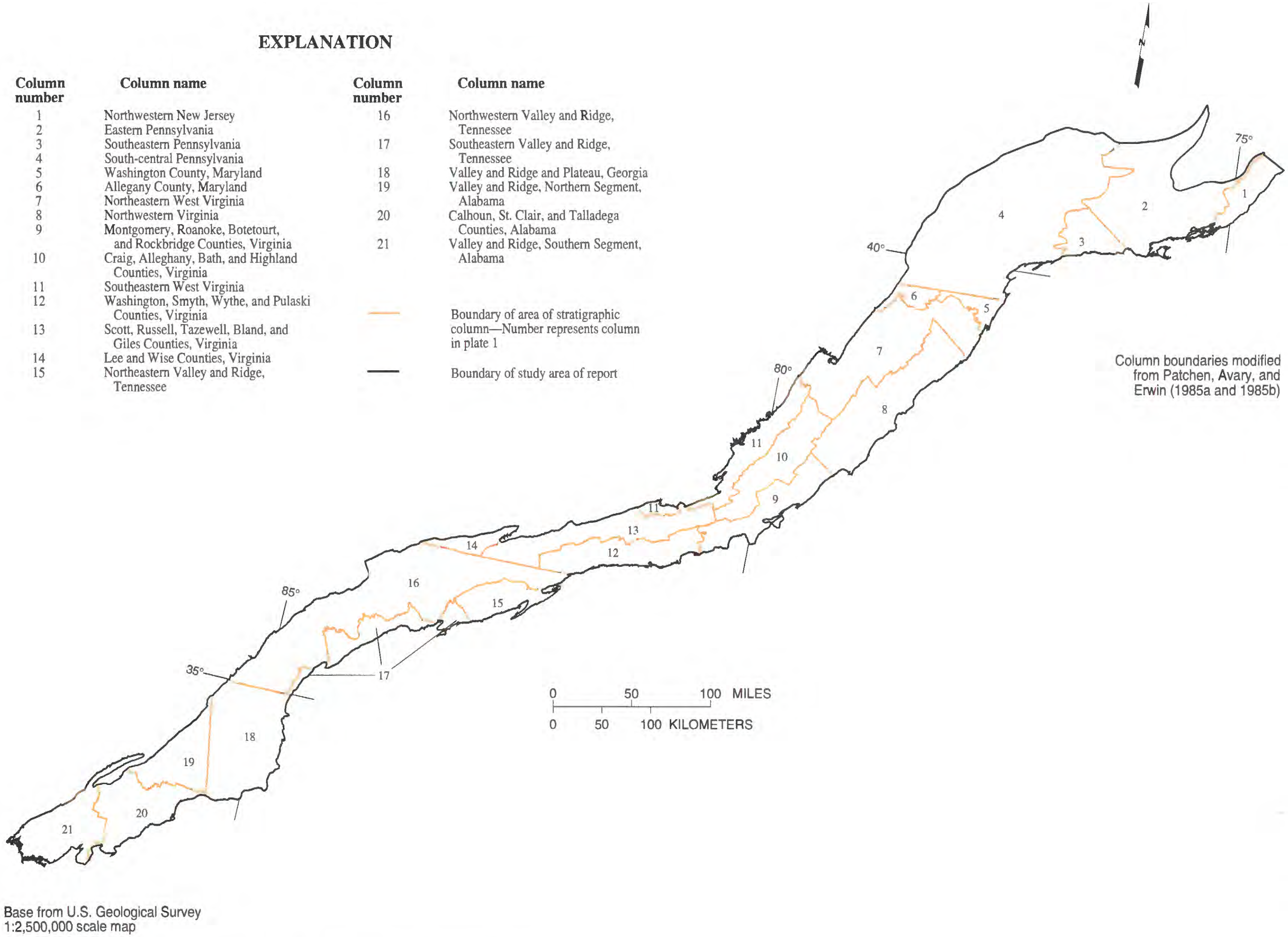



FIGURE 3.—Location of the areas described by the stratigraphic columns in plate 1.

Much of the consolidated rock in the study area is covered by residuum or glacial till. A fine-grained residuum covers the valleys and upland flats that comprise much of the study area. Residuum is thin (commonly less than 5 ft) on shale and most carbonate rock. Residuum can be thick (more than 50 ft) on rock that contains substantial amounts of blocky sandstone or chert because these resistant materials protect the surface of the residuum from erosion (Hack, 1965, p. 45–49, fig. 35). A protective surface forms either in place as a lag concentrate or as the result of the accumulation of colluvial or alluvial material transported from adjacent, topographically higher resistant rock. Glacial till with a sandy or clayey matrix covers much of the uplands in New Jersey and northern and eastern Pennsylvania and is commonly less than 3 ft thick (Sevon, 1989).

Alluvium underlies most river flood plains and is in terraces at the sides of valleys with streams that drain areas of resistant, siliciclastic rock. In major valleys of New Jersey and parts of northern and eastern Pennsylvania, alluvium commonly exceeds 30 ft in thickness and is coarse grained, well sorted, and derived directly or indirectly from glacial deposits. Alluvium in this part of the study area produces some of the largest yields of water to wells of any geologic units in the study area and is mapped as part of the report (pls. 2 and 3).

Thin, stony colluvium overlies residuum or bedrock on hill and mountain slopes that are crested by resistant siliciclastic rock (Hack, 1965, p. 30–32; Mills and Delcourt, 1991, p. 614–615). This stony colluvium commonly grades down the slope into dissected alluvial terraces that contain cobble gravel, sand, and sandy loam. Adjacent to the Blue Ridge Physiographic Province along the southeastern edge of the study area, colluvium and alluvium interfinger to form a regolith apron that covers thick residuum and carbonate bedrock. The area of this apron has been associated with large springs (Becher and Root, 1981, p. 12) and wells producing in excess of 1,000 gal/min (Leonard, 1962, p. 208, 209).

### STRUCTURE

Differences in geologic structure can account for some of the variation in the water-yielding properties of the rock in the study area. Large-scale structures (anticlines, synclines, and thrust faults) juxtapose rock types that have different water-yielding properties and bring rock to the land surface where secondary porosity and permeability can be enhanced by chemical weathering. Small-scale structures (fractures, joints, and bedding-plane partings) provide openings that allow water to enter and move through an otherwise dense rock mass.

Large-scale structures (fig. 4) control the distribution and extent of the geologic units. Complex anticlines, such as the Nittany Arch and Wills Mountain Anticline in the northeastern half of the study area and Powell Valley, Wills Valley, and Murphree Valley Anticlines in the southwestern half, bring the older rock to land surface. Complex synclines, such as the Lackawanna, Broad Top, Massanutten, and Catawba Synclines and the Anthracite Basins in the northeastern half of the study area and the Bays Mountain, Floyd, Coosa, and Cahaba Synclines in the southwestern half, preserve the younger rock in their centers. In the northeastern half of the study area, the Great Valley and the Shenandoah Valley are underlain by intricately folded and faulted rock along the southeastern edge of the Valley and Ridge Physiographic Province. The southeastern edge of most of the province generally has closely spaced faults, overturned and recumbent folds, and outcrops of the oldest rock.

Thrust faults, which range in attitude from nearly horizontal to steeply dipping (fig. 5), cut across and displace the Paleozoic rock units. Faults place older rock from the southeast over younger rock to the northwest. In the northeastern half of the study area, the displacement along thrust faults decreases with decreasing depth, and anticlinal folds replace the faults at land surface (fig. 5, *A–A′* and *B–B′*). Large anticlinal folds commonly are at land surface where the thrust faults ramp upward from depth [fig. 5, *B–B′*, (Wills Mountain Anticline), *E–E′* (anticline in the footwall of the Rome Fault)]. Near the middle of the study area (fig. 5, *C–C′* and *D–D′*), many thrust faults, such as the Pulaski and Saltville Faults, bring Ordovician and Cambrian rocks to the land surface, repeating the stratigraphic section not only vertically but also from northwest to southeast.

The rock has been broken by small-scale structures throughout the Valley and Ridge. The frequency of intersection, density, and geometry of the fractures, joints, and bedding-plane partings vary with the lithology, bed thickness, and structural setting. Locally, all or some of these minor planar openings can be sealed by deposition of natural cementing materials subsequent to deformation or can be filled with fine-grained sediment transported by infiltrating surface water.

## HYDROGEOLOGIC TERRANES

Hydrogeologic terranes are regionally mappable areas characterized by similar rock type and water-yielding properties. A classification of hydrogeologic terranes was developed and maps of hydrogeologic terranes were compiled so that the study area could be subdivided on the basis of the unique water-yielding properties of each hydrogeologic terrane.

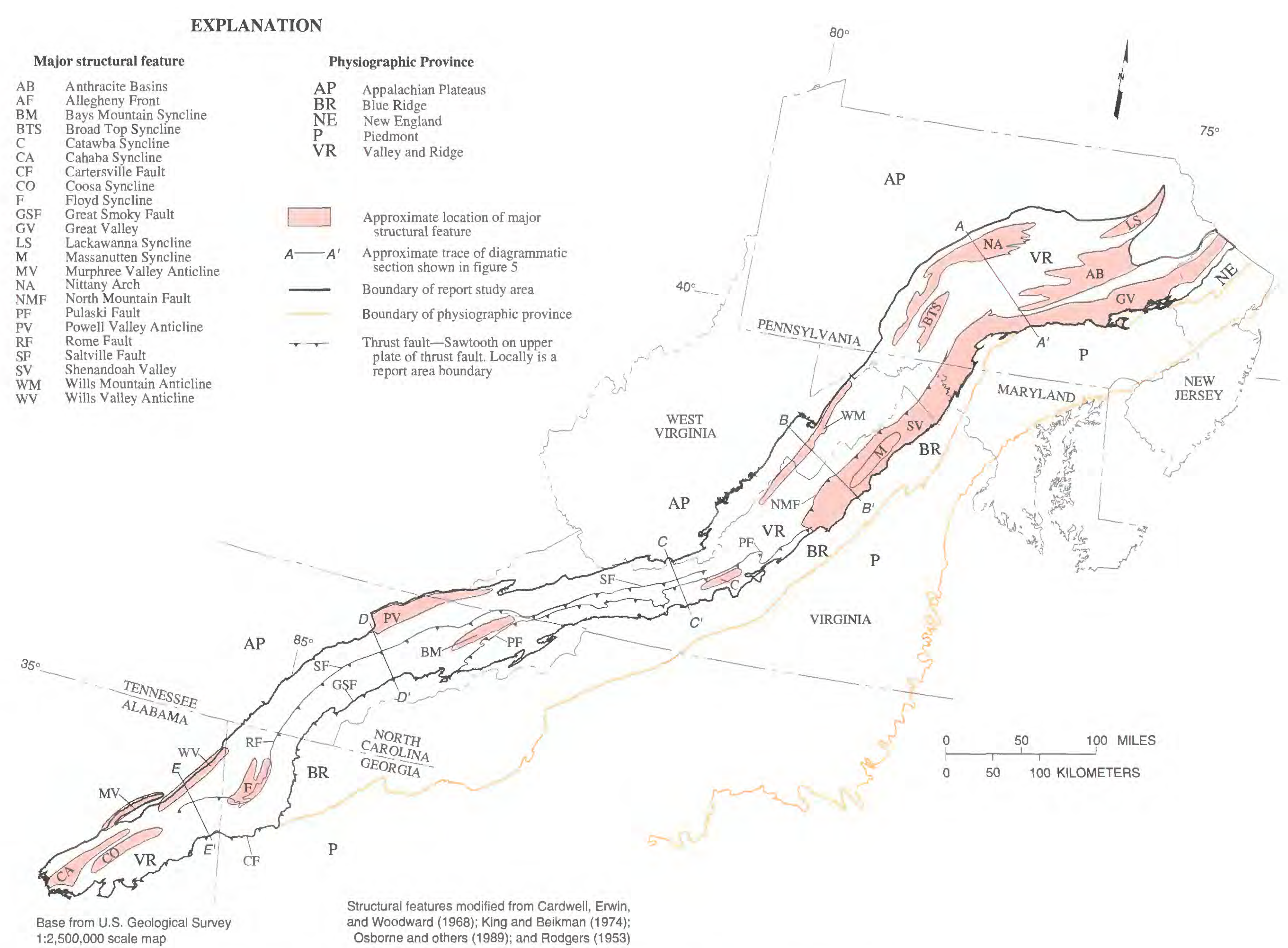



FIGURE 4.—Location of major structural features in the Valley and Ridge Physiographic Province in the Eastern and Southeastern United States.

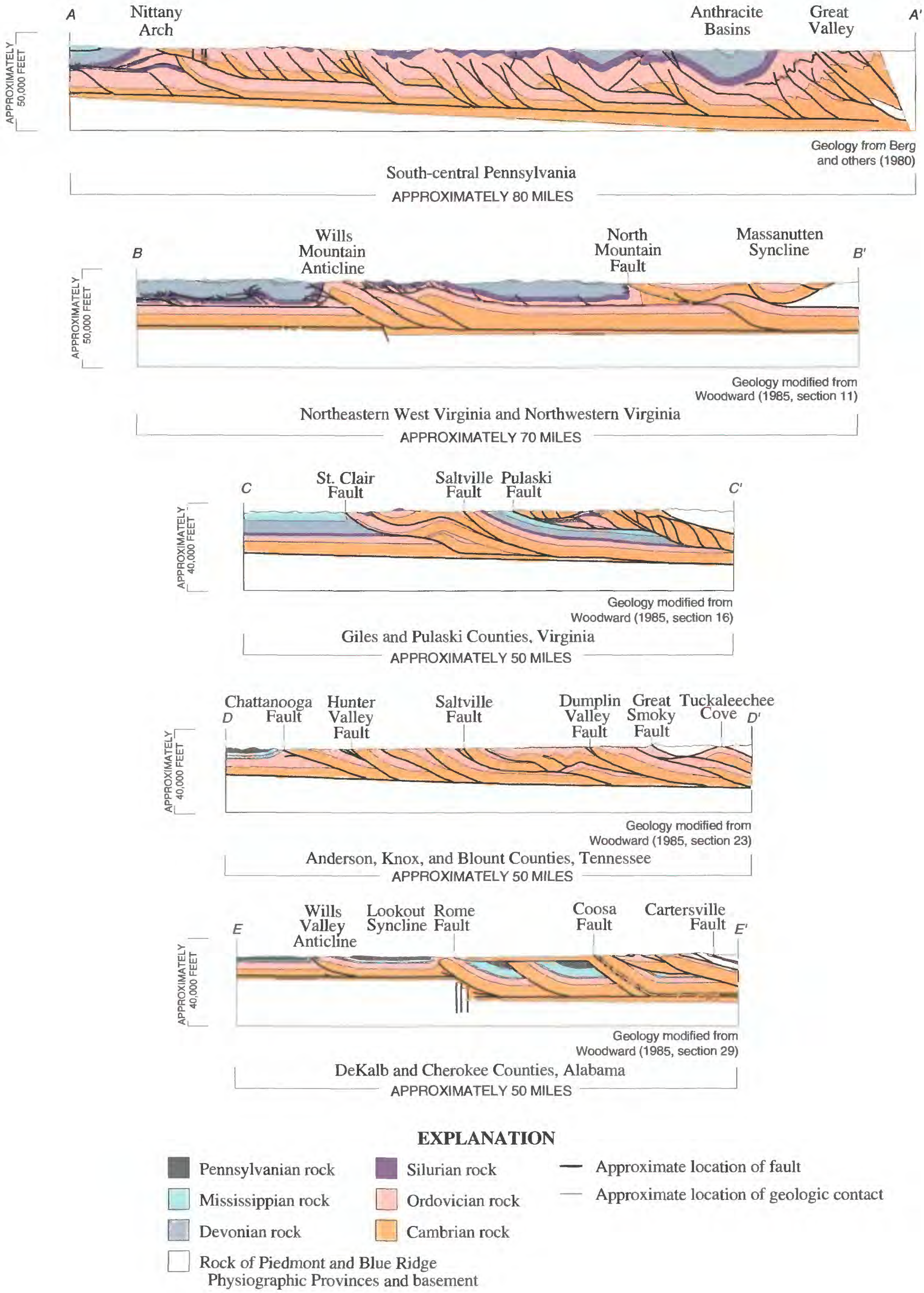



FIGURE 5.—Diagrammatic geologic sections of the Paleozoic rock of the Valley and Ridge Physiographic Province in the Eastern and Southeastern United States. See figure 4 for location of sections.

## HYDROGEOLOGIC TERRANE CLASSIFICATION

Hydrogeologic terrane classes were defined based on the relation of rock type to the nature of water-yielding openings in the rock and the water-yielding properties of the rock. Twelve lithologic descriptors from the GWSI data base were used to identify the rock type for classifying hydrogeologic terranes. For wells with lithologic descriptors, specific-capacity values were used as an approximate measure of water-yielding properties. The following five hydrogeologic terrane classes, one consisting of regolith and four consisting of consolidated sedimentary rock, are defined below: alluvium, dolomite, limestone, argillaceous carbonate rock, and siliciclastic rock. The relations among the 5 hydrogeologic terranes, the 12 lithologic descriptor groups, and the specific capacity of wells are shown in figure 6. Specific-capacity data were sufficient to treat each of the lithologic descriptor groups as a separate hydrogeologic terrane; however, as shown in figure 6, it is unlikely that all lithologic descriptor groups would have unique water-yielding properties according to specific capacity. The authors elected to reduce the number of hydrogeologic terranes in order to increase the likelihood of identifying hydrogeologic terranes that would be unique in their water-yielding properties.

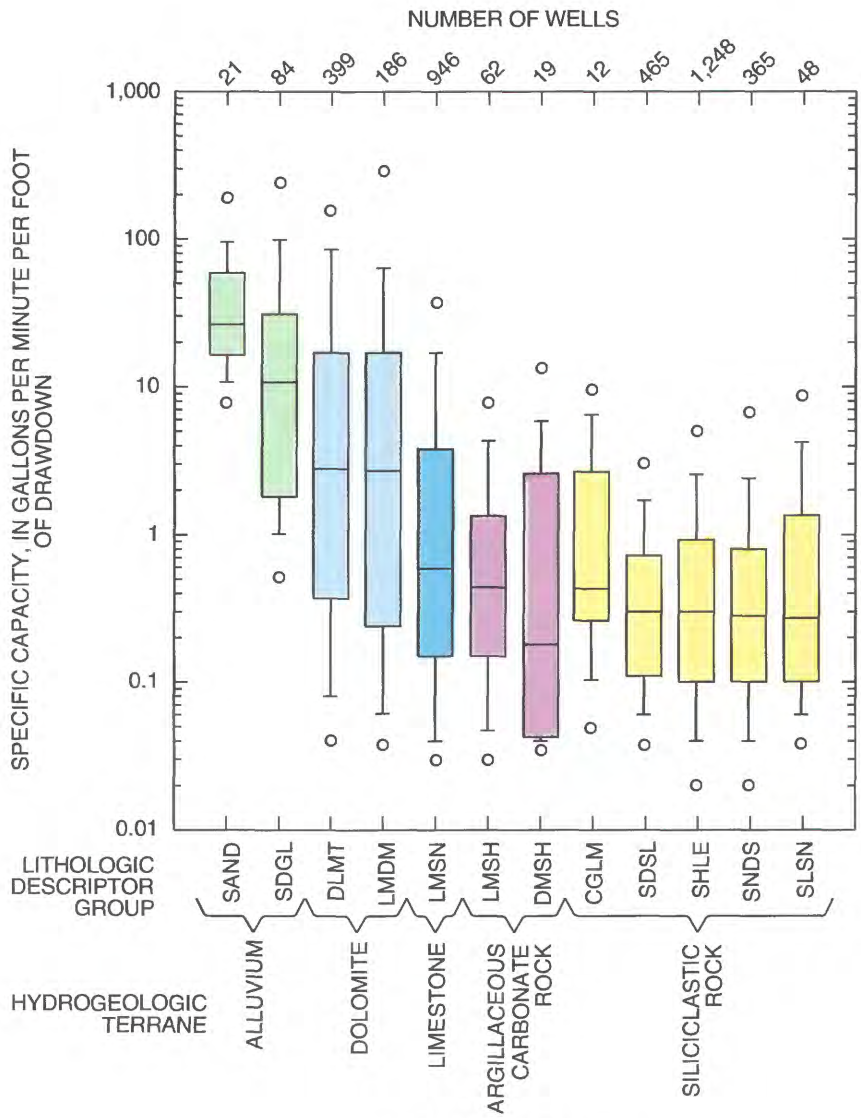
Hydrologic intuition may conflict with apparent differences in the median specific-capacity values of wells completed in selected pairs of lithologic descriptor groups (fig. 6). For example, if it is assumed that all materials are well sorted, then sand and gravel (SDGL) would be expected to have a greater median value than sand (SAND) because the larger grain sizes in sand and gravel (SDGL) are commonly related to greater permeability (Wenzel, 1942, p. 11–13; Freeze and Cherry, 1979, p. 350–352). Limestone (LMSN) would be expected to have a greater median value than dolomite (DLMT) or limestone and dolomite (LMDM), because limestone (LMSN) dissolves more quickly than dolomite (White, 1988, p. 146). A large part of the reason for the apparent differences between selected pairs is that wells in each lithologic descriptor group have different diameter, intended water use, and topographic setting. As discussed later in the report in the section "Analysis of Records and Variables," differences in well characteristics have a significant effect upon median specific-capacity values.

The distinction between regolith and consolidated rock was made on the basis of differences in the nature of the water-yielding openings and water-yielding properties. Well-sorted, coarse-grained alluvium of glacial origin is the only regolith that covers a substantial area and yields large quantities of water to wells from pore spaces between sediment grains. Water in the consolidated rock occupies fractures, bedding-plane partings, or dissolution openings. In addition, median specific-capacity values of wells completed in the alluvium hydrogeologic terrane—sand (SAND), and sand and gravel (SDGL)—were greater than those for wells completed in consolidated rock hydrogeologic terranes (fig. 6). In addition to differences due to well characteristics, sand (SAND) may have an apparently greater median specific-capacity value than sand and gravel (SDGL) because the sand may be better sorted and may have less clay than the sand and gravel.

Dolomite and limestone were defined as distinct hydrogeologic terrane classes on the basis of their composition, the nature of water-yielding openings, and water-yielding properties. Large dissolution openings are unique features of these carbonate rocks and occur in addition to the joints, fractures, and bedding-plane partings characteristic of siliciclastic rock; and contrast with the intergranular openings of unconsolidated material. Specific-capacity values further differentiate dolomite and limestone from other rock types. Wells completed in the dolomite hydrogeologic terrane—dolomite (DLMT), and limestone and dolomite (LMDM)—had the greatest median specific-capacity values of wells completed in consolidated rock hydrogeologic terranes in the study area (fig. 6). Wells completed in the limestone hydrogeologic terrane—limestone (LMSN)—had the second greatest median specific-capacity value.

In addition to differences because of well characteristics, limestone (LMSN) may have an apparently much less median specific-capacity value than dolomite (DLMT) or limestone and dolomite (LMDM) because many wells assigned by the field investigator to limestone may actually penetrate argillaceous limestone. Part of the difference between limestone and dolomite also may be that many dolomite units in the study area contain either chert or thin beds of sandstone, which weather to produce thick regolith. In some places, the thick regolith is saturated and recharges the underlying dolomite aquifer.

Argillaceous carbonate rock also was defined as a hydrogeologic terrane class on the basis of composition and nature of water-yielding openings and properties. Like dolomite and limestone, argillaceous carbonate rock mostly consists of magnesium calcite or calcite and can develop dissolution-enlarged secondary openings. However, the clay-mineral component of this rock mostly is insoluble, and when the rock is dissolved, the clay residue tends to clog some of the secondary openings and to reduce the water-yielding capacity of the rock. Median specific-capacity values for wells completed in the argillaceous carbonate rock hydrogeologic terrane—limestone and shale (LMSH), and dolomite and shale (DMSH)—were less than median values for wells completed in the dolomite or limestone hydrogeologic terranes (fig. 6).




**EXPLANATION**

**Lithologic descriptor group**

| | | | |
|---|---|---|---|
| SAND | Sand | DMSH | Dolomite and shale |
| SDGL | Sand and gravel | CGLM | Conglomerate |
| DLMT | Dolomite | SDSL | Sandstone and shale |
| LMDM | Limestone and dolomite | SHLE | Shale |
| LMSN | Limestone | SNDS | Sandstone |
| LMSH | Limestone and shale | SLSN | Siltstone |

**Percentile**—Indicates percentage of measurements equal to or less than indicated values

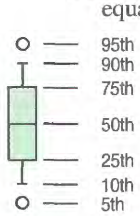



FIGURE 6.—Variation of specific-capacity values for wells grouped by selected lithologic descriptors in the Ground-Water Site Inventory data base of the U.S. Geological Survey and the relation of lithologic descriptor groups to hydrogeologic terranes.

Consolidated, non-carbonate, clastic rock was combined into a separate hydrogeologic terrane class on the basis of composition and the nature of water-yielding openings and properties. This rock, which mostly consists of insoluble silicate mineral grains or rock fragments, is termed "siliciclastic rock." It does not have primary, intergranular, water-yielding openings and generally does not develop secondary dissolution openings. The water-yielding openings in the siliciclastic rock are almost exclusively joints, fractures, and bedding-plane partings. Median specific-capacity values for wells completed in the siliciclastic rock hydrogeologic terrane—conglomerate (CGLM), sandstone and shale (SDSL), shale (SHLE), sandstone (SNDS), and siltstone (SLSN)—were similar to each other, but as a group, they were less than the values for all lithologic descriptor groups in other hydrogeologic terranes except dolomite and shale (DMSH) (fig. 6). In addition to differences due to well characteristics, sandstone (SNDS) may have the same median specific-capacity value as shale (SHLE) or sandstone and shale (SDSL) because the sandstone that has records with lithologic descriptor data is predominantly sandstone interbedded with shale or sandstone with a significant clay content.

## HYDROGEOLOGIC TERRANE MAPS

The hydrogeologic terrane maps (pls. 2–5) were compiled from the hydrogeologic terrane classification, the predominant lithology of each geologic unit, and the State geologic maps. The predominant lithology (pl. 1) was determined primarily from the lithologic descriptions in the explanations on the State geologic maps, supplemented by data tables available for the Correlation of Stratigraphic Units of North America charts (Patchen and others, 1985a and 1985b), county reports on the geology and ground-water resources, and the lithologic descriptors assigned to wells in each unit in the GWSI data base. The rock types shown by color in plate 1 correspond exactly to the hydrogeologic terrane classes in plates 2–5. Uncolored (white) parts of the maps represent areas where the geologic units consist of a mix of rock types or where the geologic units consist of rock characteristic of the Blue Ridge, New England, or Piedmont Physiographic Provinces.

The hydrogeologic terranes (pls. 2–5) coincide with the outcrop pattern of the geologic units with the corresponding predominant lithology and reflect the geologic structure of the area. In the northeastern half of the Valley and Ridge Physiographic Province (pl. 2), where few thrust faults are exposed and do not bring the older carbonate rock to the surface, the siliciclastic rock hydrogeologic terrane characterizes much of the area. The dolomite and limestone hydrogeologic terranes mostly are adjacent to the southeastern margin of this half of the province or are where folds bring them to the surface as in the Nittany Arch. In the southwestern half of the province, numerous thrust faults repeat portions of the stratigraphic section and bring rock of all four hydrogeologic terranes to land surface in bands oriented parallel to the regional strike. In general, the argillaceous carbonate rock hydrogeologic terrane occurs between the siliciclastic rock hydrogeologic terrane and other carbonate hydrogeologic terranes. The alluvium hydrogeologic terrane generally coincides with the major valleys in the northeastern one-fifth of the study area (pls. 2 and 3). The siliciclastic rock hydrogeologic terrane includes more than half the entire study area; the alluvium hydrogeologic terrane includes the least area.

## HYDROGEOLOGIC TERRANE SUBDIVISIONS

The five hydrogeologic terranes can be subdivided on the basis of factors in addition to rock type. The five hydrogeologic terranes include a wide range of hydrologic, structural, and geomorphic conditions. The terranes are regional, comprehensive, and essentially include the entire study area. Areas of more localized hydrologic conditions can be defined within these hydrogeologic terranes. An example of the subdivision of the dolomite hydrogeologic terrane is the western toe of the Blue Ridge Mountains, which is largely defined based on geomorphic conditions.

The western toe of the Blue Ridge Mountains (western toe) is an area characterized by an apron of colluvium and alluvium at the toe of the western slope of the Blue Ridge Mountains (Hinkle and Sterrett, 1976, p. 50 and 51). The colluvium consists of stony material shed from outcrops of resistant, siliciclastic rock—principally the Antietam Quartzite and equivalent units—that is associated with the Blue Ridge Mountains. The apron overlies fine-grained residuum and dolomite bedrock at the southeastern edge of the Valley and Ridge Physiographic Province (fig. 7). In parts of the western toe, the combined thickness of colluvium, alluvium, and residuum exceeds several 100 ft (King, 1950, p. 55 and 59). Within Augusta, Rockbridge, and Rockingham Counties, Virginia (fig. 8), the western toe has public and industrial supply wells that individually may produce in excess of 1,000 gal/min and together produce more than 20 million gallons of water per day from dissolution openings in the dolomite that underlies the thick regolith (Leonard, 1962; Hinkle and Sterrett, 1976, 1978; Meng and others, 1985, p. 431).

The geomorphic conditions defining the western toe, namely an apron of colluvium and alluvium that was

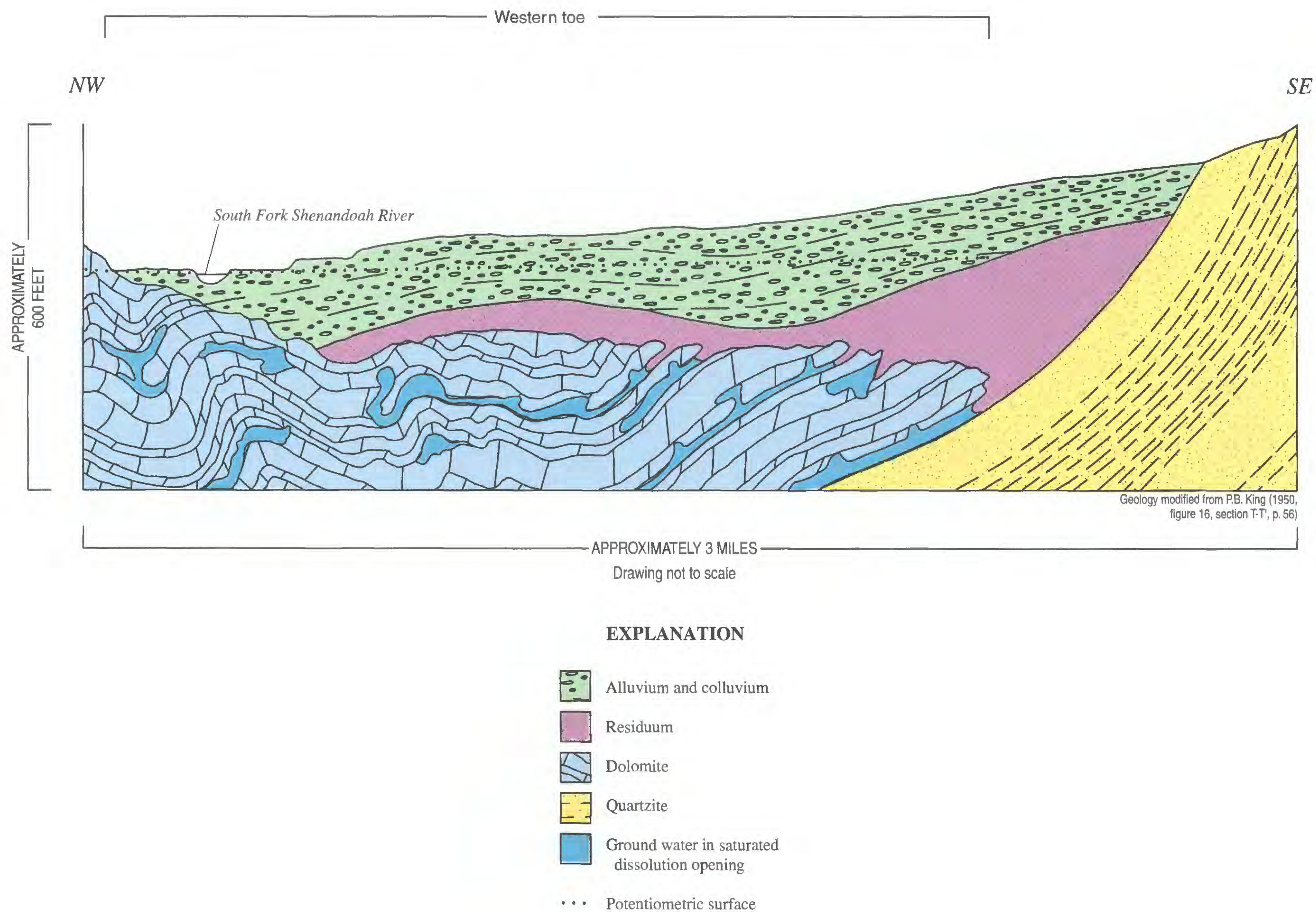
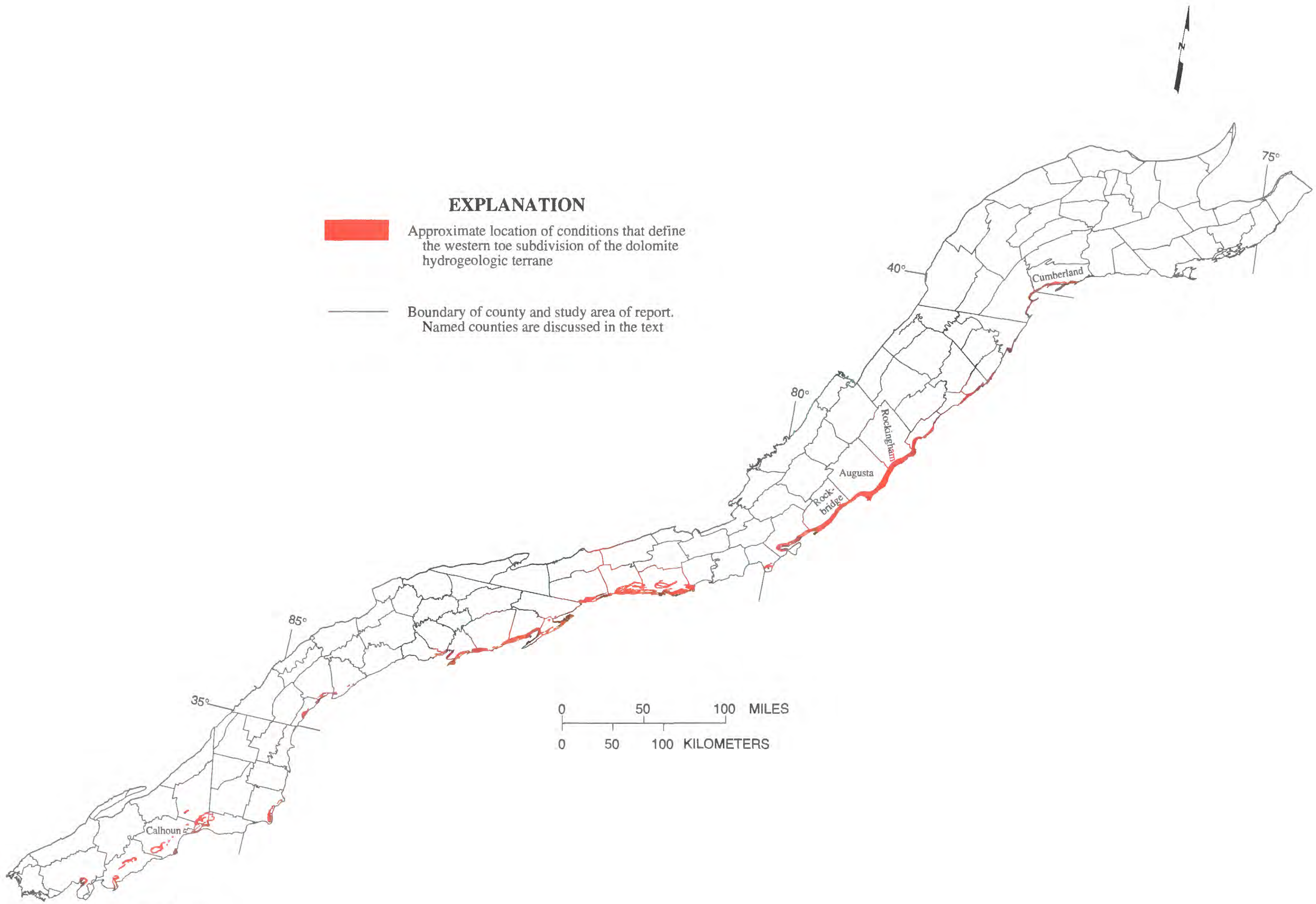



FIGURE 7.—Diagrammatic hydrogeologic section of the western toe of the Blue Ridge Mountains, southeastern Rockingham County, Virginia.




Base from U.S. Geological Survey
1:2,500,000 scale map

FIGURE 8.—Location of conditions that define the western toe subdivision of the dolomite hydrogeologic terrane in the Valley and Ridge Physiographic Province in the Eastern and Southeastern United States.

derived from resistant, siliciclastic rock and that overlies fine-grained residuum and dolomite bedrock at the southeastern edge of the Valley and Ridge Physiographic Province, extend beyond Virginia. These same conditions exist in parts of 36 counties in the study area (fig. 8). As examples, Becher and Root (1981, p. 32 and fig. 8) have mapped an area of thick colluvium and alluvium that overlies the Tomstown Dolomite in southeastern Cumberland County, Pennsylvania. An area of thick colluvium and residuum overlies the Shady Dolomite on the slope of Coldwater Mountain in southern Calhoun County, Alabama. Scott, Harris, and Cobb (1987, fig. 2 and pl. 1) included this area in the recharge area of Coldwater Spring. This spring has a measured discharge averaging 22,000 gal/min and is estimated to be the largest spring in the Valley and Ridge Physiographic Province.

## SELECTION AND ANALYSIS OF WELL RECORDS AND VARIABLES

### SELECTION OF RECORDS AND VARIABLES

A statistical analysis of well records was performed to determine if significant differences in water-yielding properties among the hydrogeologic terranes could be detected. In order to perform valid tests of significance, the authors first analyzed selected well records to investigate the influence of independent variables (casing diameter, primary use of the water, and topographic setting) upon the dependent variable (specific capacity).

All wells with values for specific capacity and well location were selected for inclusion in the data base for the study. Most of these were domestic wells, which generally have low yield and small specific capacity. Domestic wells commonly are not located in the most favorable setting, drilled to the optimum depth, developed for sufficient time, and equipped to produce large quantities of water. Consequently, domestic wells are not the most reliable source of information for classifying hydrogeologic terranes, investigating the influence of independent variables on specific capacity, testing for significance, or estimating the potential yield of water to wells. However, in a trade of quantity of data for quality of data, a large sample set (domestic wells together with nondomestic wells) was used to classify hydrogeologic terranes and to investigate the influence of independent variables, because the smaller size of the sample of nondomestic wells reduced the ability to detect potentially significant terrane classes and variables. A smaller sample set (nondomestic wells only) was used to test for significant differences among hydrogeologic terranes and to estimate potential yield of water to wells.

Records for wells with 6,891 reported specific-capacity values were retrieved from the GWSI data base for the eight-State area. Most of these records also included other data of interest—well yield, well depth, and well-casing diameter. For example, 3,834 records included a lithologic descriptor that allowed analysis of specific-capacity values by descriptor (fig. 6). The largest number of records were for wells in Maryland (fig. 9). Records for wells in Maryland and Pennsylvania were 88 percent of the total.

Specific capacity, well yield, well depth, casing depth, and casing diameter were examined to describe the variation of numeric data contained in the well records (fig. 10). Of the specific-capacity values, 90 percent (5th to 95th percentile) were between 0.02 and 27 (gal/min)/ft, a range that exceeds three orders of magnitude. The reported yields to half of the wells were 16 gal/min or less. The median depth of the wells was 166 ft; 95 percent of the wells were less than 476 ft deep, and only 5 percent of the wells were less than 57 ft deep. Half of the wells were cased to a depth of 41 ft or less. Of the casing diameters, 75 percent were 6 in. or less.

Primary use of the water and topographic setting were examined to describe the distribution of categorical data contained in the well records. With regard to primary use of the water, 63 percent of the wells were domestic; 18 percent were public or industrial supply; 7 percent were commercial, institutional, or stock; and 12 percent were used for other purposes or were unused. With regard to topographic setting, 58 percent of the wells were on hilltops or hillsides; 32 percent, in valley flats or flats; and 10 percent, in other or undesignated topographic settings. The data set predominantly consists of domestic wells on hilltops or hillsides.

Each well record was assigned to one of the five hydrogeologic terranes based on the identity of the geologic unit penetrated by the well. The geologic unit was the primary aquifer reported in the GWSI data base or, for those wells with no reported primary aquifer, was the geologic unit shown on State maps at the well location. The distribution of wells by hydrogeologic terrane was uneven. Most wells (3,324) were in the siliciclastic rock hydrogeologic terrane; the least number of wells (115) were in the alluvium hydrogeologic terrane. The dolomite, limestone, and argillaceous carbonate rock hydrogeologic terranes were the location for 1,334, 1,501, and 617 wells, respectively.

Dependent and independent variables for analysis were selected primarily on the basis of earlier work by Knopman (1990, p. 3–6), who analyzed well records for Pennsylvania in the GWSI data base to identify factors that influence the water-yielding potential of the rock. Knopman used specific capacity as the dependent

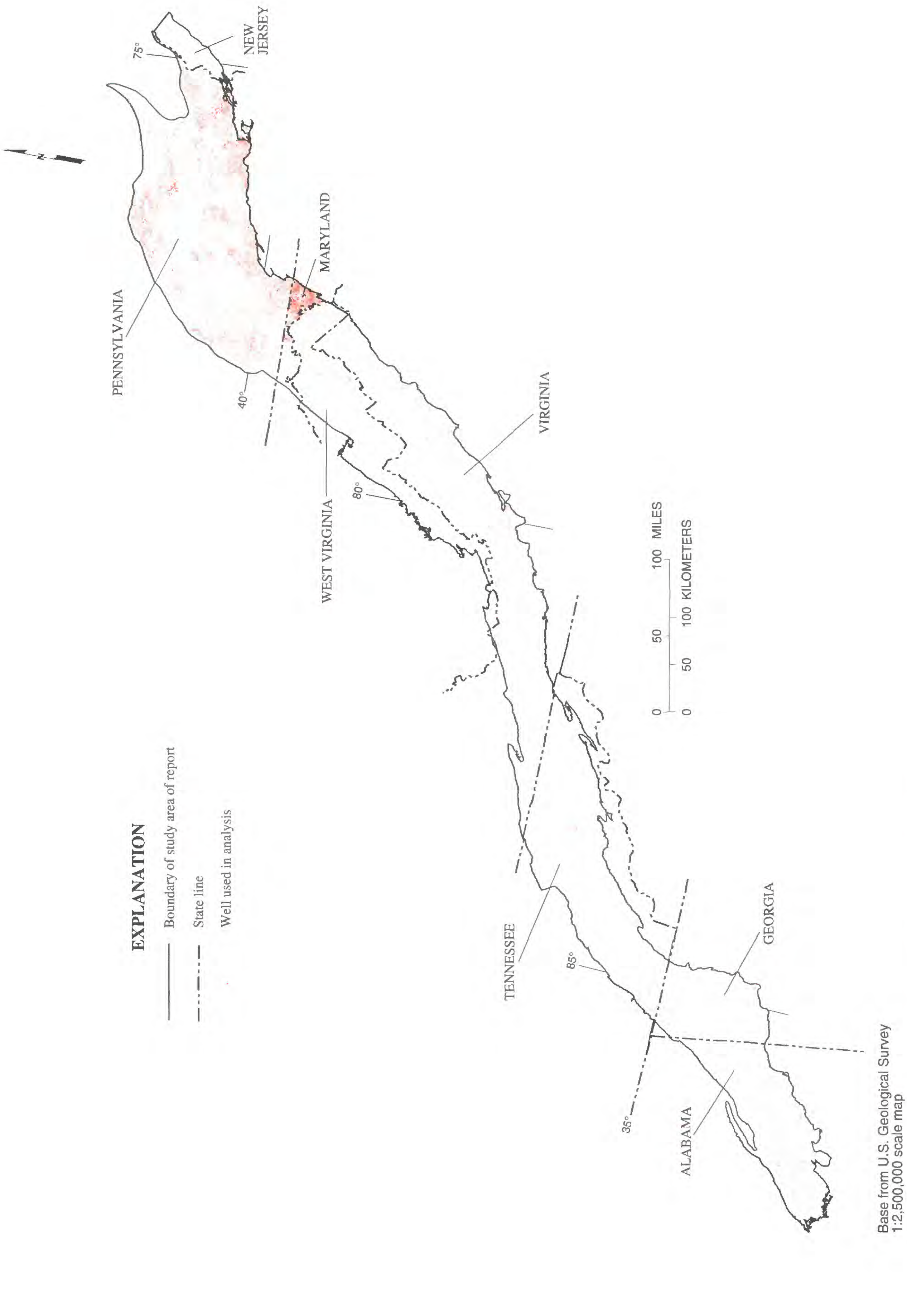



FIGURE 9.—Areal distribution of well records used in the analysis of well records.

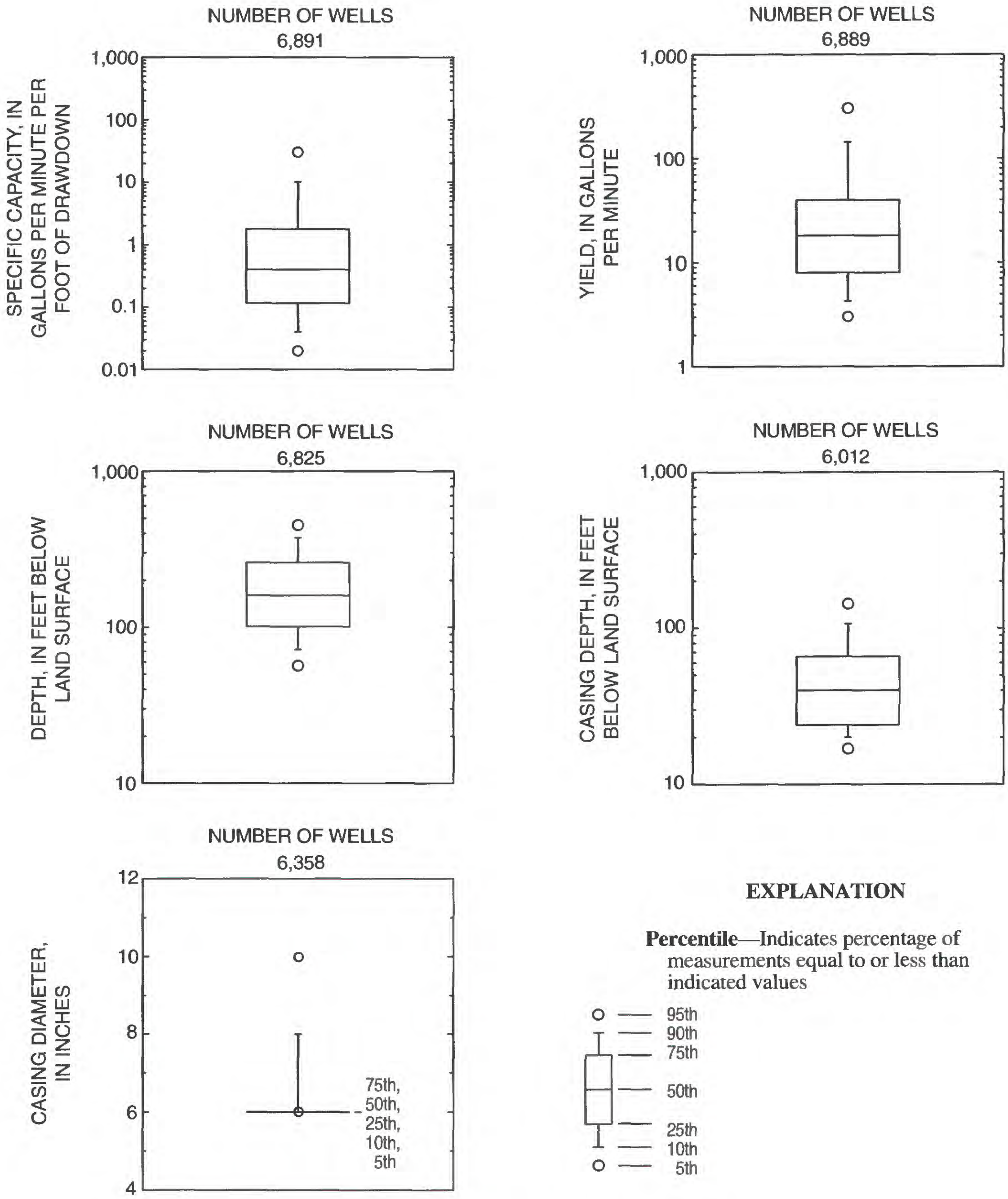



FIGURE 10.—Variation of selected hydrologic and well-construction data for wells used in analysis.

variable; and used casing diameter, primary use of the water, lithologic descriptor, topographic setting, depth of casing, depth of well, saturated interval (as calculated from depth of well, static water level, and depth of casing), and primary aquifer (or geologic unit identifier) as independent variables. She determined that casing diameter, primary use of the water, lithologic descriptor, and topographic setting (in decreasing order) accounted for the most variation in specific-capacity values (Knopman, 1990, p. 27, fig. 9).

The dependent variable for this study was specific capacity. Specific capacity and reported well discharge are measures of the yield of water to wells. Specific capacity was considered the more accurate measure because it accounts for drawdown in addition to discharge. As an example, a group of wells that produce an average 10 gal/min with 10 ft of drawdown are completed in rock that has better water-yielding properties than a group of wells that produce an average 10 gal/min with 100 ft of drawdown. Specific capacity is only an approximate indicator of the water-yielding properties of the rock, because the consolidated rock in the study area commonly is neither isotropic nor homogeneous, and because the specific capacity varies with well discharge. Of the variables available for analysis, specific capacity nevertheless was considered to be the most accurate and abundant indicator.

The independent variables for this investigation—casing diameter, primary use of the water, topographic setting, hydrogeologic terrane, and hydrogeologic terrane subdivision—were selected on the basis of the results of work by three investigators in addition to Knopman (1990). Casing diameter correlated strongly with well diameter, which in turn was reported to correlate strongly with well yield; for example, average well yield was determined to be directly proportional to the diameter of wells in the Piedmont and Blue Ridge Physiographic Provinces of North Carolina (Daniel, 1989, p. A16–A20). In the present study, casing diameter was not postulated to directly influence specific capacity. A large part of the correlation between well diameter and yield (or specific capacity) is probably due to cultural bias in the siting and construction of the wells. This bias is associated with the intended use of the water and not with the greater discharge capacity of the larger casing size. For example, wells with a diameter greater than 7 in. are likely to have been constructed at sites where a well owner who desired a large amount of water knew in advance that large quantities of water were available and warranted the expense of the larger casing size. Advance knowledge might be based on records of existing wells or the results of drilling test wells.

Concerning primary use of the water, Wood and MacLachlan (1978, p. 29–30, tables 5 and 6) provided data to show that the median specific-capacity values of nondomestic wells in carbonate geologic units are 20 times the median values of domestic wells in the same units. A large part of the correlation between primary use of the water and specific capacity of wells is probably due to cultural bias in the siting and construction of the wells; for example, well owners who intend to withdraw water for public or industrial supply purposes usually are willing to invest more time and money on their water supplies than are well owners who intend to withdraw water for domestic purposes.

## ANALYSIS OF RECORDS AND VARIABLES

Casing diameter, primary use of the water, and topographic setting influence the specific-capacity values of wells completed in the various hydrogeologic terranes. For example, when specific-capacity values for wells in the dolomite hydrogeologic terrane were grouped sequentially, first by categories of the variable casing diameter, then by categories of primary use of the water, and last by categories of topographic setting (fig. 11), substantial differences became apparent. For the dolomite hydrogeologic terrane, wells with casing diameters of less than 7 in. generally had a smaller specific capacity than wells with casing diameters of greater than 9 in. Wells used for domestic supply typically had a smaller specific capacity than wells used for public or industrial supply, and wells located on hills had a smaller specific capacity than wells located in valleys (fig. 11). The eight categories within the three variables (fig. 11) had similar relations to specific-capacity values for wells completed in the four other hydrogeologic terranes.

To further examine the apparent differences in specific-capacity values among the categories of the variables casing diameter, primary use of the water, and topographic setting, Tukey's honestly significant difference test (SAS Institute, Inc., 1985, p. 473) was employed. Tukey's test, a nonparametric statistical procedure, was used to determine if the apparent differences in median values among these categories were statistically significant from each other. The test involves a null hypothesis that no real differences in median values of specific capacity exist among wells in the various categories. An alpha level, or level of probability, is used in the test to represent the maximum probability of rejecting the null hypothesis when it is actually true. Tukey tests performed at a probability (alpha level) of 0.01 indicated a statistically significant difference between the median values of specific capacity for the following seven pairs of categories within the three variables

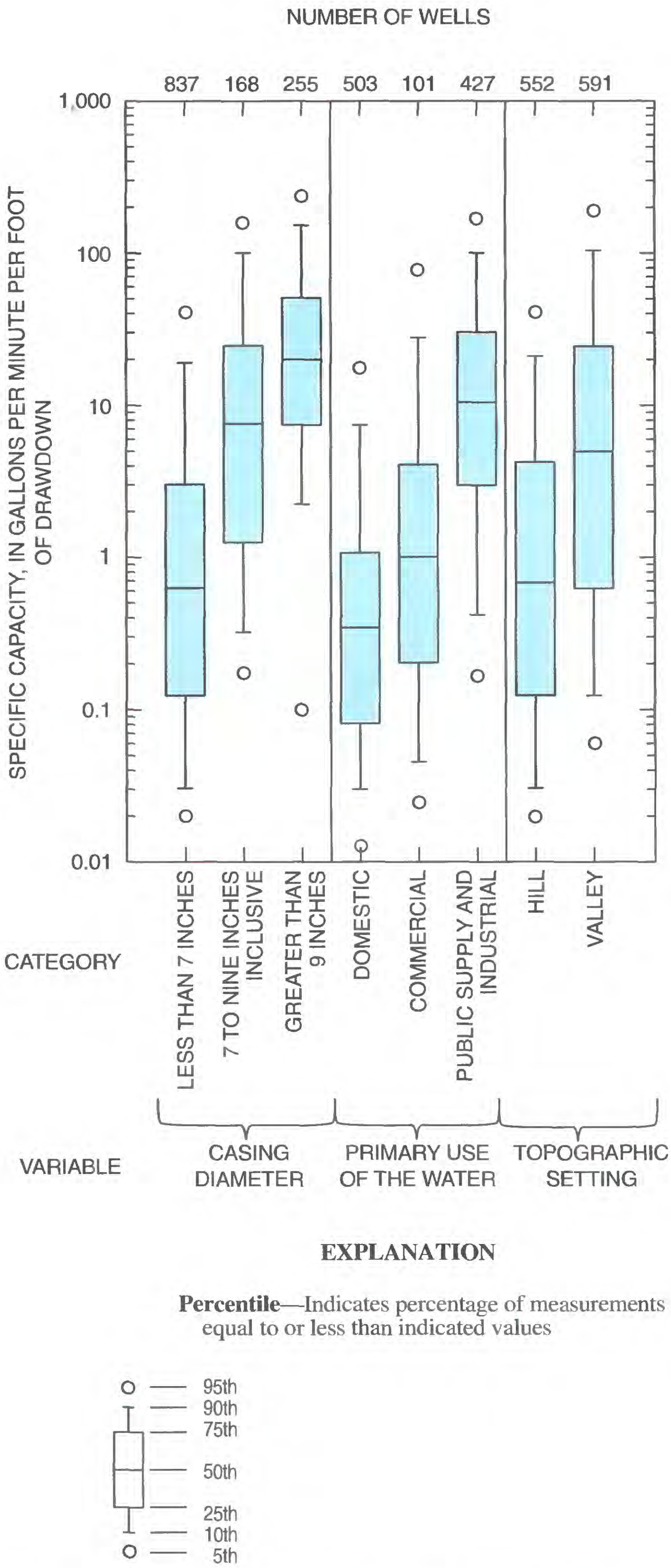



FIGURE 11.—Variation of specific-capacity values for wells in the dolomite hydrogeologic terrane grouped by categories of well-casing diameter, primary use of the water, and topographic setting of the well.

[where (less than 7 in.)/(7 to 9 in. inclusive) is an example of a single pair] (fig. 11):

Casing diameter
(less than 7 in.)/(7 to 9 in. inclusive)
(less than 7 in.)/(greater than 9 in.)
(7 to 9 in. inclusive)/(greater than 9 in.)

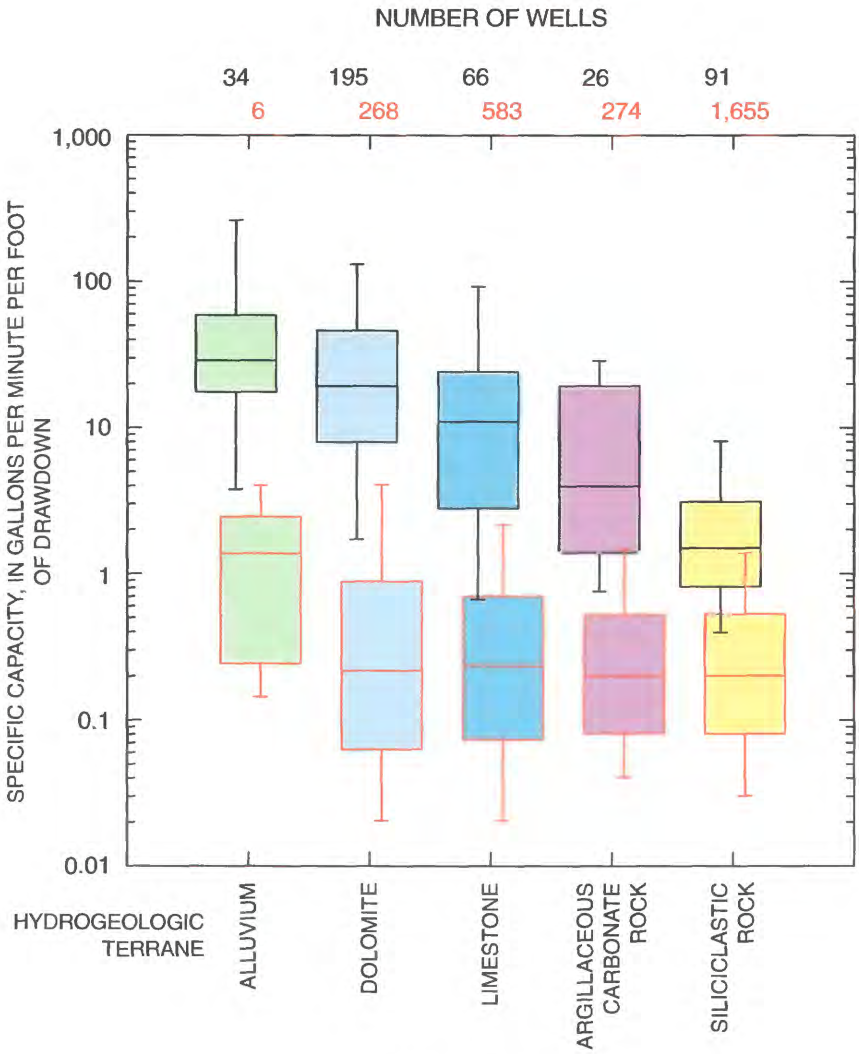
Primary use of the water
(domestic)/(commercial)
(domestic)/(public and industrial supply)
(commercial)/(public and industrial supply)

Topographic setting
(hill)/(valley).

Differences among the hydrogeologic terranes in regard to the percentage of wells in each category of the three variables tend to bias the median values of specific capacity and complicate the determination of significant differences in water-yielding properties among the hydrogeologic terranes. For example, the alluvium hydrogeologic terrane has a larger percentage of wells with casing diameters of greater than 9 in. than does the dolomite hydrogeologic terrane. This difference between the two hydrogeologic terranes tends to exaggerate the apparent difference between their median values of specific capacity. Testing for significant differences in water-yielding properties between the alluvium and dolomite hydrogeologic terranes may not be valid without accounting for differences between data sets in regard to casing diameter.

A method for reducing the influence of casing diameter, primary use of the water, and topographic setting on specific capacity is to subdivide the data base into homogeneous data sets consisting of wells with the same characteristics with respect to these three variables. Two homogeneous data sets were constructed for each hydrogeologic terrane—the most-productive wells and the least-productive wells (fig. 12). The homogeneous data set that represented the most-productive wells consisted only of wells with casing diameters of greater than or equal to 7 in., used for either public or industrial supply, and located in valleys. The homogeneous data set that represented the least-productive wells consisted only of wells with casing diameters of less than 7 in., used for domestic supply, and located on hills. The influence of these variables is so pronounced that the interquartile range (25th to 75th percentile) for the most-productive wells in siliciclastic rock does not even overlap the interquartile range for the least-productive wells in dolomite (fig. 12)

Specific-capacity values for these two homogeneous data sets for each hydrogeologic terrane are significantly different according to Tukey tests—probability (alpha level) of 0.0005. Subdividing the data into homogeneous




## EXPLANATION

**Description of homogeneous data sets**—Most-productive wells data set consists only of wells with casing diameters of greater than or equal to 7 in., used for either public or industrial supply, and located in valleys. Least-productive wells data set consists only of wells with casing diameters less than 7 in., used for domestic supply, and located on hills.

**Percentile**—Indicates percentage of measurements equal to or less than indicated values

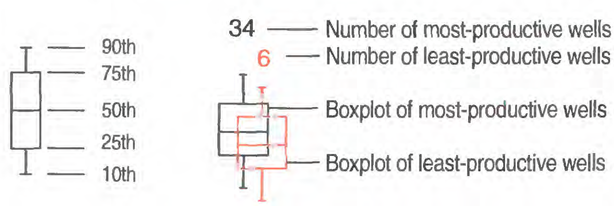



FIGURE 12.—Variation of specific-capacity values for wells grouped by five hydrogeologic terranes and two homogeneous data sets.

sets (fig. 12) revealed some of the cause for the large range in values within each hydrogeologic terrane for undivided data sets that results in overlapping values between terranes. The homogeneous data sets represent end members in a range of values wherein restrictions were made on the three variables—casing diameter, primary use of the water, and topographic setting. In contrast, when no restrictions were made on these variables as for nonhomogeneous, undivided sets, the range in specific-capacity values for each hydrogeologic terrane was sufficiently large that real differences among terranes were obscured, and the range in values for each hydrogeologic terrane had substantial overlap with the range of other terranes. Subdividing the data base by the three variables allows for better estimates of the specific capacity of the hydrogeologic terranes.

Valid conclusions about significant differences in water-yielding properties can be made by comparing subdivided data sets. Concerning a comparison of median specific-capacity values for most-productive wells, Tukey test results indicated a statistically significant difference—probability (alpha level) of 0.05—between median values for the following pairs of hydrogeologic terranes:

(alluvium)/(limestone),
(alluvium)/(argillaceous carbonate rock),
(alluvium)/(siliciclastic rock),
(dolomite)/(limestone),
(dolomite)/(argillaceous carbonate rock),
(dolomite)/(siliciclastic rock),
(limestone)/(siliciclastic rock), and
(argillaceous carbonate rock)/(siliciclastic rock).

Tukey test results did not indicate a statistically significant difference between median values of specific capacity for the remaining two pairs of hydrogeologic terranes at a probability (alpha level) of 0.05:

(alluvium)/(dolomite), and
(limestone)/(argillaceous carbonate rock).

In summary, Tukey test results indicated that the differences in median specific-capacity values were significant for at least 8 of the 10 pairs of hydrogeologic terranes by use of homogeneous data sets. Therefore, the hydrogeologic terranes are, for the most part, significantly different in their water-yielding properties.

### ANALYSIS OF HYDROGEOLOGIC TERRANE SUBDIVISIONS

A statistical analysis of well records was performed to determine if significant differences in water-yielding properties between subdivisions of the dolomite hydrogeologic terrane could be detected. To determine differences between the western toe subdivision of the dolomite hydrogeologic terrane and remaining subdivisions of this terrane, a comparison was made using 44 records of the most-productive wells from the GWSI data base of the USGS for Virginia and West Virginia. For the purpose of this comparison, wells located within the dolomite hydrogeologic terrane and within a band that is 3 mi wide along the southeastern border of the Valley and Ridge Physiographic Province in these two States were classified as "in-toe" wells, and those within the dolomite hydrogeologic terrane to the northwest were classified as "out-of-toe" wells. The ranges of the middle 90 percent of specific-capacity values overlapped and spanned about three orders of magnitude (fig. 13). The median specific-capacity value for "in-toe" wells [26 (gal/min)/ft] is more than three times the median value for "out-of-toe" wells [7.2 (gal/min)/ft].

To further examine the apparent differences in specific-capacity values between the subdivisions of the dolomite hydrogeologic terrane, a nonparametric statistical procedure, the Mann-Whitney test (Inman and Conover, 1983, p. 281) was employed. The Mann-Whitney test was used to determine if the apparent differences in median values between these subdivisions were statistically significant from each other. The Mann-Whitney test involves a null hypothesis that no real difference in median values of specific capacity exist between wells in the two subdivisions. An alpha value, or level of probability, is used in the test to represent the maximum probability of rejecting the null hypothesis when it is actually true. The alpha value used in this analysis was 0.05. The p-value represents the attained level of significance determined from the data using the Mann-Whitney test. If the p-value is less than or equal to the alpha value, the null hypothesis is rejected, and significant differences are assumed to exist between the subdivisions.

The Mann-Whitney test indicated a statistically significant difference between the median values of specific capacity for the subdivisions of the dolomite hydrogeologic terrane in Virginia and West Virginia (p-value of 0.05). Public and industrial supply wells in dolomite in the western toe had significantly greater specific-capacity values than comparable wells in dolomite elsewhere in Virginia and West Virginia.

## POTENTIAL YIELD OF WATER TO WELLS

The potential rate that water can be withdrawn from public and industrial supply wells can be estimated from the reported specific-capacity values of the most-productive wells (fig. 12) by assuming constant drawdowns for each hydrogeologic terrane and negligible

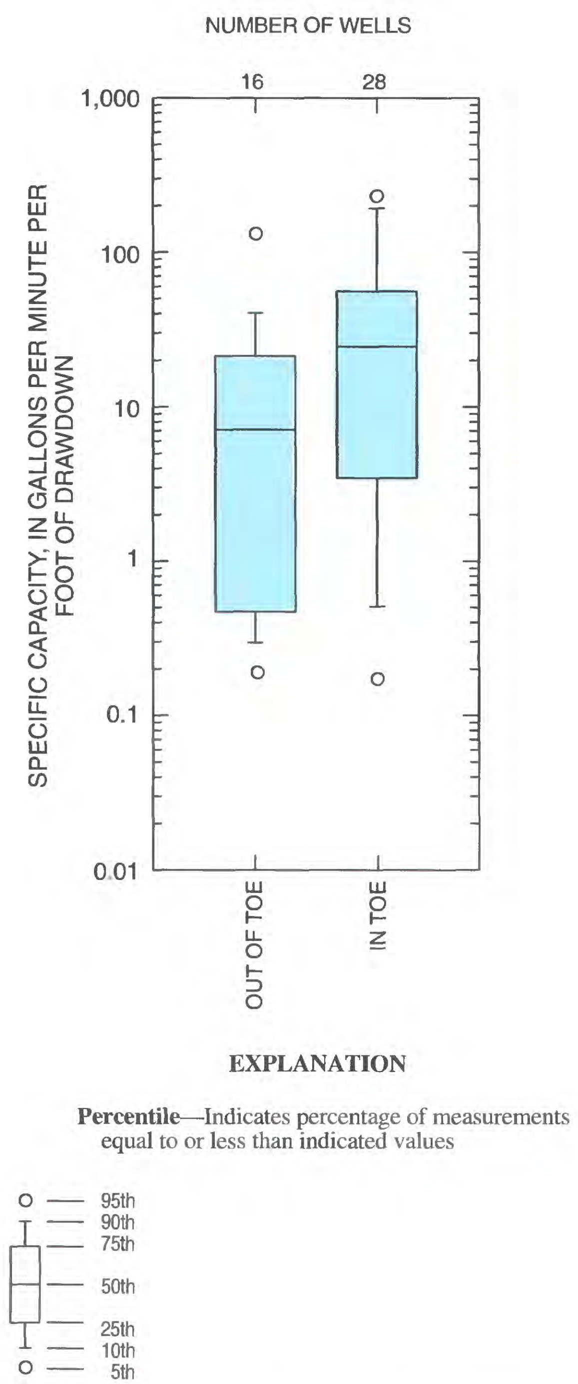


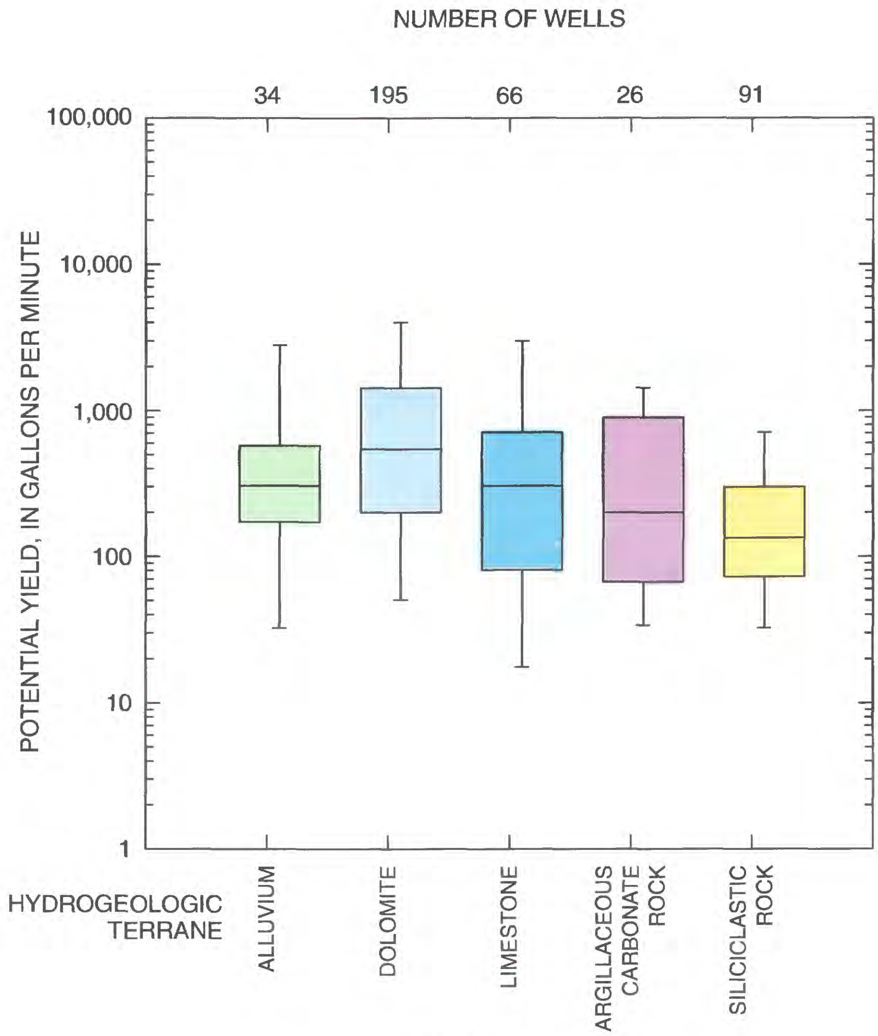

FIGURE 13.—Variation of specific-capacity values for public and industrial supply wells in and out of the western toe subdivision of the dolomite hydrogeologic terrane in Virginia and West Virginia.

well-entrance losses. These constant drawdowns were determined from the median of reported drawdowns for the most-productive wells. For these wells, the median drawdowns (rounded to the nearest 10 ft) were 10 ft, alluvium; 30 ft, dolomite and limestone; 50 ft, argillaceous carbonate rock; and 90 ft, siliciclastic rock. As an example of the calculation of potential yield, the median specific capacity of the 91 most-productive wells in siliciclastic rock (fig. 12) was 1.4 (gal/min)/ft. When multiplied by 90 ft of drawdown, this specific-capacity value resulted in an estimated median potential yield of about 130 gal/min (fig. 14). Because the water-yielding properties of the rock vary, a more realistic estimate of potential yield is given by the interquartile range in specific capacity. On the basis of data for the 412 most-productive wells, the middle 50-percent range in estimated potential yields to these public and industrial supply wells was 170 to 580 gal/min, alluvium; 210 to 1,400 gal/min, dolomite; 80 to 720 gal/min, limestone; 65 to 850 gal/min, argillaceous carbonate rock; and 70 to 280 gal/min, siliciclastic rock (fig. 14).

## SUMMARY

This report provides information on the hydrogeologic setting of the Valley and Ridge Physiographic Province, describes and maps hydrogeologic terranes within this setting, applies statistical tests to these hydrogeologic terranes to identify significant differences in water-yielding properties, and estimates the quantity of water potentially available to public and industrial supply wells in these hydrogeologic terranes.

The Valley and Ridge Physiographic Province is underlain by deformed sedimentary rock of Paleozoic age including dolomite, limestone, shale, and sandstone. Regolith (soil, sediment, and weathered rock) covers the Paleozoic rock throughout most of the province. Ground water in the consolidated sedimentary rock resides in and flows through secondary openings. Flow systems tend to be limited in depth by weathering and associated enhancement of secondary permeability and limited in areal extent by faults and folds and stream drainage networks. The largest flow systems discharge at springs in carbonate rock. Selected rock types account for a substantial part of the variation in the water-yielding properties of the rock because of the unique way in which these rock types deform and weather. Structure also accounts for some of the variation because faults juxtapose rock types with different water-yielding properties; and joints, fractures, and bedding-plane partings are a variable network of openings for ground-water movement. Well-sorted alluvium of glacial origin in the northeastern one-fifth of the area, and regolith along the




**EXPLANATION**

**Description of most-productive wells**—Most-productive wells data set consists only of wells with casing diameters of greater than or equal to 7 in., used for either public or industrial supply, and located in valleys.

**Calculation of potential yield**—Potential yield is estimated by multiplying specific capacity shown in figure 12 for most-productive wells by a median drawdown of 10 ft, alluvium; 30 ft, dolomite and limestone; 50 ft, argillaceous carbonate rock; and 90 ft, siliciclastic rock

**Percentile**—Indicates percentage of estimates equal to or less than indicated values

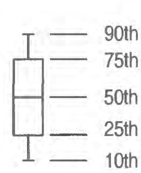



FIGURE 14.—Variation of estimated potential yield of water to most-productive wells in hydrogeologic terranes in the Valley and Ridge Physiographic Province in the Eastern and Southeastern United States.

southeastern edge of the Valley and Ridge Physiographic Province, store large quantities of ground water.

Hydrogeologic terranes are regionally mappable areas characterized by similar rock type and water-yielding properties; areas of a particular rock type and water-yielding properties were assigned to a particular terrane to help water users in locating and developing adequate water supplies. The five hydrogeologic terranes defined in the report—alluvium, dolomite, limestone, argillaceous carbonate rock, and siliciclastic rock—were defined based on the relation of rock type to the nature of water-yielding openings and water-yielding properties as indicated by the specific capacity of wells. Consolidated sedimentary rock units, which were identified from State geologic maps, and the regolith were grouped into the hydrogeologic terranes on the basis of the predominant lithology of mapped geologic units. Maps showing the distribution of the hydrogeologic terranes in the study area were compiled from the same State geologic maps. The hydrogeologic terranes coincide with the outcrop of the geologic units that have the corresponding predominant lithology. The siliciclastic rock hydrogeologic terrane includes most of the study area. The western toe of the Blue Ridge Mountains subdivision of the dolomite hydrogeologic terrane is along the southeastern edge of the Valley and Ridge Physiographic Province where siliciclastic rock debris from the adjacent highlands covers thick residuum and dolomite. The western toe has wells that produce more than 1,000 gal/min.

To determine if significant differences in water-yielding properties among the hydrogeologic terranes could be detected, records for wells with 6,891 specific-capacity values were retrieved from the GWSI data base for the study area. These data were predominantly for domestic wells on hilltops and hillsides. Building on previous investigations, the authors selected specific capacity as the variable that best represents the water-yielding properties of the hydrogeologic terranes in the study area. Casing diameter, primary use of the water, topographic setting, hydrogeologic terrane, and hydrogeologic terrane subdivision were selected as variables that influence the value of specific capacity.

Casing diameter, primary use of the water, and topographic setting influence specific-capacity values of wells completed in each hydrogeologic terrane. Homogeneous data sets, which consist of all wells that have the same characteristics with respect to casing diameter, primary use of the water, and topographic setting, however, take these three variables into account and allow valid conclusions regarding significant differences in water-yielding properties. All five hydrogeologic terranes showed differences. According to results of Tukey statistical tests at a probability (alpha level) of 0.05, 8 out of 10 pairs of hydrogeologic terranes had significantly different median specific-capacity values by using homogeneous data sets. The median specific-capacity value for public and industrial supply wells in the western toe subdivision of the dolomite hydrogeologic terrane is more than three times the value for comparable wells in the rest of the dolomite hydrogeologic terrane in Virginia and West Virginia—a significant difference.

Estimates of potential yields to public and industrial supply wells were calculated from specific-capacity data for the most-productive wells, which have casing diameter of 7 in. or more, discharge water primarily for public or industrial supply, and are in a valley. Median constant drawdowns, calculated from reported drawdowns, were determined to be between 10 and 90 ft for wells completed in each of the five hydrogeologic terranes, and well-entrance losses were assumed to be negligible. Estimated interquartile ranges in potential yields to 412 most-productive wells in the five hydrogeologic terranes were 170 to 580 gal/min, alluvium; 210 to 1,400 gal/min, dolomite; 80 to 720 gal/min, limestone; 65 to 850 gal/min, argillaceous carbonate rock; and 70 to 280 gal/min, siliciclastic rock.

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☆U.S. GOVERNMENT PRINTING OFFICE: 1997-547-552