INTRODUCTION

Severe and prolonged droughts between 1961 and 1988, combined with increased demands for freshwater supplies in the United States, have resulted in a critical need to assess the potential for development of ground- and surface-water supplies. Rapid industrial growth and urban expansion have caused existing freshwater supplies to be used at or near maximum capacity. Begun in 1978, the Regional Aquifer-System Analysis (RASA) Program of the U.S. Geological Survey (USGS) is a systematic effort to study a number of the Nation's most important aquifer systems, which, in aggregate, underlie much of the country and represent an important component of the Nation's total water supply. The broad objective for each of the 28 studies in the program 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.

In 1988, as part of the RASA Program, the USGS began a 6-year study of the ground-water resources of parts of 11 States in the Eastern United States (Swain and others, 1991). The study was designated 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, the Blue Ridge, the New England, and the Piedmont Physiographic Provinces (fig. 1). For the purposes of this report, the small area in the New England Physiographic Province that is within the study area in New Jersey and Pennsylvania was considered part of the Piedmont Physiographic Province. The results of the APRASA are contained in about 50 reports and abstracts, including reports on simulation of ground-water flow in three type areas, this atlas, and chapters in Professional Paper 1422. These chapters include the summary (Chapter A), descriptions of recharge rates and surface- and ground-water relations (Chapter B), hydrogeologic terranes in the Valley and Ridge Physiographic Province (Chapter C), and ground-water geochemistry (Chapter D).

The purposes of this atlas are to summarize the hydrogeology, to describe an analysis of maps and well records, and to present a classification and map of the hydrogeologic terranes of the Blue Ridge and Piedmont Physiographic Provinces within the APRASA study area. Hydrogeologic terranes are defined for this atlas as regionally mappable areas characterized by similar water-yielding properties of a grouping of selected rock types. The hydrogeologic terranes represent areas of distinct hydrologic character. The terranes are intended to help water users locate and develop adequate water supplies and to help hydrologists interpret the regional hydrogeology.

Previous investigations provide maps and descriptions of the geologic units, describe the local quantity and quality of 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), North Carolina (Brown and Parker, 1985), and Virginia (Calver and Hobbs, 1963). State maps show geologic 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), South Carolina (Overstreet and Bell, 1965), Tennessee (Hardeman, 1966), and West Virginia (Cardwell and others, 1968). Quadrangle geologic maps show geologic units at a scale of 1:24,000 for parts of Delaware within the APRASA area (Woodruff and Thompson, 1972, 1975). Many reports have been published describing the ground-water resources of a county, parts of a county, multi-county areas, or river basins.

The statistical methods used in this atlas are based largely on those used by Helsel and Hirsch (1992) and by Knopman (1990, p. 7-9). In her analysis of well records in the USGS Ground-Water Site Inventory (GWSI) data base, Knopman (1990) ranked factors that must be taken into account when assessing the water-yielding potential of the rocks in the Valley and Ridge, the Blue Ridge, and the Piedmont Physiographic Provinces in Pennsylvania. Readers are referred to Helsel and Hirsch (1992) and Knopman (1990) for details regarding statistical methods.

HYDROGEOLOGIC SETTING

The Blue Ridge and Piedmont Physiographic Provinces are underlain by metamorphic, igneous, and sedimentary rocks, many of which have undergone several periods of metamorphism and intrusive activity. Although 35 rock types have been identified and mapped in the Blue Ridge and 53 in the Piedmont, four rock types—gneiss, schist, granite, and phyllite—underlie more than 64 percent of each province. The bedding and foliation are usually folded and tilted, can exhibit variable orientations, and commonly intersect one another in systematic geometric patterns. Although most rocks have strong directional fabric, igneous intrusives emplaced after the last metamorphic event in the late Paleozoic Era tend to be massive and less foliated. The rocks were subjected to uplift during the Cenozoic Era, and subsequent weathering and erosion opened or widened existing fractures or created new ones by stress relief. Fault zones of differing types, scales, and orientations are common; some fault zones are characterized by an abundance of fractures.

Regolith (soil, sediment, weathered rock) covers the consolidated rock throughout the study area, and bedrock typically is exposed only in areas of rugged topography or in stream channels where erosion has removed the surficial materials. The regolith either was formed in place by the weathering of the underlying bedrock (residuum) or was deposited after being transported from the place of weathering (till, colluvium, alluvium). Much of the regolith in the study area is fine-grained residuum that retains the structural features of the parent bedrock (saprolite). Residuum commonly is thin (less than 5 ft) on shale, phyllite, and carbonate rock, but can be thick (more than 50 ft) on rock that contains substantial amounts of resistant quartz, quartzite, or well-cemented quartz sandstone. Glacial till with a sandy or clayey matrix covers much of the uplands in New Jersey and eastern Pennsylvania and is commonly less than 3 ft thick. In major valleys in the same area, alluvium commonly is more than 30 ft thick and is coarse-grained, well sorted, and derived directly or indirectly from glacial deposits. Although of small areal extent in comparison to the entire study area, this alluvium produces some of the largest yields of water to wells of any geologic unit in the study area. Within and adjacent to the Blue Ridge Physiographic Province, thin, stony colluvium overlies residuum or bedrock on hill and mountain slopes that are crested by resistant siliciclastic rock. The colluvium commonly grades downslope into disected alluvial terraces containing cobble gravel, sand, and sandy loam. In several places (Frederick Valley, Mountain City-Shady Valley, for examples), colluvial-alluvial aprons cover cavernous, carbonate rock, which discharges to large springs and maintains unusually large base flow during dry weather (Hollyday and others, 1997).

The water-storage and transmission characteristics of the bedrock and the regolith and the hydraulic connection between the bedrock and the regolith determine the water-supply potential of the aquifers in the metamorphic and igneous rocks in the two provinces (fig. 2). Wells that penetrate consolidated rocks in areas mantled by thick, saturated regolith generally have higher sustained yields than wells where regolith is thin or absent. Porosity of the regolith is about 35 to 55 percent near land surface (Stewart, 1962) but decreases with depth as the degree of weathering decreases. Porosity of the underlying bedrock is only 0.01 to 2 percent (Heath, 1984). Because of the relatively large porosity of the regolith, recharge is stored primarily in the regolith and is released slowly to underlying bedrock fractures. The transition zone between the saprolite and the unweathered bedrock is often more permeable than the saprolite. If the transition zone is sufficiently thick, significant amounts of ground water can flow laterally in this zone. Laboratory analyses of samples of saprolite in Maryland and Georgia indicate a wide range of hydraulic conductivity—0.0013 to 15 ft/d (Nutter and Otton, 1969). The abundance of connected fractures in the bedrock directly affects the yield of wells in these rocks. Because fractures act as conduits for ground-water flow, well yields are greatest where wells intersect fractures that are large, numerous, or both. Because the number and size of fractures decrease with depth in the Blue Ridge and Piedmont rocks, few wells in these two provinces are drilled more than 500 feet deep.

Several basins and valleys that are filled with sedimentary rocks lie within the expanse of metamorphic and igneous rocks of the Blue Ridge and Piedmont Physiographic Provinces and constitute less than 10 percent of the study area. Carbonate rocks underlie the Conestoga Valley section of the Piedmont in southeastern Pennsylvania, the Frederick Valley in central Maryland, and small valleys and coves in the Blue Ridge Physiographic Province in Tennessee and in the Piedmont in

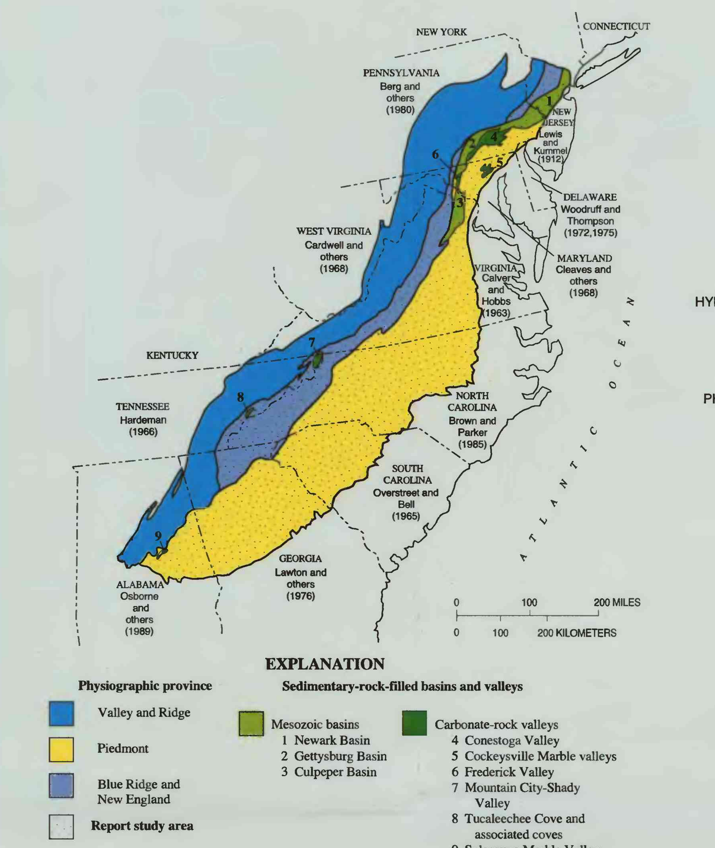


Figure 1. The Appalachian Valley and Piedmont Regional Aquifer-System Analysis study area, physiographic provinces, report study area, sedimentary-rock-filled basins and valleys, and State-geologic-map references.

Records of 40,315 wells in the two provinces in the APRASA study area were retrieved from the GWSI files of the USGS. Among these wells, 93 percent are in the Piedmont Physiographic Province; 70 percent are in Maryland, North Carolina, and Pennsylvania. More than one-half of the wells are used for domestic water supply. Because data from domestic wells usually do not reflect accurately the hydraulic conditions at a well site, these data were not used during the statistical analysis to classify the terranes. The siting, construction, and yield of domestic wells generally are biased because owners are restricted to small areas in which to place a well, often have limited funds, and require only 5 to 10 gal/min of water. Data from nondomestic wells (primarily industrial, public, and irrigation supplies) were used to statistically classify and to delineate hydrogeologic terranes even though a smaller amount of data was available as compared with data available for both nondomestic and domestic wells. About half—8,559 wells—of the records for nondomestic wells in the two provinces had values for yield and could be associated with a rock type; about one-quarter—3,864 wells—had values for specific capacity and could be associated with a rock type. Data from the GWSI data base were merged with the coverage of rock types in order to associate every record of yield and specific capacity with a rock type.

HYDROGEOLOGIC TERRANE CLASSIFICATION

Hydrogeologic terranes were classified by relating rock type to the yield of nondomestic wells in the Blue Ridge and Piedmont Physiographic Provinces. Each province was analyzed independently. Well yields for each well were grouped by province and rock type, which had been assigned to the well by merging the well location with the polygon coverage of rock types. The values were analyzed to derive statistical characteristics of yield for each rock type in each province. The rock types were then ranked in order of increasing median yield and grouped into hydrogeologic terranes according to selected ranges in median yield for each province. The medians were then tested for significant differences. If a rock type had fewer than 10 values of well yield, then the sample was considered too small to make an assignment of a rock type to a hydrogeologic terrane. For this reason, although 35 rock types had been mapped in the Blue Ridge, only 12 rock types could be used to classify and map hydrogeologic terranes. Similarly, although 53 rock types had been mapped in the Piedmont, only 26 rock types could be used. Nevertheless, almost the entire study area could be assigned to a hydrogeologic terrane and mapped because the unassigned rock types (amphibolite, mylonite, tonalite, for example) are uncommon and cover small areas relative to the study area.

Previous investigators used similar methods to group rock types into classes according to specific capacity or well yield. Knopman (1990) described factors related to the water-yielding potential of rocks in the APRASA area of Pennsylvania and suggested that there was a statistical basis for grouping geologic units into hydrogeologic units, or terranes, by rock type. Hollyday and Hileman (1996) classified and mapped hydrogeologic terranes in the Valley and Ridge Physiographic Province using statistical analysis of specific-capacity data. Daniel (1989) described a statistical analysis relating well yield to construction and location of wells in the Blue Ridge and Piedmont Physiographic Provinces of North Carolina. Daniel presented well data classified by geologic belts, hydrogeologic units composed of similar rock types, topographic setting, and other parameters. Daniel and Payne (1990) classified rock types into 21 hydrogeologic units in the Blue Ridge and Piedmont Physiographic Provinces of North Carolina on the basis of rock origin, composition, and texture. The units were ranked on the basis of the average yield of wells in each unit.

The rock types in each physiographic province were ranked in order of median yield to nondomestic wells and grouped into hydrogeologic-terrane classes according to selected ranges in median yield. Two hydrogeologic terranes (gneiss-granite and schist-sandstone) were classified in the Blue Ridge Physiographic Province, and three hydrogeologic terranes (phyllite-gabbro, gneiss-schist, and shale-sandstone) in the Piedmont Physiographic Province. The names of the hydrogeologic terranes correspond to the two rock types that compose the most area within the terrane. The classes of median well yield for the Blue Ridge Physiographic Province were less than or equal to 24 gal/min (gneiss-granite) and greater than 24 gal/min (schist-sandstone). The classes of median well yield for the Piedmont Physiographic Province were less than or equal to 12 gal/min (phyllite-gabbro), greater than 12 to 40 gal/min (gneiss-schist), and greater than 40 gal/min (shale-sandstone). An analysis of variance performed at a probability (alpha level) of 0.05 indicated that the median yield for any one hydrogeologic terrane differs significantly from the median yield of every other terrane within the same physiographic province. The hydrogeologic terranes may be concluded to be significantly different in their water-yielding properties as indicated by the yield of wells.

Although the median yields of the hydrogeologic terranes are significantly different, the data sets for the terranes overlap to such a degree (fig. 4) that the variation in yield within a terrane may be more important than the median or central tendency. One measure of the variation is the interquartile range, or middle 50 percent range (25th to 75th percentile). In the Blue Ridge Physiographic Province, the interquartile range of the schist-sandstone hydrogeologic terrane overlaps the interquartile range of the gneiss-granite hydrogeologic terrane by as much as 80 percent (fig. 4), making questionable the value of seeking a water supply from one hydrogeologic terrane versus another when only a few wells are to be used. The overlap of the interquartile ranges of adjacent classes in the Piedmont Physiographic Province is more of the order of 25 to 50 percent. The gneiss-schist hydrogeologic terrane could be divided into three hydrogeologic terranes with significantly different median yields to nondomestic wells; however, the overlap in interquartile ranges among adjacent classes would be of the order of 60 to 85 percent.

Perhaps a more realistic estimate of well yields than the median value and an indication of their variation within hydrogeologic terranes is the interquartile range. The interquartile ranges in yields to nondomestic wells in the two hydrogeologic terranes in the Blue Ridge are 8 to 32 gal/min, gneiss-granite, and 10 to 61 gal/min, schist-sandstone. The interquartile ranges in the three hydrogeologic terranes of the Piedmont Physiographic Province are 5 to 20 gal/min, phyllite-gabbro; 10 to 60 gal/min, gneiss-schist; and 35 to 220 gal/min, shale-sandstone.

Statistical characteristics of the yield values of nondomestic wells in selected rock types in each of the hydrogeologic terranes are given in table 1. In the Blue Ridge Physiographic Province, limestone in the schist-sandstone hydrogeologic terrane has nondomestic wells with the largest median (50th percentile) yield of any rock type in that province. In the Piedmont Physiographic Province, marble and shale in the shale-sandstone hydrogeologic terrane have nondomestic wells with the next to the largest median yields of any two rock types in that province. In the same hydrogeologic terrane, siltstone has nondomestic wells with the largest median yield of any rock type in the study area. Essentially all wells in siltstone are in the siliciclastic rocks in the Mesozoic basins in New Jersey.

If the quantity of data were adequate for analysis, specific capacity, in addition to well yield, could be used to classify and map hydrogeologic terranes. Unfortunately, the distribution of specific-capacity measurements among rock types and the small number of measurements for wells in the Blue Ridge Physiographic Province prevented a complete analysis by rock type of these data in this province. Specific-capacity data were sufficient, however, to at least evaluate the classification of hydrogeologic terranes based on well yield. To perform this evaluation, the authors assigned specific-capacity values grouped by rock types to the same rock types and hydrogeologic terranes as used in the analysis of well yields (fig. 5). The ranking of median values of specific capacity is the same as for well yield. Generally, the grouping of rock types into terranes using median values of specific capacity would be similar to groupings using values of well yield. An analysis of variance performed at a probability (alpha level) of 0.05 indicated that the median specific-capacity value for any one hydrogeologic terrane differs significantly from the median specific capacity for every other terrane within the same physiographic province. The hydrogeologic terranes may be concluded to be significantly different in their water-yielding properties as indicated by the specific capacity of wells.

Statistical characteristics of the specific-capacity values of nondomestic wells in selected rock types in each of the hydrogeologic terranes of the Piedmont Physiographic Province are given in table 2. A comparison of the value of the median specific capacity for a selected rock type with the median values for other rock types in the same hydrogeologic terrane reveals how well the selected rock type (assigned to the hydrogeologic terranes by yield) fits into its hydrogeologic terrane. In regard to the median (50th percentile) specific capacity, the following rock types would appear to be poor fits within their respective hydrogeologic terranes: tuff and granite in the gneiss-schist hydrogeologic terrane have median values that would fit more appropriately in the phyllite-gabbro terrane; limestone and conglomerate in the gneiss-schist hydrogeologic terrane have median values that would fit more appropriately in the shale-sandstone hydrogeologic terrane. Tuff can be dismissed because of the small sample size. The remaining misfits suggest the possibility of a different classification based on specific capacity alone. However, the classification of hydrogeologic terranes based on well yield has significant differences among terranes and is a useful hydrologic subdivision of the Blue Ridge and Piedmont Physiographic Provinces.

HYDROGEOLOGIC TERRANE MAP

Hydrogeologic terranes were mapped by assigning rock types in the coverage of rock types to the appropriate hydrogeologic terrane that was based on well yield. This hydrogeologic terrane coverage was then combined with a base map having the same coordinate system to produce the hydrogeologic terrane map (fig. 6). The hydrogeologic terranes coincide with the outcrop areas of the geologic units with the corresponding rock types. The map unit "hydrogeologic terrane not defined" contains two general categories of rocks. The more abundantly populated category contains rock types for which there were fewer than 10 measurements of well yield, and the rock type could not be assigned to a hydrogeologic terrane. The less abundantly populated category contains rock types for which no single rock-type term could be applied because of the varied lithologic composition of the original geologic unit.

The schist-sandstone hydrogeologic terrane in the Blue Ridge Physiographic Province has the largest median well yields in that province and is predominantly schist, sandstone, and quartzite at the southwestern end and along the northwestern edge of the province. The shale-sandstone hydrogeologic terrane in the Piedmont Physiographic Province has the largest median well yields and is predominantly shale, sandstone, and siltstone in the three northeasternmost Mesozoic basins in the study area in Maryland, New Jersey, Pennsylvania, and Virginia.

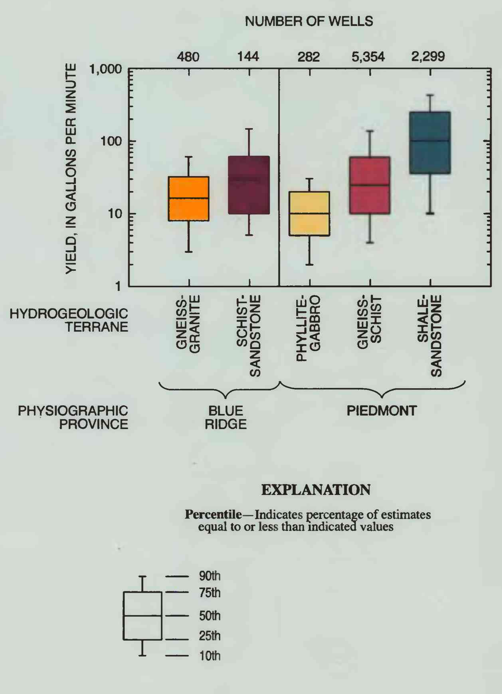


Figure 4. Variation of yield values for nondomestic wells grouped by five hydrogeologic terranes and two physiographic provinces.

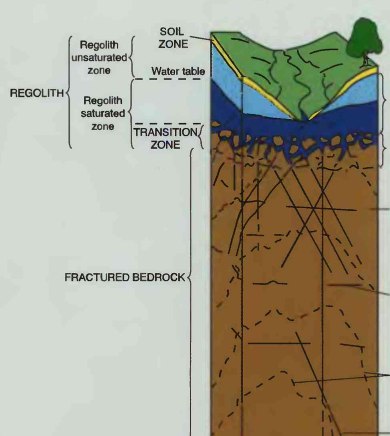


Figure 2. Generalized block diagram of the principal hydrogeologic components of metamorphic and igneous rocks in the Blue Ridge and Piedmont Physiographic Provinces (From Daniel and others, 1997, fig. 4).

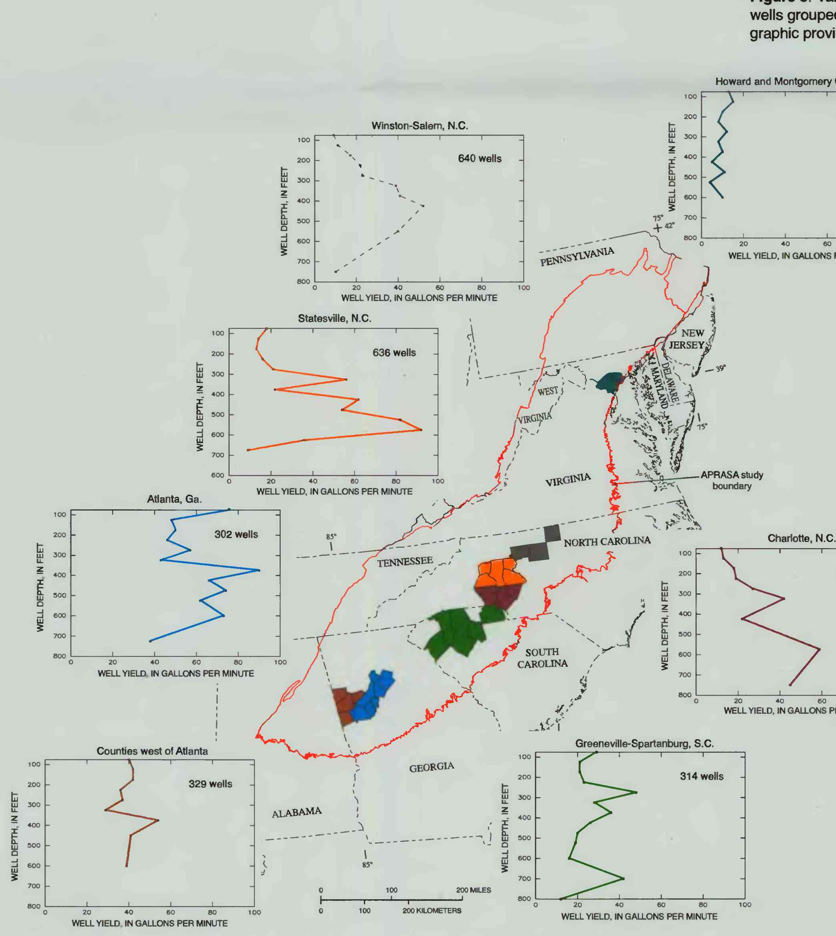


Figure 3. Relation between average well yield and average total depth of well for 50-foot depth intervals in seven areas of the Piedmont Physiographic Province.

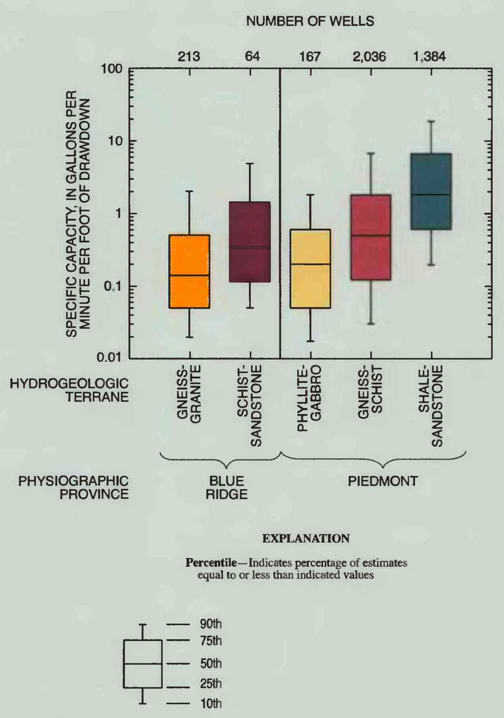
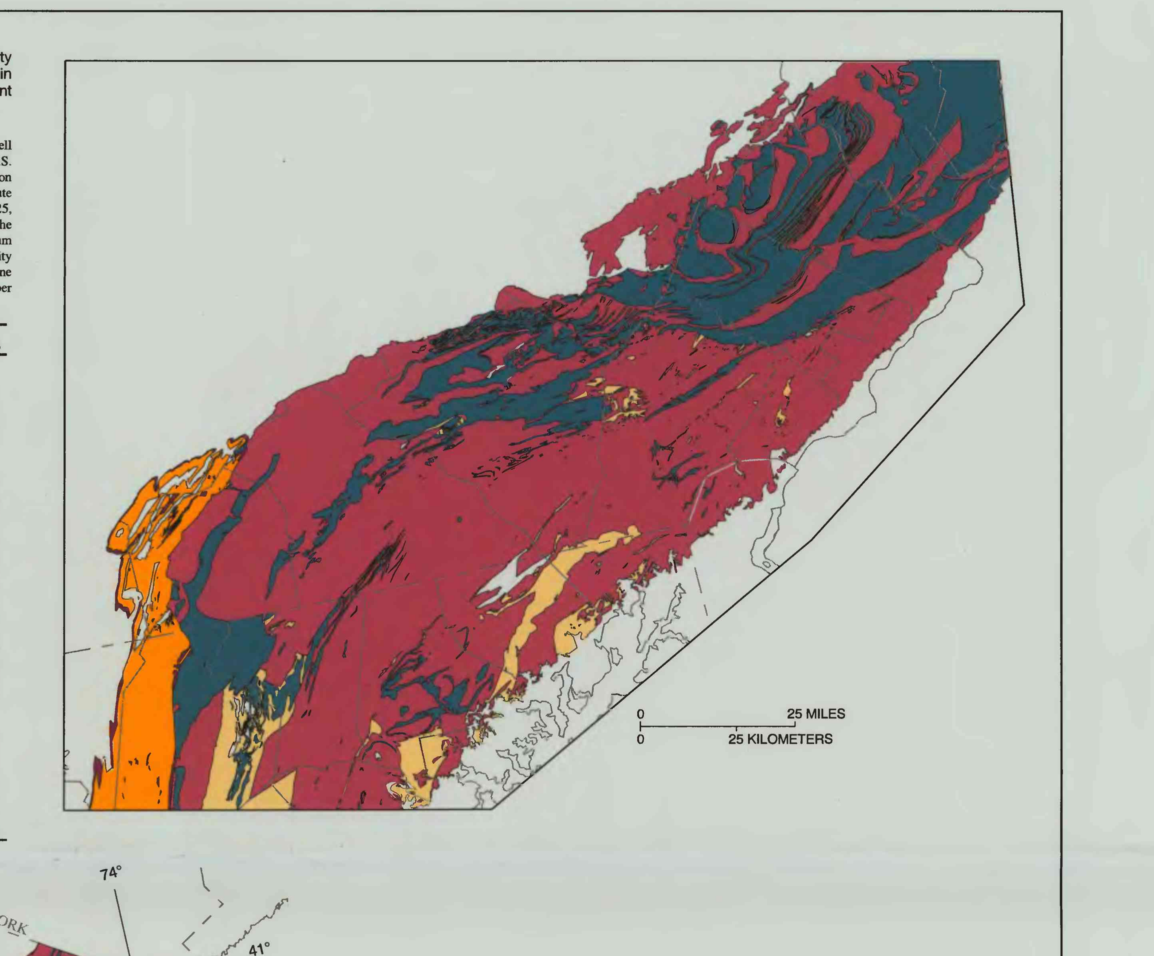
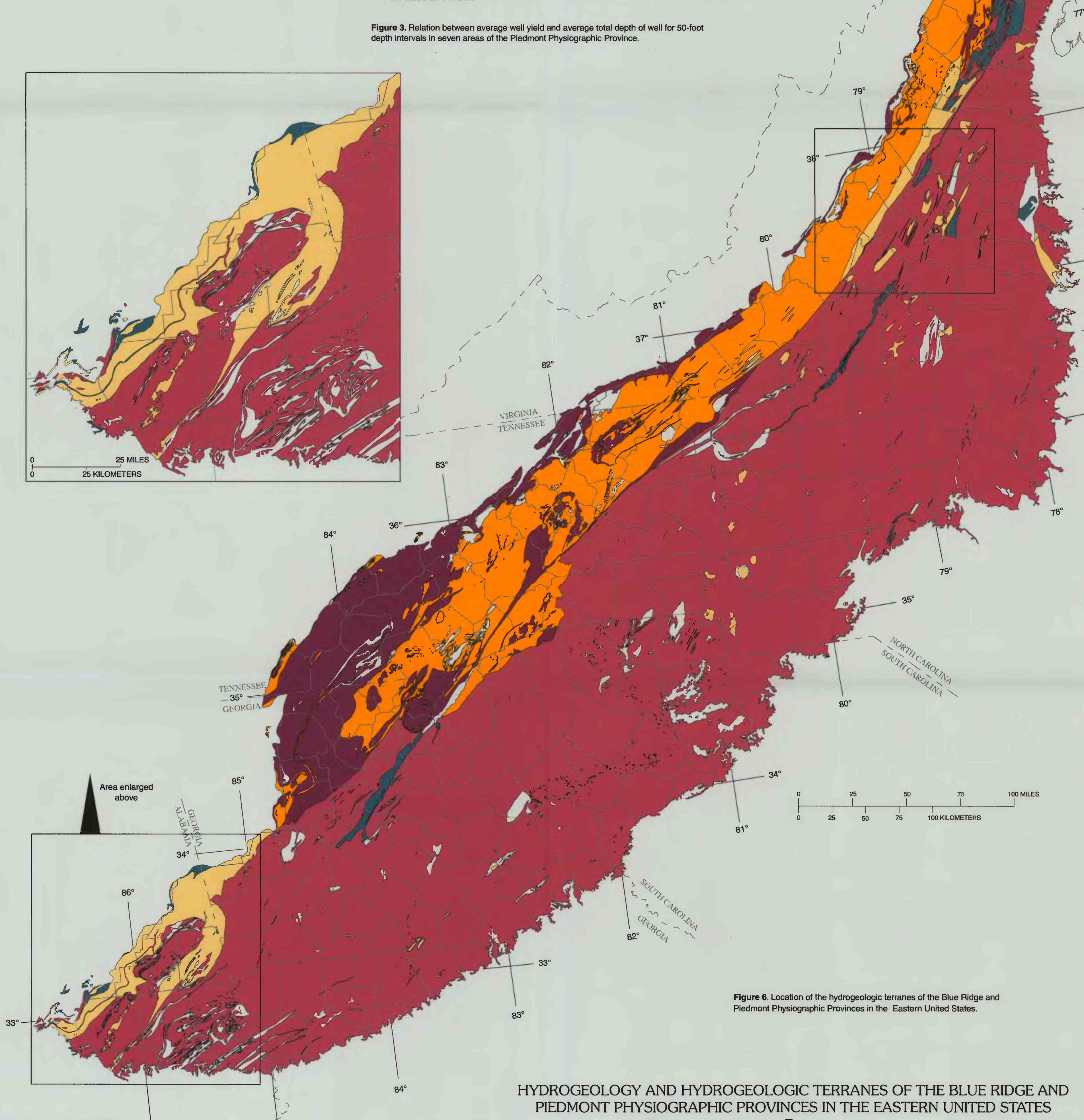


Figure 5. Variation of specific-capacity values for nondomestic wells grouped by five hydrogeologic terranes and two physiographic provinces.





Base from U.S. Geological Survey DLG data, 1:100,000

Figure 6. Location of the hydrogeologic terranes of the Blue Ridge and Piedmont Physiographic Provinces in the Eastern United States.

HYDROGEOLOGY AND HYDROGEOLOGIC TERRANES OF THE BLUE RIDGE AND PIEDMONT PHYSIOGRAPHIC PROVINCES IN THE EASTERN UNITED STATES

By
T.O. Mesko, L.A. Swain, and E.F. Hollyday

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