U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

GEOLOGIC RADON POTENTIAL OF EPA REGION 3

Delaware Maryland Pennsylvania Virginia West Virginia

OPEN-FILE REPORT 93-292-C

Prepared in Cooperation with the
U.S. Environmental Protection Agency

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R. Randall Schumann

EDITOR

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This report is preliminary and has not been reviewed for conformity with U.S. Geological Survey editorial standards or with the North American Stratigraphic Code.

CONTENTS

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THE USGS/EPA RADON POTENTIAL ASSESSMENTS: AN INTRODUCTION

by
Linda C.S. Gundersen and R. Randall Schumann
U.S. Geological Survey
and
Sharon W. White
U.S. Environmental Protection Agency

BACKGROUND

The Indoor Radon Abatement Act of 1988 (Public Law 100-551) directed the U.S. Environmental Protection Agency (EPA) to identify areas of the United States that have the potential to produce harmful levels of indoor radon. These characterizations were to be based on both geological data and on indoor radon levels in homes and other structures. The EPA also was directed to develop model standards and techniques for new building construction that would provide adequate prevention or mitigation of radon entry. As part of an Interagency Agreement between the EPA and the U.S. Geological Survey (USGS), the USGS has prepared radon potential estimates for the United States. This report is one of ten booklets that document this effort. The purpose and intended use of these reports is to help identify areas where states can target their radon program resources, to provide guidance in selecting the most appropriate building code options for areas, and to provide general information on radon and geology for each state for federal, state, and municipal officials dealing with radon issues. *These reports are not intended to be used as a substitute for indoor radon testing, and they cannot and should not be used to estimate or predict the indoor radon concentrations of individual homes, building sites, or housing tracts. Elevated levels of indoor radon have been found in every State, and EPA recommends that all homes be tested for indoor radon.*

USGS geologists are the authors of the booklets. The booklets are organized by EPA Federal boundaries (Regions). Each Regional booklet consists of several components, the first being this introduction to the project, including a general discussion of radon (occurrence, transport, etc.), and details concerning the types of data used. The second component is a summary chapter outlining the general geology and geologic radon potential of the EPA Region. The third component is an individual chapter for each state in the Region. Each state chapter discusses the state's specific geographic setting, soils, geologic setting, geologic radon potential, indoor radon data, and a summary outlining the radon potential rankings of geologic areas in the state. A variety of maps are presented in each chapter—geologic, geographic, population, soils, aerial radioactivity, and indoor radon data by county.

Because of constraints on the scales of maps presented in these reports and because the smallest units used to present the indoor radon data are counties, some generalizations have been made in order to estimate the radon potential of each area. Variations in geology, soil characteristics, climatic factors, homeowner lifestyles, and other factors that influence radon concentrations can be quite large within any particular geologic area, so these reports cannot be used to estimate or predict the indoor radon concentrations of individual homes or housing tracts. Within any area of a given geologic radon potential ranking, there are likely to be areas where the radon potential is lower or higher than that assigned to the area as a whole, especially in larger areas such as the large counties in some western states.

In each state chapter, references to additional reports related to radon are listed for the state, and the reader is urged to consult these reports for more detailed information. In most cases the best sources of information on radon for specific areas are state and local departments of health, state departments responsible for nuclear safety or environmental protection, and U.S. EPA regional offices. More detailed information on state or local geology may be obtained from the state geological surveys. Addresses and telephone numbers of state radon contacts, geological surveys, and EPA regional offices are listed in Appendix C at the end of this chapter.

RADON GENERATION AND TRANSPORT IN SOILS

Radon (^{222}Rn) is produced from the radioactive decay of radium (^{226}Ra), which is, in turn, a product of the decay of uranium (^{238}U) (fig. 1). The half-life of ^{222}Rn is 3.825 days. Other isotopes of radon occur naturally, but, with the exception of thoron (^{220}Rn), which occurs in concentrations high enough to be of concern in a few localized areas, they are less important in terms of indoor radon risk because of their extremely short half-lives and less common occurrence. In general, the concentration and mobility of radon in soil are dependent on several factors, the most important of which are the soil's radium content and distribution, porosity, permeability to gas movement, and moisture content. These characteristics are, in turn, determined by the soil's parent-material composition, climate, and the soil's age or maturity. If parent-material composition, climate, vegetation, age of the soil, and topography are known, the physical and chemical properties of a soil in a given area can be predicted.

As soils form, they develop distinct layers, or horizons, that are cumulatively called the soil profile. The A horizon is a surface or near-surface horizon containing a relative abundance of organic matter but dominated by mineral matter. Some soils contain an E horizon, directly below the A horizon, that is generally characterized by loss of clays, iron, or aluminum, and has a characteristically lighter color than the A horizon. The B horizon underlies the A or E horizon. Important characteristics of B horizons include accumulation of clays, iron oxides, calcium carbonate or other soluble salts, and organic matter complexes. In drier environments, a horizon may exist within or below the B horizon that is dominated by calcium carbonate, often called caliche or calcrete. This carbonate-cemented horizon is designated the K horizon in modern soil classification schemes. The C horizon underlies the B (or K) and is a zone of weathered parent material that does not exhibit characteristics of A or B horizons; that is, it is generally not a zone of leaching or accumulation. In soils formed in place from the underlying bedrock, the C horizon is a zone of unconsolidated, weathered bedrock overlying the unweathered bedrock.

The shape and orientation of soil particles (soil structure) control permeability and affect water movement in the soil. Soils with blocky or granular structure have roughly equivalent permeabilities in the horizontal and vertical directions, and air and water can infiltrate the soil relatively easily. However, in soils with platy structure, horizontal permeability is much greater than vertical permeability, and air and moisture infiltration is generally slow. Soils with prismatic or columnar structure have dominantly vertical permeability. Platy and prismatic structures form in soils with high clay contents. In soils with shrink-swell clays, air and moisture infiltration rates and depth of wetting may be limited when the cracks in the surface soil layers swell shut. Clay-rich B horizons, particularly those with massive or platy structure, can form a capping layer that impedes the escape of soil gas to the surface (Schumann and others, 1992). However, the shrinkage of clays can act to open or widen cracks upon drying, thus increasing the soil's permeability to gas flow during drier periods.

Radon transport in soils occurs by two processes: (1) diffusion and (2) flow (Tanner, 1964). Diffusion is the process whereby radon atoms move from areas of higher concentration to

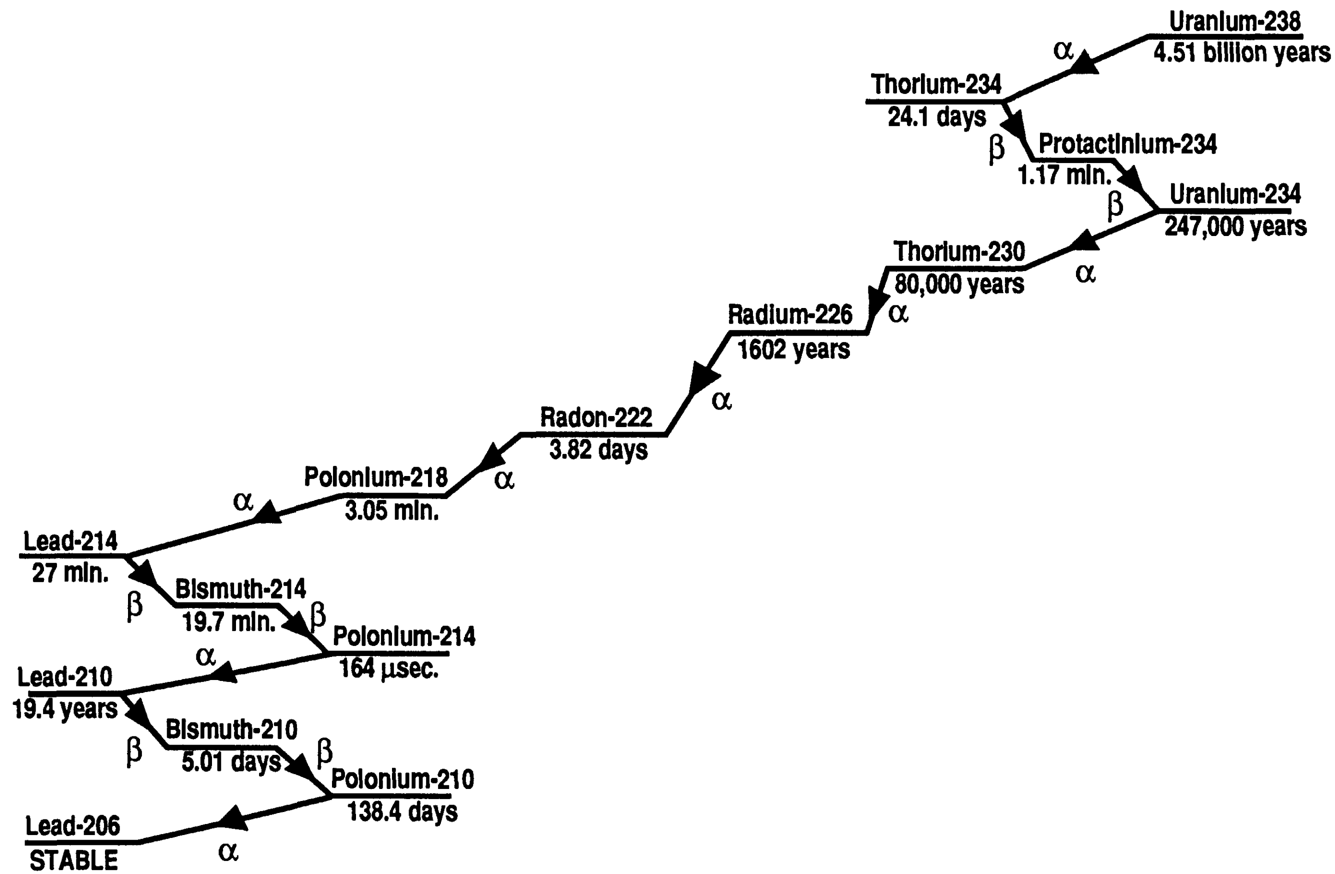

Figure 1. The uranium-238 decay series, showing the half-lives of elements and their modes of decay (after Wanty and Schoen, 1991). α denotes alpha decay, β denotes beta decay.

areas of lower concentration in response to a concentration gradient. Flow is the process by which soil air moves through soil pores in response to differences in pressure within the soil or between the soil and the atmosphere, carrying the radon atoms along with it. Diffusion is the dominant radon transport process in soils of low permeability, whereas flow tends to dominate in highly permeable soils (Sextro and others, 1987). In low-permeability soils, much of the radon may decay before it is able to enter a building because its transport rate is reduced. Conversely, highly permeable soils, even those that are relatively low in radium, such as those derived from some types of glacial deposits, have been associated with high indoor radon levels in Europe and in the northern United States (Akerblom and others, 1984; Kunz and others, 1989; Sextro and others, 1987). In areas of karst topography formed in carbonate rock (limestone or dolomite) environments, solution cavities and fissures can increase soil permeability at depth by providing additional pathways for gas flow.

Not all radium contained in soil grains and grain coatings will result in mobile radon when the radium decays. Depending on where the radium is distributed in the soil, many of the radon atoms may remain imbedded in the soil grain containing the parent radium atom, or become imbedded in adjacent soil grains. The portion of radium that releases radon into the pores and fractures of rocks and soils is called the emanating fraction. When a radium atom decays to radon, the energy generated is strong enough to send the radon atom a distance of about 40 nanometers (1 nm = 10^{-9} meters), or about 2×10^{-6} inches—this is known as alpha recoil (Tanner, 1980). Moisture in the soil lessens the chance of a recoiling radon atom becoming imbedded in an adjacent grain. Because water is more dense than air, a radon atom will travel a shorter distance in a water-filled pore than in an air-filled pore, thus increasing the likelihood that the radon atom will remain in the pore space. Intermediate moisture levels enhance radon emanation but do not significantly affect permeability. However, high moisture levels can significantly decrease the gas permeability of the soil and impede radon movement through the soil.

Concentrations of radon in soils are generally many times higher than those inside of buildings, ranging from tens of pCi/L to more than 100,000 pCi/L, but typically in the range of hundreds to low thousands of pCi/L. Soil-gas radon concentrations can vary in response to variations in climate and weather on hourly, daily, or seasonal time scales. Schumann and others (1992) and Rose and others (1988) recorded order-of-magnitude variations in soil-gas radon concentrations between seasons in Colorado and Pennsylvania. The most important factors appear to be (1) soil moisture conditions, which are controlled in large part by precipitation; (2) barometric pressure; and (3) temperature. Washington and Rose (1990) suggest that temperature-controlled partitioning of radon between water and gas in soil pores also has a significant influence on the amount of mobile radon in soil gas.

Homes in hilly limestone regions of the southern Appalachians were found to have higher indoor radon concentrations during the summer than in the winter. A suggested cause for this phenomenon involves temperature/pressure-driven flow of radon-laden air from subsurface solution cavities in the carbonate rock into houses. As warm air enters solution cavities that are higher on the hillslope than the homes, it cools and settles, pushing radon-laden air from lower in the cave or cavity system into structures on the hillslope (Gammage and others, 1993). In contrast, homes built over caves having openings situated below the level of the home had higher indoor radon levels in the winter, caused by cooler outside air entering the cave, driving radon-laden air into cracks and solution cavities in the rock and soil, and ultimately, into homes (Gammage and others, 1993).

RADON ENTRY INTO BUILDINGS

A driving force (reduced atmospheric pressure in the house relative to the soil, producing a pressure gradient) and entry points must exist for radon to enter a building from the soil. The negative pressure caused by furnace combustion, ventilation devices, and the stack effect (the rising and escape of warm air from the upper floors of the building, causing a temperature and pressure gradient within the structure) during cold winter months are common driving forces. Cracks and other penetrations through building foundations, sump holes, and slab-to-foundation wall joints are common entry points.

Radon levels in the basement are generally higher than those on the main floor or upper floors of most structures. Homes with basements generally provide more entry points for radon, commonly have a more pronounced stack effect, and typically have lower air pressure relative to the surrounding soil than nonbasement homes. The term "nonbasement" applies to slab-on-grade or crawl space construction.

METHODS AND SOURCES OF DATA

The assessments of radon potential in the booklets that follow this introduction were made using five main types of data: (1) geologic (lithologic); (2) aerial radiometric; (3) soil characteristics, including soil moisture, permeability, and drainage characteristics; (4) indoor radon data; and (5) building architecture (specifically, whether homes in each area are built slab-on-grade or have a basement or crawl space). These five factors were evaluated and integrated to produce estimates of radon potential. Field measurements of soil-gas radon or soil radioactivity were not used except where such data were available in existing, published reports of local field studies. Where applicable, such field studies are described in the individual state chapters.

GEOLOGIC DATA

The types and distribution of lithologic units and other geologic features in an assessment area are of primary importance in determining radon potential. Rock types that are most likely to cause indoor radon problems include carbonaceous black shales, glauconite-bearing sandstones, certain kinds of fluvial sandstones and fluvial sediments, phosphorites, chalk, karst-producing carbonate rocks, certain kinds of glacial deposits, bauxite, uranium-rich granitic rocks, metamorphic rocks of granitic composition, silica-rich volcanic rocks, many sheared or faulted rocks, some coals, and certain kinds of contact metamorphosed rocks. Rock types least likely to cause radon problems include marine quartz sands, non-carbonaceous shales and siltstones, certain kinds of clays, silica-poor metamorphic and igneous rocks, and basalts. Exceptions exist within these general lithologic groups because of the occurrence of localized uranium deposits, commonly of the hydrothermal type in crystalline rocks or the "roll-front" type in sedimentary rocks. Uranium and radium are commonly sited in heavy minerals, iron-oxide coatings on rock and soil grains, and organic materials in soils and sediments. Less common are uranium associated with phosphate and carbonate complexes in rocks and soils, and uranium minerals.

Although many cases of elevated indoor radon levels can be traced to high radium and (or) uranium concentrations in parent rocks, some structural features, most notably faults and shear zones, have been identified as sites of localized uranium concentrations (Deffeyes and MacGregor, 1980) and have been associated with some of the highest reported indoor radon levels (Gundersen, 1991). The two highest known indoor radon occurrences are associated with sheared fault zones in Boyertown, Pennsylvania (Gundersen and others, 1988a; Smith and others, 1987), and in Clinton, New Jersey (Henry and others, 1991; Muessig and Bell, 1988).

NURE AERIAL RADIOMETRIC DATA

Aerial radiometric data are used to quantify the radioactivity of rocks and soils. Equivalent uranium (eU) data provide an estimate of the surficial concentrations of radon parent materials (uranium, radium) in rocks and soils. Equivalent uranium is calculated from the counts received by a gamma-ray detector from the 1.76 MeV (mega-electron volts) emission energy corresponding to bismuth-214 (^{214}Bi), with the assumption that uranium and its decay products are in secular equilibrium. Equivalent uranium is expressed in units of parts per million (ppm). Gamma radioactivity also may be expressed in terms of a radium activity; 3 ppm eU corresponds to approximately 1 picocurie per gram (pCi/g) of radium-226. Although radon is highly mobile in soil and its concentration is affected by meteorological conditions (Kovach, 1945; Klusman and Jaacks, 1987; Schery and others, 1984; Schumann and others, 1992), statistical correlations between average soil-gas radon concentrations and average eU values for a wide variety of soils have been documented (Gundersen and others, 1988a, 1988b; Schumann and Owen, 1988). Aerial radiometric data can provide an estimate of radon source strength over a region, but the amount of radon that is able to enter a home from the soil is dependent on several local factors, including soil structure, grain size distribution, moisture content, and permeability, as well as type of house construction and its structural condition.

The aerial radiometric data used for these characterizations were collected as part of the Department of Energy National Uranium Resource Evaluation (NURE) program of the 1970s and early 1980s. The purpose of the NURE program was to identify and describe areas in the United States having potential uranium resources (U.S. Department of Energy, 1976). The NURE aerial radiometric data were collected by aircraft in which a gamma-ray spectrometer was mounted, flying approximately 122 m (400 ft) above the ground surface. The equivalent uranium maps presented in the state chapters were generated from reprocessed NURE data in which smoothing, filtering, recalibrating, and matching of adjacent quadrangle data sets were performed to compensate for background, altitude, calibration, and other types of errors and inconsistencies in the original data set (Duval and others, 1989). The data were then gridded and contoured to produce maps of eU with a pixel size corresponding to approximately 2.5 x 2.5 km (1.6 x 1.6 mi).

Figure 2 is an index map of NURE 1° x 2° quadrangles showing the flight-line spacing for each quadrangle. In general, the more closely spaced the flightlines are, the more area was covered by the aerial gamma survey, and thus, more detail is available in the data set. For an altitude of 400 ft above the ground surface and with primary flightline spacing typically between 3 and 6 miles, less than 10 percent of the ground surface of the United States was actually measured by the airborne gamma-ray detectors (Duval and others, 1989), although some areas had better coverage than others due to the differences in flight-line spacing between areas (fig. 2). This suggests that some localized uranium anomalies may not have been detected by the aerial surveys, but the good correlations of eU patterns with geologic outcrop patterns indicate that, at relatively small scales (approximately 1:1,000,000 or smaller) the National eU map (Duval and others, 1989) gives reasonably good estimates of average surface uranium concentrations and thus can assist in the prediction of radon potential of rocks and soils, especially when augmented with additional geologic and soil data.

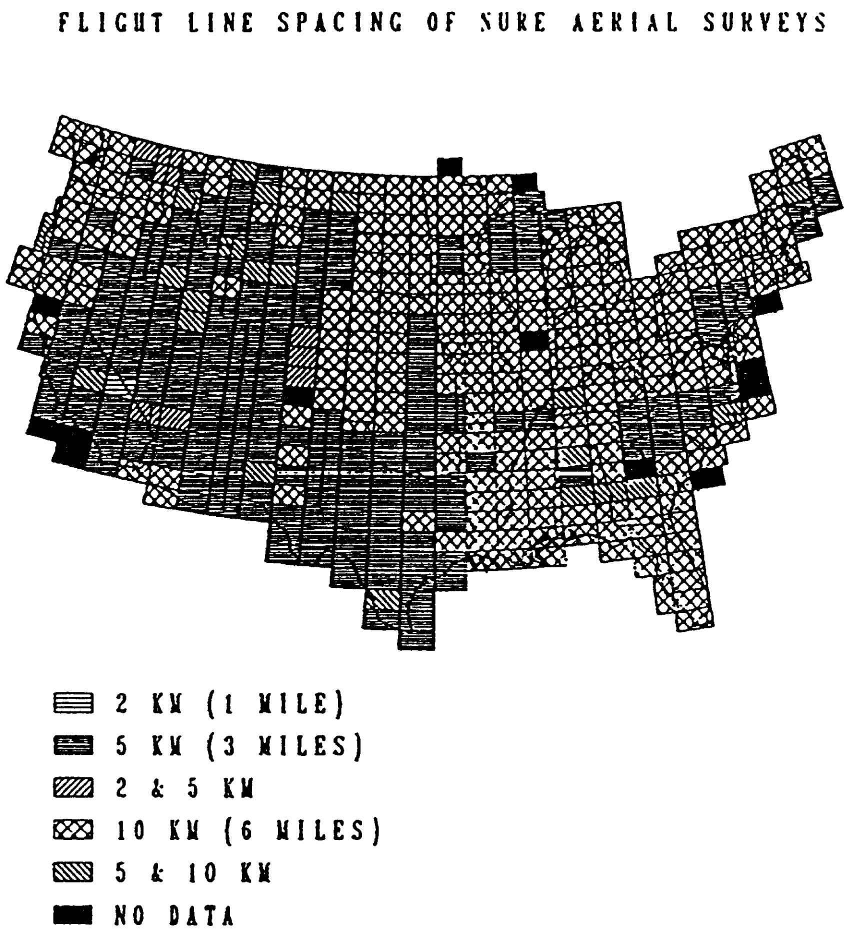

Figure 2. Nominal flightline spacings for NURE aerial gamma-ray surveys covering the contiguous United States (from Duval and others, 1990). Rectangles represent 1°x2° quadrangles.

The shallow (20-30 cm) depth of investigation of gamma-ray spectrometers, either ground-based or airborne (Duval and others, 1971; Durrance, 1986), suggests that gamma-ray data may sometimes underestimate the radon-source strength in soils in which some of the radionuclides in the near-surface soil layers have been transported downward through the soil profile. In such cases the concentration of radioactive minerals in the A horizon would be lower than in the B horizon, where such minerals are typically concentrated. The concentration of radionuclides in the C horizon and below may be relatively unaffected by surface solution processes. Under these conditions the surface gamma-ray signal may indicate a lower radon source concentration than actually exists in the deeper soil layers, which are most likely to affect radon levels in structures with basements. The redistribution of radionuclides in soil profiles is dependent on a combination of climatic, geologic, and geochemical factors. There is reason to believe that correlations of eU with actual soil radium and uranium concentrations at a depth relevant to radon entry into structures may be regionally variable (Duval, 1989; Schumann and Gundersen, 1991). Given sufficient understanding of the factors cited above, these regional differences may be predictable.

SOIL SURVEY DATA

Soil surveys prepared by the U.S. Soil Conservation Service (SCS) provide data on soil characteristics, including soil-cover thickness, grain-size distribution, permeability, shrink-swell potential, vegetative cover, generalized groundwater characteristics, and land use. The reports are available in county formats and State summaries. The county reports typically contain both generalized and detailed maps of soils in the area.

Because of time and map-scale constraints, it was impractical to examine county soil reports for each county in the United States, so more generalized summaries at appropriate scales were used where available. For State or regional-scale radon characterizations, soil maps were compared to geologic maps of the area, and the soil descriptions, shrink-swell potential, drainage characteristics, depth to seasonal high water table, permeability, and other relevant characteristics of each soil group noted. Technical soil terms used in soil surveys are generally complex; however, a good summary of soil engineering terms and the national distribution of technical soil types is the "Soils" sheet of the National Atlas (U.S. Department of Agriculture, 1987).

Soil permeability is commonly expressed in SCS soil surveys in terms of the speed, in inches per hour (in/hr), at which water soaks into the soil, as measured in a soil percolation test. Although in/hr are not truly units of permeability, these units are in widespread use and are referred to as "permeability" in SCS soil surveys. The permeabilities listed in the SCS surveys are for water, but they generally correlate well with gas permeability. Because data on gas permeability of soils is extremely limited, data on permeability to water is used as a substitute except in cases in which excessive soil moisture is known to exist. Water in soil pores inhibits gas transport, so the amount of radon available to a home is effectively reduced by a high water table. Areas likely to have high water tables include river valleys, coastal areas, and some areas overlain by deposits of glacial origin (for example, loess).

Soil permeabilities greater than 6.0 in/hr may be considered high, and permeabilities less than 0.6 in/hr may be considered low in terms of soil-gas transport. Soils with low permeability may generally be considered to have a lower radon potential than more permeable soils with similar radium concentrations. Many well-developed soils contain a clay-rich B horizon that may impede vertical soil gas transport. Radon generated below this horizon cannot readily escape to the surface, so it would instead tend to move laterally, especially under the influence of a negative pressure exerted by a building.

Shrink-swell potential is an indicator of the abundance of smectitic (swelling) clays in a soil. Soils with a high shrink-swell potential may cause building foundations to crack, creating pathways for radon entry into the structure. During dry periods, desiccation cracks in shrink-swell soils provide additional pathways for soil-gas transport and effectively increase the gas permeability of the soil. Soil permeability data and soil profile data thus provide important information for regional radon assessments.

INDOOR RADON DATA

Two major sources of indoor radon data were used. The first and largest source of data is from the State/EPA Residential Radon Survey (Ronca-Battista and others, 1988; Dziuban and others, 1990). Forty-two states completed EPA-sponsored indoor radon surveys between 1986 and 1992 (fig. 3). The State/EPA Residential Radon Surveys were designed to be comprehensive and statistically significant at the state level, and were subjected to high levels of quality assurance and control. The surveys collected screening indoor radon measurements, defined as 2-7 day measurements using charcoal canister radon detectors placed in the lowest livable area of the home. The target population for the surveys included owner-occupied single family, detached housing units (White and others, 1989), although attached structures such as duplexes, townhouses, or condominiums were included in some of the surveys if they met the other criteria and had contact with the ground surface. Participants were selected randomly from telephone-directory listings. In total, approximately 60,000 homes were tested in the State/EPA surveys.

The second source of indoor radon data comes from residential surveys that have been conducted in a specific state or region of the country (e.g. independent state surveys or utility company surveys). Several states, including Delaware, Florida, Illinois, New Hampshire, New Jersey, New York, Oregon, and Utah, have conducted their own surveys of indoor radon. The quality and design of a state or other independent survey are discussed and referenced where the data are used.

Data for only those counties with five or more measurements are shown in the indoor radon maps in the state chapters, although data for all counties with a nonzero number of measurements are listed in the indoor radon data tables in each state chapter. In total, indoor radon data from more than 100,000 homes nationwide were used in the compilation of these assessments. Radon data from State or regional indoor radon surveys, public health organizations, or other sources are discussed in addition to the primary data sources where they are available. Nearly all of the data used in these evaluations represent short-term (2-7 day) screening measurements from the lowest livable space of the homes. Specific details concerning the nature and use of indoor radon data sets other than the State/EPA Residential Radon Survey are discussed in the individual State chapters.

RADON INDEX AND CONFIDENCE INDEX

Many of the geologic methods used to evaluate an area for radon potential require subjective opinions based on the professional judgment and experience of the individual geologist. The evaluations are nevertheless based on established scientific principles that are universally applicable to any geographic area or geologic setting. This section describes the methods and conceptual framework used by the U.S. Geological Survey to evaluate areas for radon potential

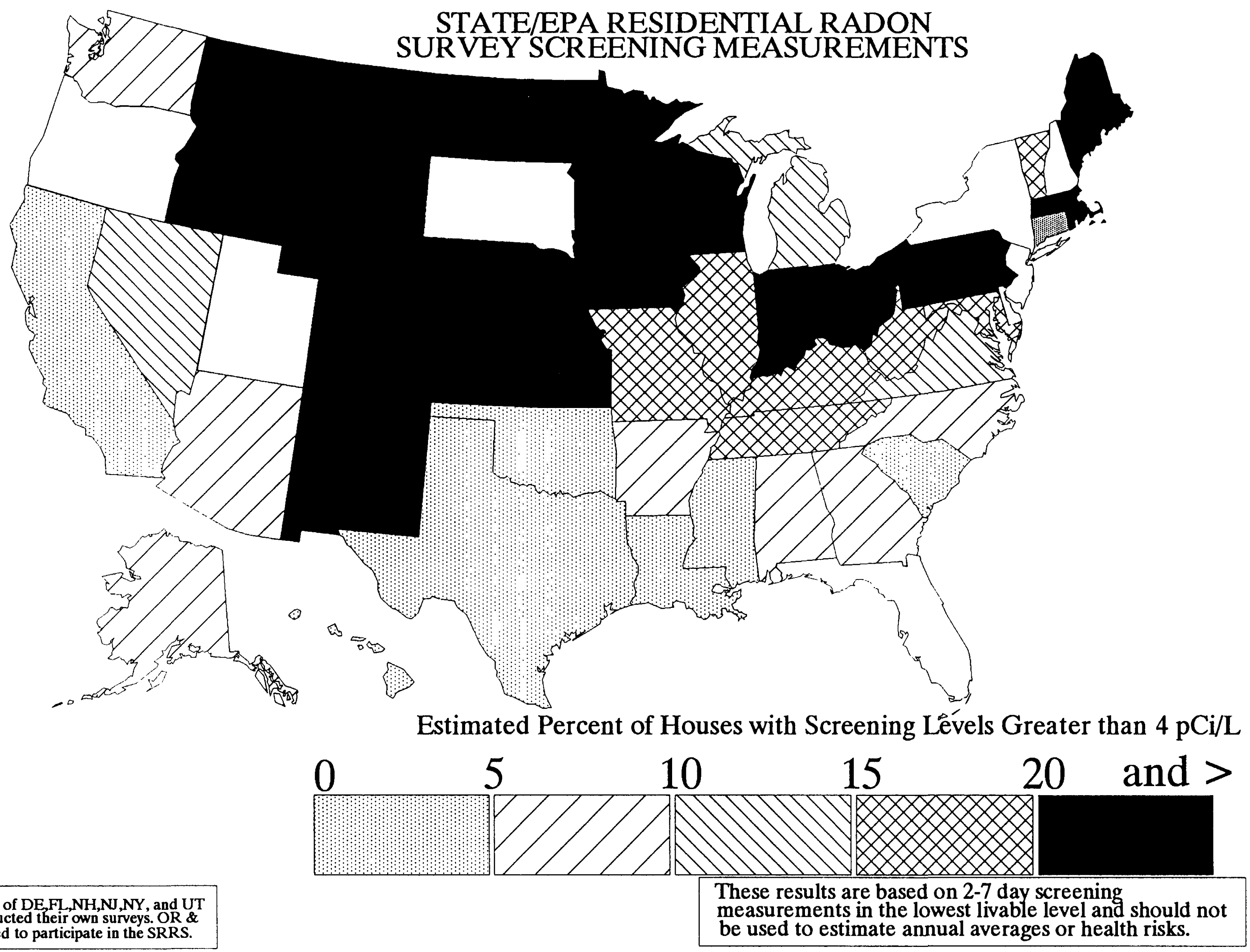

Figure 3. Percent of homes tested in the State/EPA Residential Radon Survey with screening indoor radon levels exceeding 4 pCi/L.

based on the five factors discussed in the previous sections. The scheme is divided into two basic parts, a Radon Index (RI), used to rank the general radon potential of the area, and the Confidence Index (CI), used to express the level of confidence in the prediction based on the quantity and quality of the data used to make the determination. This scheme works best if the areas to be evaluated are delineated by geologically-based boundaries (geologic provinces) rather than political ones (state/county boundaries) in which the geology may vary across the area.

Radon Index. Table 1 presents the Radon Index (RI) matrix. The five factors—indoor radon data, geology, aerial radioactivity, soil parameters, and house foundation type—were quantitatively ranked (using a point value of 1, 2, or 3) for their respective contribution to radon potential in a given area. At least some data for the 5 factors are consistently available for every geologic province. Because each of these main factors encompass a wide variety of complex and variable components, the geologists performing the evaluation relied heavily on their professional judgment and experience in assigning point values to each category and in determining the overall radon potential ranking. Background information on these factors is discussed in more detail in the preceding sections of this introduction.

Indoor radon was evaluated using unweighted arithmetic means of the indoor radon data for each geologic area to be assessed. Other expressions of indoor radon levels in an area also could have been used, such as weighted averages or annual averages, but these types of data were not consistently available for the entire United States at the time of this writing, or the schemes were not considered sufficient to provide a means of consistent comparison across all areas. For this report, charcoal-canister screening measurement data from the State/EPA Residential Radon Surveys and other carefully selected sources were used, as described in the preceding section. To maintain consistency, other indoor radon data sets (vendor, state, or other data) were not considered in scoring the indoor radon factor of the Radon Index if they were not randomly sampled or could not be statistically combined with the primary indoor radon data sets. However, these additional radon data sets can provide a means to further refine correlations between geologic factors and radon potential, so they are included as supplementary information and are discussed in the individual State chapters. If the average screening indoor radon level for an area was less than 2 pCi/L, the indoor radon factor was assigned 1 point, if it was between 2 and 4 pCi/L, it was scored 2 points, and if the average screening indoor radon level for an area was greater than 4 pCi/L, the indoor radon factor was assigned 3 RI points.

Aerial radioactivity data used in this report are from the equivalent uranium map of the conterminous United States compiled from NURE aerial gamma-ray surveys (Duval and others, 1989). These data indicate the gamma radioactivity from approximately the upper 30 cm of rock and soil, expressed in units of ppm equivalent uranium. An approximate average value of eU was determined visually for each area and point values assigned based on whether the overall eU for the area falls below 1.5 ppm (1 point), between 1.5 and 2.5 ppm (2 points), or greater than 2.5 ppm (3 points).

The geology factor is complex and actually incorporates many geologic characteristics. In the matrix, "positive" and "negative" refer to the presence or absence and distribution of rock types known to have high uranium contents and to generate elevated radon in soils or indoors. Examples of "positive" rock types include granites, black shales, phosphatic rocks, and other rock types described in the preceding "geologic data" section. Examples of "negative" rock types include marine quartz sands and some clays. The term "variable" indicates that the geology within the region is variable or that the rock types in the area are known or suspected to generate elevated radon in some areas but not in others due to compositional differences, climatic effects, localized

TABLE 1. RADON INDEX MATRIX. "ppm eU" indicates parts per million of equivalent uranium, as indicated by NURE aerial radiometric data. See text discussion for details.

INCREASING RADON POTENTIAL →

FACTOR	POINT VALUE		
	1	2	3
INDOOR RADON (average)	< 2 pCi/L	2 - 4 pCi/L	> 4 pCi/L
AERIAL RADIOACTIVITY	< 1.5 ppm eU	1.5 - 2.5 ppm eU	> 2.5 ppm eU
GEOLOGY*	negative	variable	positive
SOIL PERMEABILITY	low	moderate	high
ARCHITECTURE TYPE	mostly slab	mixed	mostly basement

*GEOLOGIC FIELD EVIDENCE (GFE) POINTS: GFE points are assigned in addition to points for the "Geology" factor for specific, relevant geologic field studies. See text for details.

Geologic evidence supporting:	HIGH radon	+2 points
	MODERATE	+1 point
	LOW	-2 points
	No relevant geologic field studies	0 points

SCORING:

Radon potential category	Point range	Probable average screening indoor radon for area
LOW	3-8 points	< 2 pCi/L
MODERATE/VARIABLE	9-11 points	2 - 4 pCi/L
HIGH	12-17 points	> 4 pCi/L

POSSIBLE RANGE OF POINTS = 3 to 17

TABLE 2. CONFIDENCE INDEX MATRIX

INCREASING CONFIDENCE →

FACTOR	POINT VALUE		
	1	2	3
INDOOR RADON DATA	sparse/no data	fair coverage/quality	good coverage/quality
AERIAL RADIOACTIVITY	questionable/no data	glacial cover	no glacial cover
GEOLOGIC DATA	questionable	variable	proven geol. model
SOIL PERMEABILITY	questionable/no data	variable	reliable, abundant

SCORING:

LOW CONFIDENCE	4 - 6 points
MODERATE CONFIDENCE	7 - 9 points
HIGH CONFIDENCE	10 - 12 points

POSSIBLE RANGE OF POINTS = 4 to 12

distribution of uranium, or other factors. Geologic information indicates not only how much uranium is present in the rocks and soils but also gives clues for predicting general radon emanation and mobility characteristics through additional factors such as structure (notably the presence of faults or shears) and geochemical characteristics (for example, a phosphate-rich sandstone will likely contain more uranium than a sandstone containing little or no phosphate because the phosphate forms chemical complexes with uranium). "Negative", "variable", and "positive" geology were assigned 1, 2, and 3 points, respectively.

In cases where additional reinforcing or contradictory geologic evidence is available, Geologic Field Evidence (GFE) points were added to or subtracted from an area's score (Table 1). Relevant geologic field studies are important to enhancing our understanding of how geologic processes affect radon distribution. In some cases, geologic models and supporting field data reinforced an already strong (high or low) score; in others, they provided important contradictory data. GFE points were applied for geologically-sound evidence that supports the prediction (but which may contradict one or more factors) on the basis of known geologic field studies in the area or in areas with geologic and climatic settings similar enough that they could be applied with full confidence. For example, areas of the Dakotas, Minnesota, and Iowa that are covered with Wisconsin-age glacial deposits exhibit a low aerial radiometric signature and score only one RI point in that category. However, data from geologic field studies in North Dakota and Minnesota (Schumann and others, 1991) suggest that eU is a poor predictor of geologic radon potential in this area because radionuclides have been leached from the upper soil layers but are present and possibly even concentrated in deeper soil horizons, generating significant soil-gas radon. This positive supporting field evidence adds two GFE points to the score, which helps to counteract the invalid conclusion suggested by the radiometric data. No GFE points are awarded if there are no documented field studies for the area.

"Soil permeability" refers to several soil characteristics that influence radon concentration and mobility, including soil type, grain size, structure, soil moisture, drainage, slope, and permeability. In the matrix, "low" refers to permeabilities less than about 0.6 in/hr; "high" corresponds to greater than about 6.0 in/hr, in U.S. Soil Conservation Service (SCS) standard soil percolation tests. The SCS data are for water permeability, which generally correlates well with the gas permeability of the soil except when the soil moisture content is very high. Areas with consistently high water tables were thus considered to have low gas permeability. "Low, "moderate", and "high" permeability were assigned 1, 2, and 3 points, respectively.

Architecture type refers to whether homes in the area have mostly basements (3 points), mostly slab-on-grade construction (1 point), or a mixture of the two. Split-level and crawl space homes fall into the "mixed" category (2 points). Architecture information is necessary to properly interpret the indoor radon data and produce geologic radon potential categories that are consistent with screening indoor radon data.

The overall RI for an area is calculated by adding the individual RI scores for the 5 factors, plus or minus GFE points, if any. The total RI for an area falls in one of three categories—low, moderate or variable, or high. The point ranges for the three categories were determined by examining the possible combinations of points for the 5 factors and setting rules such that a majority (3 of 5 factors) would determine the final score for the low and high categories, with allowances for possible deviation from an ideal score by the other two factors. The moderate/variable category lies between these two ranges. A total deviation of 3 points from the "ideal" score was considered reasonable to allow for natural variability of factors—if two of the five factors are allowed to vary from the "ideal" for a category, they can differ by a minimum of 2

(1 point different each) and a maximum of 4 points (2 points different each). With "ideal" scores of 5, 10, and 15 points describing low, moderate, and high geologic radon potential, respectively, an ideal low score of 5 points plus 3 points for possible variability allows a maximum of 8 points in the low category. Similarly, an ideal high score of 15 points minus 3 points gives a minimum of 12 points for the high category. Note, however, that if both other factors differ by two points from the "ideal", indicating considerable variability in the system, the total point score would lie in the adjacent (i.e., moderate/variable) category.

Confidence Index. Except for architecture type, the same factors were used to establish a Confidence Index (CI) for the radon potential prediction for each area (Table 2). Architecture type was not included in the confidence index because house construction data are readily and reliably available through surveys taken by agencies and industry groups including the National Association of Home Builders, U.S. Department of Housing and Urban Development, and the Federal Housing Administration; thus it was not considered necessary to question the quality or validity of these data. The other factors were scored on the basis of the quality and quantity of the data used to complete the RI matrix.

Indoor radon data were evaluated based on the distribution and number of data points and on whether the data were collected by random sampling (State/EPA Residential Radon Survey or other state survey data) or volunteered vendor data (likely to be nonrandom and biased toward population centers and/or high indoor radon levels). The categories listed in the CI matrix for indoor radon data ("sparse or no data", "fair coverage or quality", and "good coverage/quality") indicate the sampling density and statistical robustness of an indoor radon data set. Data from the State/EPA Residential Radon Survey and statistically valid state surveys were typically assigned 3 Confidence Index points unless the data were poorly distributed or absent in the area evaluated.

Aerial radioactivity data are available for all but a few areas of the continental United States and for part of Alaska. An evaluation of the quality of the radioactivity data was based on whether there appeared to be a good correlation between the radioactivity and the actual amount of uranium or radium available to generate mobile radon in the rocks and soils of the area evaluated. In general, the greatest problems with correlations among eU, geology, and soil-gas or indoor radon levels were associated with glacial deposits (see the discussion in a previous section) and typically were assigned a 2-point Confidence Index score. Correlations among eU, geology, and radon were generally sound in unglaciated areas and were usually assigned 3 CI points. Again, however, radioactivity data in some unglaciated areas may have been assigned fewer than 3 points, and in glaciated areas may be assigned only one point, if the data were considered questionable or if coverage was poor.

To assign Confidence Index scores for the geologic data factor, rock types and geologic settings for which a physical-chemical, process-based understanding of radon generation and mobility exists were regarded as having "proven geologic models" (3 points); a high confidence could be held for predictions in such areas. Rocks for which the processes are less well known or for which data are contradictory were regarded as "variable" (2 points), and those about which little is known or for which no apparent correlations have been found were deemed "questionable" (1 point).

The soil permeability factor was also scored based on quality and amount of data. The three categories for soil permeability in the Confidence Index are similar in concept, and scored similarly, to those for the geologic data factor. Soil permeability can be roughly estimated from grain size and drainage class if data from standard, accepted soil percolation tests are unavailable; however, the reliability of the data would be lower than if percolation test figures or other measured permeability data are available, because an estimate of this type does not encompass all the factors that affect soil permeability and thus may be inaccurate in some instances. Most published soil permeability data are for water; although this is generally closely related to the air permeability of the soil, there are some instances when it may provide an incorrect estimate. Examples of areas in which water permeability data may not accurately reflect air permeability include areas with consistently high levels of soil moisture, or clay-rich soils, which would have a low water permeability but may have a significantly higher air permeability when dry due to shrinkage cracks in the soil. These additional factors were applied to the soil permeability factor when assigning the RI score, but may have less certainty in some cases and thus would be assigned a lower CI score.

The Radon Index and Confidence Index give a general indication of the relative contributions of the interrelated geologic factors influencing radon generation and transport in rocks and soils, and thus, of the potential for elevated indoor radon levels to occur in a particular area. However, because these reports are somewhat generalized to cover relatively large areas of States, it is highly recommended that more detailed studies be performed in local areas of interest, using the methods and general information in these booklets as a guide.

EPA COUNTY RADON POTENTIAL MAPS

EPA has produced maps of radon potential, referred to as "radon zone maps", using counties as the primary geographic units. The maps were produced by adapting the results of the geologic radon potential evaluations of the approximately 360 geologic provinces defined for the United States, to fit county boundaries. Because the geologic province boundaries cross State and county boundaries, a strict translation of counties from the geologic province map was not possible. When a county fell within varying radon potential areas, the radon potential designation that covers the most area was chosen as the county designation. The geologic province assessments were adapted to a county map format because many planning, outreach, and information programs are based on political boundaries such as counties. The county-based EPA Radon Zone Maps are not included in the USGS geologic radon potential booklets. They are available from EPA headquarters and regional offices or through the state radon program offices.

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APPENDIX A
GEOLOGIC TIME SCALE

Subdivisions (and their symbols)						Age estimates of boundaries in mega-annum (Ma)[1]
Eon or Eonothem	Era or Erathem	Period, System, Subperiod, Subsystem		Epoch or Series		
Phanerozoic[2]	Cenozoic[2] (Cz)	Quaternary[2] (Q)		Holocene		0.010
				Pleistocene		1.6 (1.6–1.9)
		Tertiary (T)	Neogene[2] Subperiod or Subsystem (N)	Pliocene		5 (4.9–5.3)
				Miocene		24 (23–26)
			Paleogene[2] Subperiod or Subsystem (Pɛ)	Oligocene		38 (34–38)
				Eocene		55 (54–56)
				Paleocene		66 (63–66)
	Mesozoic[2] (Mz)	Cretaceous (K)		Late	Upper	96 (95–97)
				Early	Lower	138 (135–141)
		Jurassic (J)		Late	Upper	
				Middle	Middle	
				Early	Lower	205 (200–215)
		Triassic (T̶R)		Late	Upper	
				Middle	Middle	
				Early	Lower	~240
	Paleozoic[2] (Pz)	Permian (P)		Late	Upper	
				Early	Lower	290 (290–305)
		Carboniferous Systems (C)	Pennsylvanian (IP)	Late	Upper	
				Middle	Middle	
				Early	Lower	~330
			Mississippian (M)	Late	Upper	
				Early	Lower	360 (360–365)
		Devonian (D)		Late	Upper	
				Middle	Middle	
				Early	Lower	410 (405–415)
		Silurian (S)		Late	Upper	
				Middle	Middle	
				Early	Lower	435 (435–440)
		Ordovician (O)		Late	Upper	
				Middle	Middle	
				Early	Lower	500 (495–510)
		Cambrian (Є)		Late	Upper	
				Middle	Middle	
				Early	Lower	~570[3]
Proterozoic (P̶)	Late Proterozoic (Z)	None defined				900
	Middle Proterozoic (Y)	None defined				1600
	Early Proterozoic (X)	None defined				2500
Archean (A)	Late Archean (W)	None defined				3000
	Middle Archean (V)	None defined				3400
	Early Archean (U)	None defined				3800 ?
pre-Archean (pA)[4]						

[1] Ranges reflect uncertainties of isotopic and biostratigraphic age assignments. Age boundaries not closely bracketed by existing data shown by ~. Decay constants and isotopic ratios employed are cited in Steiger and Jäger (1977). Designation m.y. used for an interval of time.

[2] Modifiers (lower, middle, upper or early, middle, late) when used with these items are informal divisions of the larger unit; the first letter of the modifier is lowercase.

[3] Rocks older than 570 Ma also called Precambrian (p-Є), a time term without specific rank.

[4] Informal time term without specific rank.

APPENDIX B
GLOSSARY OF TERMS

Units of measure

pCi/L (picocuries per liter)- a unit of measure of radioactivity used to describe radon concentrations in a volume of air. One picocurie (10^{-12} curies) is equal to about 2.2 disintegrations of radon atoms per minute. A liter is about 1.06 quarts. The average concentration of radon in U.S. homes measured to date is between 1 and 2 pCi/L.

Bq/m^3 (Becquerels per cubic meter)- a metric unit of radioactivity used to describe radon concentrations in a volume of air. One becquerel is equal to one radioactive disintegration per second. One pCi/L is equal to 37 Bq/m^3.

ppm (parts per million)- a unit of measure of concentration by weight of an element in a substance, in this case, soil or rock. One ppm of uranium contained in a ton of rock corresponds to about 0.03 ounces of uranium. The average concentration of uranium in soils in the United States is between 1 and 2 ppm.

in/hr (inches per hour)- a unit of measure used by soil scientists and engineers to describe the permeability of a soil to water flowing through it. It is measured by digging a hole 1 foot (12 inches) square and one foot deep, filling it with water, and measuring the time it takes for the water to drain from the hole. The drop in height of the water level in the hole, measured in inches, is then divided by the time (in hours) to determine the permeability. Soils range in permeability from less than 0.06 in/hr to greater than 20 in/hr, but most soils in the United States have permeabilities between these two extremes.

Geologic terms and terms related to the study of radon

aerial radiometric, aeroradiometric survey A survey of radioactivity, usually gamma rays, taken by an aircraft carrying a gamma-ray spectrometer pointed at the ground surface.

alluvial fan A low, widespread mass of loose rock and soil material, shaped like an open fan and deposited by a stream at the point where it flows from a narrow mountain valley out onto a plain or broader valley. May also form at the junction with larger streams or when the gradient of the stream abruptly decreases.

alluvium, alluvial General terms referring to unconsolidated detrital material deposited by a stream or other body of running water.

alpha-track detector A passive radon measurement device consisting of a plastic film that is sensitive to alpha particles. The film is etched with acid in a laboratory after it is exposed. The etching reveals scratches, or "tracks", left by the alpha particles resulting from radon decay , which can then be counted to calculate the radon concentration. Useful for long-term (1-12 months) radon tests.

amphibolite A mafic metamorphic rock consisting mainly of pyroxenes and(or) amphibole and plagioclase.

argillite, argillaceous Terms referring to a rock derived from clay or shale, or any sedimentary rock containing an appreciable amount of clay-size material, i.e., argillaceous sandstone.

arid Term describing a climate characterized by dryness, or an evaporation rate that exceeds the amount of precipitation.

basalt A general term for a dark-colored mafic igneous rocks that may be of extrusive origin, such as volcanic basalt flows, or intrusive origin, such as basalt dikes.

batholith A mass of plutonic igneous rock that has more than 40 square miles of surface exposure and no known bottom.

carbonate A sedimentary rock consisting of the carbonate (CO_3) compounds of calcium, magnesium, or iron, e.g. limestone and dolomite.

carbonaceous Said of a rock or sediment that is rich in carbon, is coaly, or contains organic matter.

charcoal canister A passive radon measurement device consisting of a small container of granulated activated charcoal that is designed to adsorb radon. Useful for short duration (2-7 days) measurements only. May be referred to as a "screening" test.

chert A hard, extremely dense sedimentary rock consisting dominantly of interlocking crystals of quartz. Crystals are not visible to the naked eye, giving the rock a milky, dull luster. It may be white or gray but is commonly colored red, black, yellow, blue, pink, brown, or green.

clastic pertaining to a rock or sediment composed of fragments that are derived from preexisting rocks or minerals. The most common clastic sedimentary rocks are sandstone and shale.

clay A rock containing clay mineral fragments or material of any composition having a diameter less than 1/256 mm.

clay mineral One of a complex and loosely defined group of finely crystalline minerals made up of water, silicate and aluminum (and a wide variety of other elements). They are formed chiefly by alteration or weathering of primary silicate minerals. Certain clay minerals are noted for their small size and ability to absorb substantial amounts of water, causing them to swell. The change in size that occurs as these clays change between dry and wet is referred to as their **"shrink-swell"** potential.

concretion A hard, compact mass of mineral matter, normally subspherical but commonly irregular in shape; formed by precipitation from a water solution about a nucleus or center, such as a leaf, shell, bone, or fossil, within a sedimentary or fractured rock.

conglomerate A coarse-grained, clastic sedimentary rock composed of rock and mineral fragments larger than 2 mm, set in a finer-grained matrix of clastic material.

cuesta A hill or ridge with a gentle slope on one side and a steep slope on the other. The formation of a cuesta is controlled by the different weathering properties and the structural dip of the rocks forming the hill or ridge.

daughter product A nuclide formed by the disintegration of a radioactive precursor or "parent" atom.

delta, deltaic Referring to a low, flat, alluvial tract of land having a triangular or fan shape, located at or near the mouth of a river. It results from the accumulation of sediment deposited by a river at the point at which the river loses its ability to transport the sediment, commonly where a river meets a larger body of water such as a lake or ocean.

dike A tabular igneous intrusion of rock, younger than the surrounding rock, that commonly cuts across the bedding or foliation of the rock it intrudes.

diorite A plutonic igneous rock that is medium in color and contains visible dark minerals that make up less than 50% of the rock. It also contains abundant sodium plagioclase and minor quartz.

dolomite A carbonate sedimentary rock of which more than 50% consists of the mineral dolomite ($CaMg(CO_3)_2$), and is commonly white, gray, brown, yellow, or pinkish in color.

drainage The manner in which the waters of an area pass, flow off of, or flow into the soil. Also refers to the water features of an area, such as lakes and rivers, that drain it.

eolian Pertaining to sediments deposited by the wind.

esker A long, narrow, steep-sided ridge composed of irregular beds of sand and gravel deposited by streams beneath a glacier and left behind when the ice melted.

evapotranspiration Loss of water from a land area by evaporation from the soil and transpiration from plants.

extrusive Said of igneous rocks that have been erupted onto the surface of the Earth.

fault A fracture or zone of fractures in rock or sediment along which there has been movement.

fluvial, fluvial deposit Pertaining to sediment that has been deposited by a river or stream.

foliation A linear feature in a rock defined by both mineralogic and structural characteristics. It may be formed during deformation or metamorphism.

formation A mappable body of rock having similar characteristics.

glacial deposit Any sediment transported and deposited by a glacier or processes associated with glaciers, such as glaciofluvial sediments deposited by streams flowing from melting glaciers.

gneiss A rock formed by metamorphism in which bands and lenses of minerals of similar composition alternate with bands and lenses of different composition, giving the rock a striped or "foliated" appearance.

granite Broadly applied, any coarsely crystalline, quartz- and feldspar-bearing igneous plutonic rock. Technically, granites have between 10 and 50% quartz, and alkali feldspar comprises at least 65% of the total feldspar.

gravel An unconsolidated, natural accumulation of rock fragments consisting predominantly of particles greater than 2 mm in size.

heavy minerals Mineral grains in sediment or sedimentary rock having higher than average specific gravity. May form layers and lenses because of wind or water sorting by weight and size and may be referred to as a "placer deposit." Some heavy minerals are magnetite, garnet, zircon, monazite, and xenotime.

igneous Said of a rock or mineral that solidified from molten or partly molten rock material. It is one of the three main classes into which rocks are divided, the others being sedimentary and metamorphic.

intermontane A term that refers to an area between two mountains or mountain ranges.

intrusion, intrusive The processes of emplacement or injection of molten rock into pre-existing rock. Also refers to the rock formed by intrusive processes, such as an "intrusive igneous rock".

kame A low mound, knob, hummock, or short irregular ridge formed by a glacial stream at the margin of a melting glacier; composed of bedded sand and gravel.

karst terrain A type of topography that is formed on limestone, gypsum and other rocks by dissolution of the rock by water, forming sinkholes and caves.

lignite A brownish-black coal that is intermediate in coalification between peat and subbituminous coal.

limestone A carbonate sedimentary rock consisting of more than 50% calcium carbonate, primarily in the form of the mineral calcite ($CaCO_3$).

lithology The description of rocks in hand specimen and in outcrop on the basis of color, composition, and grain size.

loam A permeable soil composed of a mixture of relatively equal parts clay, silt, and sand, and usually containing some organic matter.

loess A fine-grained eolian deposit composed of silt-sized particles generally thought to have been deposited from windblown dust of Pleistocene age.

mafic Term describing an igneous rock containing more than 50% dark-colored minerals.

marine Term describing sediments deposited in the ocean, or precipitated from ocean waters.

metamorphic Any rock derived from pre-existing rocks by mineralogical, chemical, or structural changes in response to changes in temperature, pressure, stress, and the chemical environment. Phyllite, schist, amphibolite, and gneiss are metamorphic rocks.

moraine A mound, ridge, or other distinct accumulation of unsorted, unbedded glacial material, predominantly till, deposited by the action of glacial ice.

outcrop That part of a geologic formation or structure that appears at the surface of the Earth, as in "rock outcrop".

percolation test A term used in engineering for a test to determine the water permeability of a soil. A hole is dug and filled with water and the rate of water level decline is measured.

permeability The capacity of a rock, sediment, or soil to transmit liquid or gas.

phosphate, phosphatic, phosphorite Any rock or sediment containing a significant amount of phosphate minerals, i.e., minerals containing PO_4.

physiographic province A region in which all parts are similar in geologic structure and climate, which has had a uniform geomorphic history, and whose topography or landforms differ significantly from adjacent regions.

placer deposit See heavy minerals

residual Formed by weathering of a material in place.

residuum Deposit of residual material.

rhyolite An extrusive igneous rock of volcanic origin, compositionally equivalent to granite.

sandstone A clastic sedimentary rock composed of sand-sized rock and mineral material that is more or less firmly cemented. Sand particles range from 1/16 to 2 mm in size.

schist A strongly foliated crystalline rock, formed by metamorphism, that can be readily split into thin flakes or slabs. Contains mica; minerals are typically aligned.

screening level Result of an indoor radon test taken with a charcoal canister or similar device, for a short period of time, usually less than seven days. May indicate the potential for an indoor radon problem but does not indicate annual exposure to radon.

sediment Deposits of rock and mineral particles or fragments originating from material that is transported by air, water or ice, or that accumulate by natural chemical precipitation or secretion of organisms.

semiarid Refers to a climate that has slightly more precipitation than an arid climate.

shale A fine-grained sedimentary rock formed from solidification (lithification) of clay or mud.

shear zone Refers to a roughly linear zone of rock that has been faulted by ductile or non-ductile processes in which the rock is sheared and both sides are displaced relative to one another.

shrink-swell clay See clay mineral.

siltstone A fine-grained clastic sedimentary rock composed of silt-sized rock and mineral material and more or less firmly cemented. Silt particles range from 1/16 to 1/256 mm in size.

sinkhole A roughly circular depression in a karst area measuring meters to tens of meters in diameter. It is funnel shaped and is formed by collapse of the surface material into an underlying void created by the dissolution of carbonate rock.

slope An inclined part of the earth's surface.

solution cavity A hole, channel or cave-like cavity formed by dissolution of rock.

stratigraphy The study of rock strata; also refers to the succession of rocks of a particular area.

surficial materials Unconsolidated glacial, wind-, or waterborne deposits occurring on the earth's surface.

tablelands General term for a broad, elevated region with a nearly level surface of considerable extent.

terrace gravel Gravel-sized material that caps ridges and terraces, left behind by a stream as it cuts down to a lower level.

terrain A tract or region of the Earth's surface considered as a physical feature or an ecological environment.

till Unsorted, generally unconsolidated and unbedded rock and mineral material deposited directly adjacent to and underneath a glacier, without reworking by meltwater. Size of grains varies greatly from clay to boulders.

uraniferous Containing uranium, usually more than 2 ppm.

vendor data Used in this report to refer to indoor radon data collected and measured by commercial vendors of radon measurement devices and/or services.

volcanic Pertaining to the activities, structures, and extrusive rock types of a volcano.

water table The surface forming the boundary between the zone of saturation and the zone of aeration; the top surface of a body of unconfined groundwater in rock or soil.

weathering The destructive process by which earth and rock materials, on exposure to atmospheric elements, are changed in color, texture, composition, firmness, or form with little or no transport of the material.

APPENDIX C
EPA REGIONAL OFFICES

EPA Regional Offices

EPA Region 1
JFK Federal Building
Boston, MA 02203
(617) 565-4502

EPA Region 2
(2AIR:RAD)
26 Federal Plaza
New York, NY 10278
(212) 264-4110

Region 3 (3AH14)
841 Chestnut Street
Philadelphia, PA 19107
(215) 597-8326

EPA Region 4
345 Courtland Street, N.E.
Atlanta, GA 30365
(404) 347-3907

EPA Region 5 (5AR26)
77 West Jackson Blvd.
Chicago, IL 60604-3507
(312) 886-6175

EPA Region 6 (6T-AS)
1445 Ross Avenue
Dallas, TX 75202-2733
(214) 655-7224

EPA Region 7
726 Minnesota Avenue
Kansas City, KS 66101
(913) 551-7604

EPA Region 8
(8HWM-RP)
999 18th Street
One Denver Place, Suite 1300
Denver, CO 80202-2413
(303) 293-1713

EPA Region 9 (A-3)
75 Hawthorne Street
San Francisco, CA 94105
(415) 744-1048

EPA Region 10
1200 Sixth Avenue
Seattle, WA 98101
(202) 442-7660

State	EPA Region
Alabama	4
Alaska	10
Arizona	9
Arkansas	6
California	9
Colorado	8
Connecticut	1
Delaware	3
District of Columbia	3
Florida	4
Georgia	4
Hawaii	9
Idaho	10
Illinois	5
Indiana	5
Iowa	7
Kansas	7
Kentucky	4
Louisiana	6
Maine	1
Maryland	3
Massachusetts	1
Michigan	5
Minnesota	5
Mississippi	4
Missouri	7
Montana	8
Nebraska	7
Nevada	9
New Hampshire	1
New Jersey	2
New Mexico	6
New York	2
North Carolina	4
North Dakota	8
Ohio	5
Oklahoma	6
Oregon	10
Pennsylvania	3
Rhode Island	1
South Carolina	4
South Dakota	8
Tennessee	4
Texas	6
Utah	8
Vermont	1
Virginia	3
Washington	10
West Virginia	3
Wisconsin	5
Wyoming	8

STATE RADON CONTACTS

May, 1993

<u>Alabama</u>
James McNees
Division of Radiation Control
Alabama Department of Public Health
State Office Building
Montgomery, AL 36130
(205) 242-5315
1-800-582-1866 in state

<u>Alaska</u>
Charles Tedford
Department of Health and Social Services
P.O. Box 110613
Juneau, AK 99811-0613
(907) 465-3019
1-800-478-4845 in state

<u>Arizona</u>
John Stewart
Arizona Radiation Regulatory Agency
4814 South 40th St.
Phoenix, AZ 85040
(602) 255-4845

<u>Arkansas</u>
Lee Gershner
Division of Radiation Control
Department of Health
4815 Markham Street, Slot 30
Little Rock, AR 72205-3867
(501) 661-2301

<u>California</u>
J. David Quinton
Department of Health Services
714 P Street, Room 600
Sacramento, CA 94234-7320
(916) 324-2208
1-800-745-7236 in state

<u>Colorado</u>
Linda Martin
Department of Health
4210 East 11th Avenue
Denver, CO 80220
(303) 692-3057
1-800-846-3986 in state

<u>Connecticut</u>
Alan J. Siniscalchi
Radon Program
Connecticut Department of Health Services
150 Washington Street
Hartford, CT 06106-4474
(203) 566-3122

<u>Delaware</u>
Marai G. Rejai
Office of Radiation Control
Division of Public Health
P.O. Box 637
Dover, DE 19903
(302) 736-3028
1-800-554-4636 In State

<u>District of Columbia</u>
Robert Davis
DC Department of Consumer and Regulatory Affairs
614 H Street NW
Room 1014
Washington, DC 20001
(202) 727-71068

<u>Florida</u>
N. Michael Gilley
Office of Radiation Control
Department of Health and Rehabilitative Services
1317 Winewood Boulevard
Tallahassee, FL 32399-0700
(904) 488-1525
1-800-543-8279 in state

<u>Georgia</u>
Richard Schreiber
Georgia Department of Human Resources
878 Peachtree St., Room 100
Atlanta, GA 30309
(404) 894-6644
1-800-745-0037 in state

<u>Hawaii</u>
Russell Takata
Environmental Health Services Division
591 Ala Moana Boulevard
Honolulu, HI 96813-2498
(808) 586-4700

Idaho	Pat McGavarn Office of Environmental Health 450 West State Street Boise, ID 83720 (208) 334-6584 1-800-445-8647 in state	Louisiana	Matt Schlenker Louisiana Department of Environmental Quality P.O. Box 82135 Baton Rouge, LA 70884-2135 (504) 925-7042 1-800-256-2494 in state
Illinois	Richard Allen Illinois Department of Nuclear Safety 1301 Outer Park Drive Springfield, IL 62704 (217) 524-5614 1-800-325-1245 in state	Maine	Bob Stilwell Division of Health Engineering Department of Human Services State House, Station 10 Augusta, ME 04333 (207) 289-5676 1-800-232-0842 in state
Indiana	Lorand Magyar Radiological Health Section Indiana State Department of Health 1330 West Michigan Street P.O. Box 1964 Indianapolis, IN 46206 (317) 633-8563 1-800-272-9723 In State	Maryland	Leon J. Rachuba Radiological Health Program Maryland Department of the Environment 2500 Broening Highway Baltimore, MD 21224 (410) 631-3301 1-800-872-3666 In State
Iowa	Donald A. Flater Bureau of Radiological Health Iowa Department of Public Health Lucas State Office Building Des Moines, IA 50319-0075 (515) 281-3478 1-800-383-5992 In State	Massachusetts	William J. Bell Radiation Control Program Department of Public Health 23 Service Center Northampton, MA 01060 (413) 586-7525 1-800-445-1255 in state
Kansas	Harold Spiker Radiation Control Program Kansas Department of Health and Environment 109 SW 9th Street 6th Floor Mills Building Topeka, KS 66612 (913) 296-1561	Michigan	Sue Hendershott Division of Radiological Health Bureau of Environmental and Occupational Health 3423 North Logan Street P.O. Box 30195 Lansing, MI 48909 (517) 335-8194
Kentucky	Jeana Phelps Radiation Control Branch Department of Health Services Cabinet for Human Resources 275 East Main Street Frankfort, KY 40601 (502) 564-3700	Minnesota	Laura Oatmann Indoor Air Quality Unit 925 Delaware Street, SE P.O. Box 59040 Minneapolis, MN 55459-0040 (612) 627-5480 1-800-798-9050 in state

Mississippi

Silas Anderson
Division of Radiological Health
Department of Health
3150 Lawson Street
P.O. Box 1700
Jackson, MS 39215-1700
(601) 354-6657
1-800-626-7739 in state

Missouri

Kenneth V. Miller
Bureau of Radiological Health
Missouri Department of Health
1730 East Elm
P.O. Box 570
Jefferson City, MO 65102
(314) 751-6083
1-800-669-7236 In State

Montana

Adrian C. Howe
Occupational Health Bureau
Montana Department of Health and Environmental Sciences
Cogswell Building A113
Helena, MT 59620
(406) 444-3671

Nebraska

Joseph Milone
Division of Radiological Health
Nebraska Department of Health
301 Centennial Mall, South
P.O. Box 95007
Lincoln, NE 68509
(402) 471-2168
1-800-334-9491 In State

Nevada

Stan Marshall
Department of Human Resources
505 East King Street
Room 203
Carson City, NV 89710
(702) 687-5394

New Hampshire

David Chase
Bureau of Radiological Health
Division of Public Health Services
Health and Welfare Building
Six Hazen Drive
Concord, NH 03301
(603) 271-4674
1-800-852-3345 x4674

New Jersey

Tonalee Carlson Key
Division of Environmental Quality
Department of Environmental Protection
CN 415
Trenton, NJ 08625-0145
(609) 987-6369
1-800-648-0394 in state

New Mexico

William M. Floyd
Radiation Licensing and Registration Section
New Mexico Environmental Improvement Division
1190 St. Francis Drive
Santa Fe, NM 87503
(505) 827-4300

New York

William J. Condon
Bureau of Environmental Radiation Protection
New York State Health Department
Two University Place
Albany, NY 12202
(518) 458-6495
1-800-458-1158 in state

North Carolina

Dr. Felix Fong
Radiation Protection Division
Department of Environmental Health and Natural Resources
701 Barbour Drive
Raleigh, NC 27603-2008
(919) 571-4141
1-800-662-7301 (recorded info x4196)

North Dakota

Arlen Jacobson
North Dakota Department of Health
1200 Missouri Avenue, Room 304
P.O. Box 5520
Bismarck, ND 58502-5520
(701) 221-5188

Ohio

Marcie Matthews
Radiological Health Program
Department of Health
1224 Kinnear Road - Suite 120
Columbus, OH 43212
(614) 644-2727
1-800-523-4439 in state

Oklahoma
Gene Smith
Radiation Protection Division
Oklahoma State Department of Health
P.O. Box 53551
Oklahoma City, OK 73152
(405) 271-5221

Oregon
George Toombs
Department of Human Resources
Health Division
1400 SW 5th Avenue
Portland, OR 97201
(503) 731-4014

Pennsylvania
Michael Pyles
Pennsylvania Department of Environmental Resources
Bureau of Radiation Protection
P.O. Box 2063
Harrisburg, PA 17120
(717) 783-3594
1-800-23-RADON In State

Puerto Rico
David Saldana
Radiological Health Division
G.P.O. Call Box 70184
Rio Piedras, Puerto Rico 00936
(809) 767-3563

Rhode Island
Edmund Arcand
Division of Occupational Health and Radiation
Department of Health
205 Cannon Building
Davis Street
Providence, RI 02908
(401) 277-2438

South Carolina
Bureau of Radiological Health
Department of Health and Environmental Control
2600 Bull Street
Columbia, SC 29201
(803) 734-4631
1-800-768-0362

South Dakota
Mike Pochop
Division of Environment Regulation
Department of Water and Natural Resources
Joe Foss Building, Room 217
523 E. Capitol
Pierre, SD 57501-3181
(605) 773-3351

Tennessee
Susie Shimek
Division of Air Pollution Control
Bureau of the Environment
Department of Environment and Conservation
Customs House, 701 Broadway
Nashville, TN 37219-5403
(615) 532-0733
1-800-232-1139 in state

Texas
Gary Smith
Bureau of Radiation Control
Texas Department of Health
1100 West 49th Street
Austin, TX 78756-3189
(512) 834-6688

Utah
John Hultquist
Bureau of Radiation Control
Utah State Department of Health
288 North, 1460 West
P.O. Box 16690
Salt Lake City, UT 84116-0690
(801) 536-4250

Vermont
Paul Clemons
Occupational and Radiological Health Division
Vermont Department of Health
10 Baldwin Street
Montpelier, VT 05602
(802) 828-2886
1-800-640-0601 in state

Virgin Islands
Contact the U.S. Environmental Protection Agency, Region II in New York
(212) 264-4110

Virginia	Shelly Ottenbrite Bureau of Radiological Health Department of Health 109 Governor Street Richmond, VA 23219 (804) 786-5932 1-800-468-0138 in state
Washington	Kate Coleman Department of Health Office of Radiation Protection Airdustrial Building 5, LE-13 Olympia, WA 98504 (206) 753-4518 1-800-323-9727 In State
West Virginia	Beattie L. DeBord Industrial Hygiene Division West Virginia Department of Health 151 11th Avenue South Charleston, WV 25303 (304) 558-3526 1-800-922-1255 In State
Wisconsin	Conrad Weiffenbach Radiation Protection Section Division of Health Department of Health and Social Services P.O. Box 309 Madison, WI 53701-0309 (608) 267-4796 1-800-798-9050 in state
Wyoming	Janet Hough Wyoming Department of Health and Social Services Hathway Building, 4th Floor Cheyenne, WY 82002-0710 (307) 777-6015 1-800-458-5847 in state

STATE GEOLOGICAL SURVEYS

May, 1993

Alabama
Ernest A. Mancini
Geological Survey of Alabama
P.O. Box 0
420 Hackberry Lane
Tuscaloosa, AL 35486-9780
(205) 349-2852

Alaska
Thomas E. Smith
Alaska Division of Geological & Geophysical Surveys
794 University Ave., Suite 200
Fairbanks, AK 99709-3645
(907) 479-7147

Arizona
Larry D. Fellows
Arizona Geological Survey
845 North Park Ave., Suite 100
Tucson, AZ 85719
(602) 882-4795

Arkansas
Norman F. Williams
Arkansas Geological Commission
Vardelle Parham Geology Center
3815 West Roosevelt Rd.
Little Rock, AR 72204
(501) 324-9165

California
James F. Davis
California Division of Mines & Geology
801 K Street, MS 12-30
Sacramento, CA 95814-3531
(916) 445-1923

Colorado
Pat Rogers (Acting)
Colorado Geological Survey
1313 Sherman St., Rm 715
Denver, CO 80203
(303) 866-2611

Connecticut
Richard C. Hyde
Connecticut Geological & Natural History Survey
165 Capitol Ave., Rm. 553
Hartford, CT 06106
(203) 566-3540

Delaware
Robert R. Jordan
Delaware Geological Survey
University of Delaware
101 Penny Hall
Newark, DE 19716-7501
(302) 831-2833

Florida
Walter Schmidt
Florida Geological Survey
903 W. Tennessee St.
Tallahassee, FL 32304-7700
(904) 488-4191

Georgia
William H. McLemore
Georgia Geologic Survey
Rm. 400
19 Martin Luther King Jr. Dr. SW
Atlanta, GA 30334
(404) 656-3214

Hawaii
Manabu Tagomori
Dept. of Land and Natural Resources
Division of Water & Land Mgt
P.O. Box 373
Honolulu, HI 96809
(808) 548-7539

Idaho
Earl H. Bennett
Idaho Geological Survey
University of Idaho
Morrill Hall, Rm. 332
Moscow, ID 83843
(208) 885-7991

Illinois
Morris W. Leighton
Illinois State Geological Survey
Natural Resources Building
615 East Peabody Dr.
Champaign, IL 61820
(217) 333-4747

Indiana
Norman C. Hester
Indiana Geological Survey
611 North Walnut Grove
Bloomington, IN 47405
(812) 855-9350

Iowa
Donald L. Koch
Iowa Department of Natural Resources
Geological Survey Bureau
109 Trowbridge Hall
Iowa City, IA 52242-1319
(319) 335-1575

Kansas
Lee C. Gerhard
Kansas Geological Survey
1930 Constant Ave., West Campus
University of Kansas
Lawrence, KS 66047
(913) 864-3965

Kentucky
Donald C. Haney
Kentucky Geological Survey
University of Kentucky
228 Mining & Mineral Resources Building
Lexington, KY 40506-0107
(606) 257-5500

Louisiana
William E. Marsalis
Louisiana Geological Survey
P.O. Box 2827
University Station
Baton Rouge, LA 70821-2827
(504) 388-5320

Maine
Walter A. Anderson
Maine Geological Survey
Department of Conservation
State House, Station 22
Augusta, ME 04333
(207) 289-2801

Maryland
Emery T. Cleaves
Maryland Geological Survey
2300 St. Paul Street
Baltimore, MD 21218-5210
(410) 554-5500

Massachusetts
Joseph A. Sinnott
Massachusetts Office of Environmental Affairs
100 Cambridge St., Room 2000
Boston, MA 02202
(617) 727-9800

Michigan
R. Thomas Segall
Michigan Geological Survey Division
Box 30256
Lansing, MI 48909
(517) 334-6923

Minnesota
Priscilla C. Grew
Minnesota Geological Survey
2642 University Ave.
St. Paul, MN 55114-1057
(612) 627-4780

Mississippi
S. Cragin Knox
Mississippi Office of Geology
P.O. Box 20307
Jackson, MS 39289-1307
(601) 961-5500

Missouri
James H. Williams
Missouri Division of Geology & Land Survey
111 Fairgrounds Road
P.O. Box 250
Rolla, MO 65401
(314) 368-2100

Montana
Edward T. Ruppel
Montana Bureau of Mines & Geology
Montana College of Mineral Science and Technology, Main Hall
Butte, MT 59701
(406) 496-4180

Nebraska
Perry B. Wigley
Nebraska Conservation & Survey Division
113 Nebraska Hall
University of Nebraska
Lincoln, NE 68588-0517
(402) 472-2410

Nevada
Jonathan G. Price
Nevada Bureau of Mines & Geology
Stop 178
University of Nevada-Reno
Reno, NV 89557-0088
(702) 784-6691

New Hampshire
Eugene L. Boudette
Dept. of Environmental Services
117 James Hall
University of New Hampshire
Durham, NH 03824-3589
(603) 862-3160

New Jersey
Haig F. Kasabach
New Jersey Geological Survey
P.O. Box 427
Trenton, NJ 08625
(609) 292-1185

New Mexico
Charles E. Chapin
New Mexico Bureau of Mines & Mineral Resources
Campus Station
Socorro, NM 87801
(505) 835-5420

New York
Robert H. Fakundiny
New York State Geological Survey
3136 Cultural Education Center
Empire State Plaza
Albany, NY 12230
(518) 474-5816

North Carolina
Charles H. Gardner
North Carolina Geological Survey
P.O. Box 27687
Raleigh, NC 27611-7687
(919) 733-3833

North Dakota
John P. Bluemle
North Dakota Geological Survey
600 East Blvd.
Bismarck, ND 58505-0840
(701) 224-4109

Ohio
Thomas M. Berg
Ohio Dept. of Natural Resources
Division of Geological Survey
4383 Fountain Square Drive
Columbus, OH 43224-1362
(614) 265-6576

Oklahoma
Charles J. Mankin
Oklahoma Geological Survey
Room N-131, Energy Center
100 E. Boyd
Norman, OK 73019-0628
(405) 325-3031

Oregon
Donald A. Hull
Dept. of Geology & Mineral Indust.
Suite 965
800 NE Oregon St. #28
Portland, OR 97232-2162
(503) 731-4600

Pennsylvania
Donald M. Hoskins
Dept. of Environmental Resources
Bureau of Topographic & Geologic Survey
P.O. Box 2357
Harrisburg, PA 17105-2357
(717) 787-2169

Puerto Rico
Ramón M. Alonso
Puerto Rico Geological Survey Division
Box 5887
Puerta de Tierra Station
San Juan, P.R. 00906
(809) 722-2526

Rhode Island
J. Allan Cain
Department of Geology
University of Rhode Island
315 Green Hall
Kingston, RI 02881
(401) 792-2265

South Carolina
Alan-Jon W. Zupan (Acting)
South Carolina Geological Survey
5 Geology Road
Columbia, SC 29210-9998
(803) 737-9440

South Dakota
C.M. Christensen (Acting)
South Dakota Geological Survey
Science Center
University of South Dakota
Vermillion, SD 57069-2390
(605) 677-5227

Tennessee
Edward T. Luther
Tennessee Division of Geology
13th Floor, L & C Tower
401 Church Street
Nashville, TN 37243-0445
(615) 532-1500

Texas
William L. Fisher
Texas Bureau of Economic Geology
University of Texas
University Station, Box X
Austin, TX 78713-7508
(512) 471-7721

Utah
M. Lee Allison
Utah Geological & Mineral Survey
2363 S. Foothill Dr.
Salt Lake City, UT 84109-1491
(801) 467-7970

Vermont
Diane L. Conrad
Vermont Division of Geology and Mineral Resources
103 South Main St.
Waterbury, VT 05671
(802) 244-5164

Virginia
Stanley S. Johnson
Virginia Division of Mineral Resources
P.O. Box 3667
Charlottesville, VA 22903
(804) 293-5121

Washington
Raymond Lasmanis
Washington Division of Geology & Earth Resources
Department of Natural Resources
P.O. Box 47007
Olympia, Washington 98504-7007
(206) 902-1450

West Virginia	Larry D. Woodfork West Virginia Geological and Economic Survey Mont Chateau Research Center P.O. Box 879 Morgantown, WV 26507-0879 (304) 594-2331
Wisconsin	James Robertson Wisconsin Geological & Natural History Survey 3817 Mineral Point Road Madison, WI 53705-5100 (608) 263-7384
Wyoming	Gary B. Glass Geological Survey of Wyoming University of Wyoming Box 3008, University Station Laramie, WY 82071-3008 (307) 766-2286

EPA REGION 3 GEOLOGIC RADON POTENTIAL SUMMARY

by
Linda C.S. Gundersen, James K. Otton, and Sandra L. Szarzi
U.S. Geological Survey

EPA Region 3 includes the states of Delaware, Maryland, Pennsylvania, Virginia, and West Virginia.. For each state, geologic radon potential areas were delineated and ranked on the basis of geologic, soil, housing construction, and other factors. Areas in which the *average screening indoor radon level of all homes within the area* is estimated to be greater than 4 pCi/L were ranked high. Areas in which the average screening indoor radon level of all homes within the area is estimated to be between 2 and 4 pCi/L were ranked moderate/variable, and areas in which the average screening indoor radon level of all homes within the area is estimated to be less than 2 pCi/L were ranked low. Information on the data used and on the radon potential ranking scheme is given in the introduction to this volume. More detailed information on the geology and radon potential of each state in Region 3 is given in the individual state chapters. The individual chapters describing the geology and radon potential of the states in EPA Region 3, though much more detailed than this summary, still are generalized assessments and there is no substitute for having a home tested. Within any radon potential area homes with indoor radon levels both above and below the predicted average will likely be found.

Figure 1 shows a generalized map of the major physiographic/geologic provinces in EPA Region 3. The summary of radon potential in Region 3 that follows refers to these provinces. Figure 2 shows average screening indoor radon levels by county. The data for Maryland, Pennsylvania, Virginia, and West Virginia are from the State/EPA Residential Radon Survey. Data for Delaware were compiled by the Delaware Department of Health and Social Services. Figure 3 shows the geologic radon potential areas in Region 3, combined and summarized from the individual state chapters in this booklet.

DELAWARE

Piedmont

The Piedmont in Delaware has been ranked moderate in geologic radon potential. Average measured indoor radon levels in the Piedmont vary from low (<2 pCi/L) to moderate (2-4 pCi/L). Individual readings within the Piedmont can be locally very high (> 20 pCi/L). This is not unexpected when a regional-scale look at the Atlantic coastal states shows that the Piedmont is consistently an area of moderate to high radon potential. Much of the western Piedmont in Delaware is underlain by the Wissahickon Formation, which consists predominantly of schist. This formation has moderate to locally high geologic radon potential. Equivalent schists in the Piedmont of Maryland can have uranium concentrations of 3–5 ppm, especially where faulted. The Wilmington Complex and James Run Formation, in the central and eastern portions of the Delaware Piedmont, are variable in radon potential. In these units, the felsic gneiss and schist may contribute to elevated radon levels, whereas mafic rocks such as amphibolite and gabbro, and relatively quartz-poor granitic rocks such as charnockite and diorite are probably lower in radon potential. The average indoor radon is distinctly lower in parts of the Wilmington Complex than in surrounding areas, particularly in areas underlain by the Bringhurst Gabbro and the Arden pluton. The permeability of soils in the Piedmont is variable and dependent on the composition of the rocks from which the soils are derived. Most soils are moderately permeable, with local areas of slow to

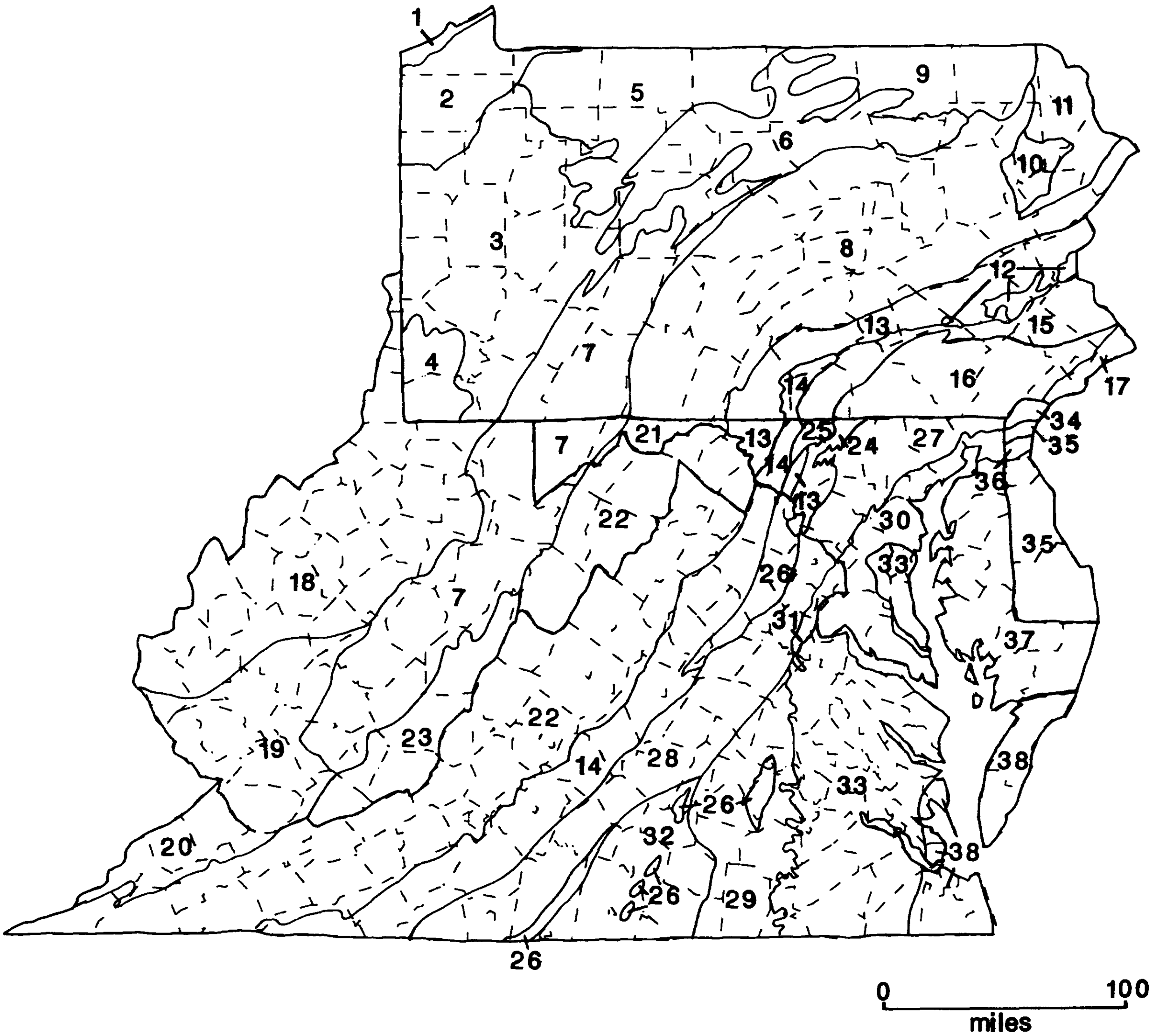

Figure 1. Geologic radon potential areas of EPA Region 3. 1–Central Lowland; 2–Glaciated Pittsburgh Plateau; 3–Pennsylvanian rocks of the Pittsburgh Low Plateau; 4–Permian rocks of the Pittsburgh Low Plateau; 5–High Plateau Section; 6–Mountainous High Plateau; 7–Allegheny Plateau and Mountains; 8–Appalachian Mountains; 9–Glaciated Low Plateau, Western Portion; 10–Glaciated Pocono Plateau ; 11–Glaciated Low Plateau, Eastern Portion; 12–Reading Prong; 13–Great Valley/Frederick Valley carbonates and clastics; 14–Blue Ridge Province; 15–Gettysburg-Newark Lowland Section (Newark basin) 16, 34–Piedmont; 17–Atlantic Coastal Plain; 18–Central Allegheny Plateau; 19–Cumberland Plateau and Mountains; 20–Appalachian Plateau; 21–Silurian and Devonian rocks in Valley and Ridge; 22, 23–Valley and Ridge (Appalachian Mountains); 24–Western Piedmont Phyllite; 25–Culpeper, Gettysburg, and other Mesozoic basins; 26–Mesozoic basins; 27–Eastern Piedmont, schist and gneiss; 28–Inner Piedmont; 29–Goochland Terrane; 30, 31–Coastal Plain (Cretaceous, Quaternary, minor Tertiary sediments); 32–Carolina terrane; 33–Coastal Plain (Tertiary sediments); 35, 37, 38–Coastal Plain (quartz-rich Quaternary sediments); 36–Glauconitic Coastal Plain sediments.

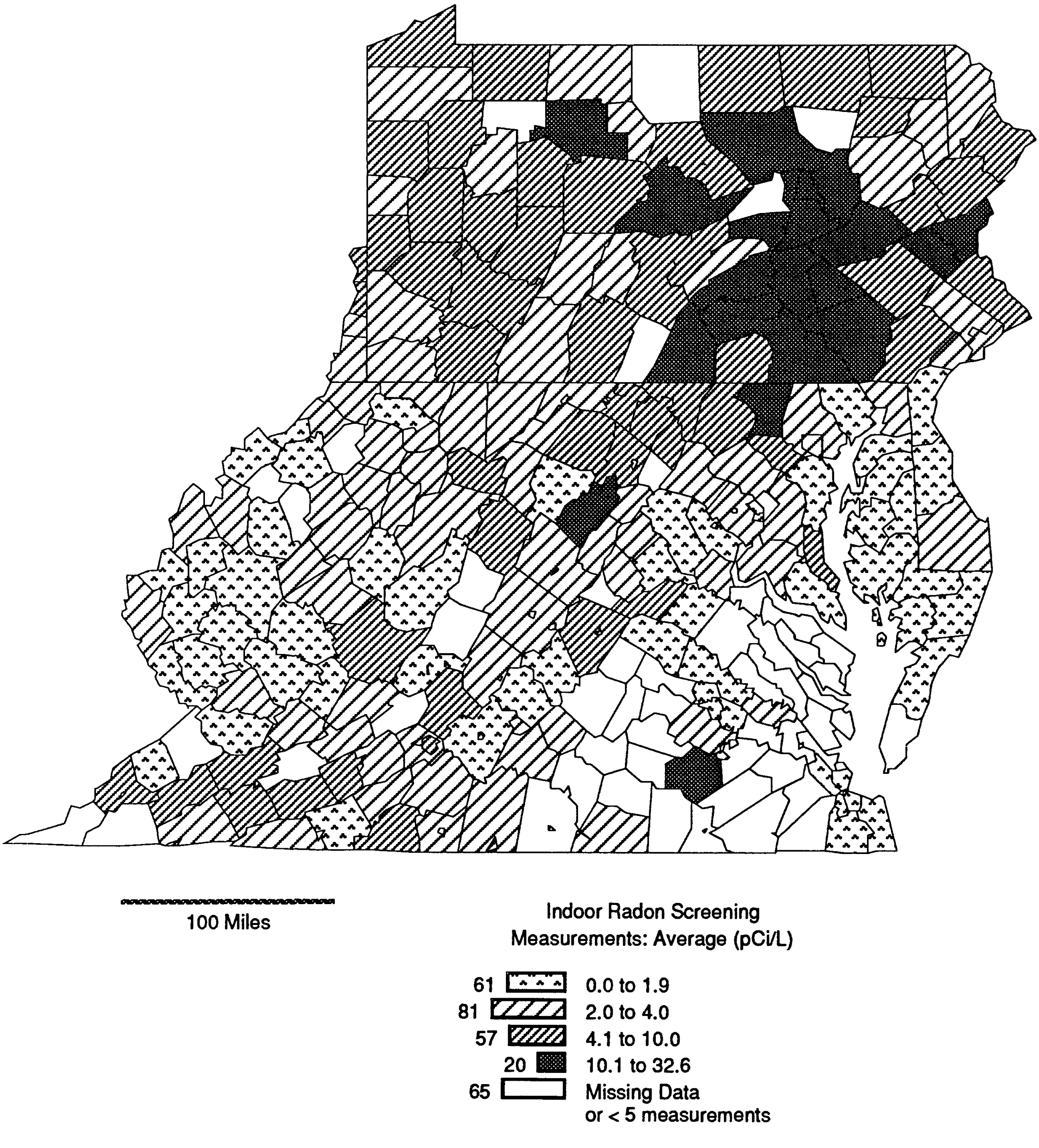

Figure 2. Screening indoor radon averages for counties with 5 or more measurements in EPA Region 3. Data for Maryland, Pennsylvania, Virginia, and West Virginia are from the State/EPA Residential Radon Survey. Data for Delaware were compiled by the Delaware Department of Health and Social Services. Histograms in map legend show the number of counties in each category.

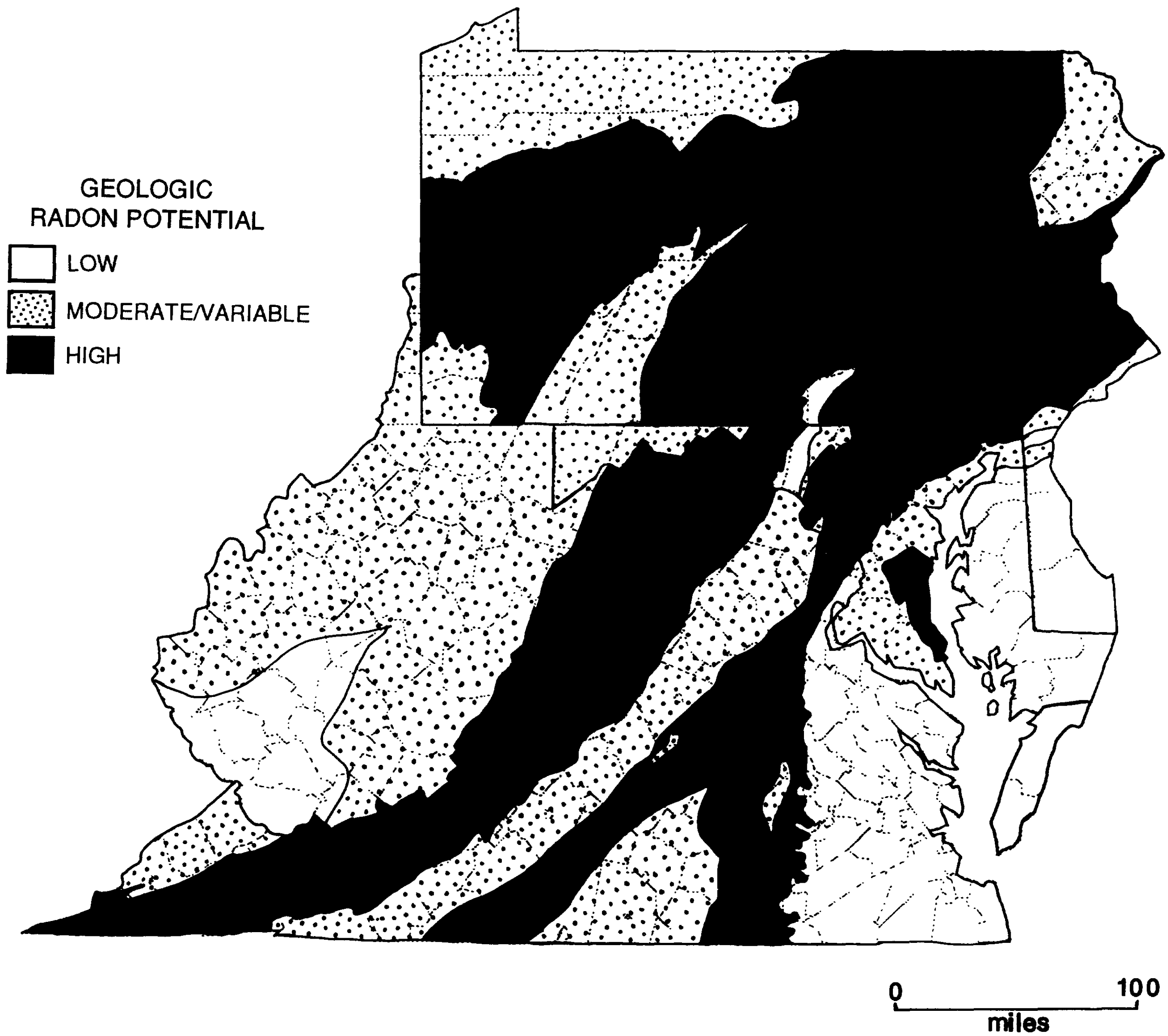

Figure 3. Geologic radon potential of EPA Region 3. For more detail, refer to individual state radon potential chapters.

rapid permeability. Limited aereal radioactivity data for the Delaware Piedmont indicates that equivalent uranium is generally moderate (1.5-2.5 ppm).

Coastal Plain

Studies of radon and uranium in Coastal Plain sediments in New Jersey and Maryland suggest that glauconitic marine sediments equivalent to those in the northern portion of the Delaware Coastal Plain can cause elevated levels of indoor radon. Central New Castle County is underlain by glauconitic marine sediments of Cretaceous and Tertiary age that have moderate to locally high radon potential. Aerial radiometric data indicate that moderate concentrations of uranium occur in rocks and soils associated with the Piedmont and parts of the Coastal Plain of northern Delaware. Chemical analyses of Cretaceous and Tertiary glauconitic marine sediments and fluvial sediments of the Columbia Formation performed by the Delaware geological survey indicate variable but generally moderate concentrations of uranium, averaging 1.89 ppm or greater. The permeability of soils in these areas is variable but generally moderate to high, allowing radon gas to move readily through the soil. Data for New Castle County from the State indoor radon survey shows that areas underlain by the Cretaceous fluvial sediments (not glauconitic) have lower average indoor radon levels than the glauconitic parts of the upper Cretaceous and lower Tertiary sequence to the south. Kent County and all of Sussex County are underlain by quartz-dominated sands, silts, gravels, and clays with low radon potential. These sediments are low in radioactivity and generally have a low percentage of homes with indoor radon levels greater than 4 pCi/L.

MARYLAND

Coastal Plain

The Western Shore of Maryland has been ranked moderate to locally high in radon potential and the Eastern Shore has been ranked low in radon potential. The Coastal Plain Province is underlain by relatively unconsolidated fluvial and marine sediments that are variably phosphatic and glauconitic on the Western Shore, and dominated by quartz in the Eastern Shore. Radioactivity in the Coastal Plain is moderate over parts of the Western Shore sediments, particularly in the Upper Cretaceous and Tertiary sediments of Prince George's, Anne Arundel, and northern Calvert counties. Moderate radioactivity also appears to be associated with the Cretaceous and Tertiary sediments of the Eastern Shore where these sediments are exposed in major drainages in Kent, Queen Anne's, and Talbot counties. Soil-gas radon studies in Prince George's County indicate that soils formed from the locally phosphatic, carbonaceous, or glauconitic sediments of the Calvert, Aquia, and Nanjemoy Formations can produce significantly high radon (average soil radon > 1500 pCi/L). The Cretaceous Potomac Group had more moderate levels of soil radon, averaging 800-900 pCi/L, and the Tertiary-Cretaceous Brightseat Formation and Monmouth Group had average soil radon of 1300 pCi/L. Soil permeability on the Western Shore varies from low to moderate with some high permeability in sandier soils. Well-developed clayey B horizons with low permeability are common. Indoor radon levels measured in the State/EPA Residential Radon Survey are variable among the counties of the Western Shore but are generally low to moderate. Moderate to high average indoor radon is found in most of the Western Shore counties.

For this assessment we have ranked part of the Western Shore as high in radon potential, including Calvert County, southern Anne Arundel County, and eastern Prince George's County. This area has the highest radioactivity, high indoor radon, and significant exposure of Tertiary rock units. The part of the Western Shore ranked moderate consists of Quaternary sediments with low radon potential, Cretaceous sediments with moderate radon potential, and lesser amounts of Tertiary sediments with high radon potential. The Quaternary sediments of the Eastern Shore have low radioactivity associated with them and are generally quartzose and thus low in uranium. Heavy-mineral concentrations within these sediments may be very local sources of uranium. Indoor radon appears to be generally low on the Eastern Shore with only a few measurements over 4 pCi/L reported.

Piedmont

Gneisses and schists in the eastern Piedmont, phyllites in the western Piedmont, and Paleozoic metasedimentary rocks of the Frederick Valley are ranked high in radon potential. Sedimentary and igneous rocks of the Mesozoic basins have been ranked moderate in radon potential. Radioactivity in the Piedmont is generally moderate to high. Indoor radon is moderate to high in the eastern Piedmont and nearly uniformly high in the western Piedmont. Permeability is low to moderate in soils developed on the mica schists and gneisses of the eastern Piedmont, Paleozoic sedimentary rocks of the Frederick Valley, and igneous and sedimentary rocks of the Mesozoic Basins. Permeability is moderate to high in the soils developed on the phyllites of the western Piedmont. The Maryland Geological Survey has compared the geology of Maryland with the Maryland indoor radon data. They report that most of the Piedmont rocks, with the exception of ultramafic rocks, can contribute to indoor radon readings exceeding 4 pCi/L. Their data indicate that the phyllites of the western Piedmont have much higher radon potential than the schists in the east. Ninety-five percent of the homes built on phyllites of the Gillis Formation had indoor radon measurements greater than 4 pCi/L, and 47 percent of the measurements were greater than 20 pCi/L. In comparison, 80 percent of the homes built on the schists and gneiss of the Loch Raven and Oella Formations had indoor radon readings greater than 4 pCi/L, but only 9 percent were greater than 20 pCi/L.

Studies of the phyllites in Frederick County show high average soil-gas radon (>1000 pCi/L) when compared to other rock types in the county. Limestone and shale soils of the Frederick Valley and some of the Triassic sedimentary rocks may be significant sources of radon (500-2000 pCi/L in soil gas). Because of the highly variable nature of the Triassic sediments and the amount of area that the rocks cover with respect to the county boundaries, it is difficult to say with confidence whether the high indoor radon in Montgomery, Frederick, and Carroll counties is partly attributable to the Triassic sediments. In Montgomery County, high uranium concentrations in fluvial crossbeds of the upper Manassas Sandstone containing gray carbonaceous clay intraclasts and drapes have been documented. Similar lithologic associations are common in the upper New Oxford Formation. Black shales and gray sandstones of the Heidlersburg Member are similar to uranium-bearing strata in the Culpeper basin in Virginia and may be a source of radon. Black shales in the overlying Gettysburg Formation may also be locally uranium rich. The lower New Oxford Formation, the lower Manassas Sandstone, the lower Gettysburg Formation, and the Balls Bluff Siltstone in Maryland are not likely to have concentrations of uranium except where altered by diabase intrusives and/or faulted. The diabase bodies are low in radon potential.

Appalachian Mountains

The Appalachian Province is divided into the Blue Ridge, Great Valley, Valley and Ridge, and Allegheny Plateau. Each of these areas is underlain by a distinct suite of rocks with a particular geologic radon potential. The Blue Ridge is ranked low in radon potential but may be locally moderate to high. The Catoctin volcanic rocks that underlie a significant portion of the Blue Ridge have low radioactivity, yield low soil radon and have low soil permeability. The quartzite and conglomerates overlying the Catoctin also have low radioactivity and low soil-gas radon. Further, the Pennsylvania Topographic and Geologic Survey calculated the median uranium content of 80 samples of Catoctin metabasalt and metadiabase to be less than 0.5 ppm. The Harpers Formation phyllite bordering the Catoctin volcanic rocks yields high soil-gas radon (>1000 pCi/L), has greater surface radioactivity than the surrounding rocks and is a potential source of radon. The Precambrian gneiss that crops out in the Middletown Valley of the southern Blue Ridge appears to have moderate radioactivity associated with it and yielded some high radon in soil gas. It is difficult, given the constraints of the indoor radon data, to associate the high average indoor radon in the part of Frederick County underlain by parts of this province with the actual rocks. The Blue Ridge is provisionally ranked low in geologic radon potential, but this cannot be verified with the presently existing indoor radon data.

Carbonates and black shales in the Great Valley in Maryland have been ranked high in radon potential. Radioactivity is moderate to high over the Great Valley in Washington County. Washington County has more than 100 indoor radon measurements, has an average indoor radon concentration of 8.1 pCi/L in the State/EPA Survey, with over half of the readings greater than 4 pCi/L. To the north in Pennsylvania, carbonate rocks of the Great Valley and Appalachian Mountain section have been the focus of several studies and the carbonate rocks in these areas produce soils with high uranium and radium contents that generate high radon concentrations. In general, indoor radon in these areas is higher than 4 pCi/L. Studies in the carbonates of the Great Valley in West Virginia suggest that the deepest, most mature soils have the highest radium and radon concentrations and generate moderate to high indoor radon. High radon in soils and high indoor radon in homes over the black shales of the Martinsburg Formation of the Great Valley were also measured in West Virginia.

The Silurian and Devonian rocks of the Valley and Ridge have been ranked moderate to locally high in geologic radon potential. Indoor radon measurements are generally moderate to high in Allegany County. Soil permeability is variable but is generally moderate. Radioactivity in this part of the Valley and Ridge is moderate to locally high. The Tonoloway, Keyser, and Wills Creek Formations, and Clinton and Hamilton Groups have high equivalent uranium associated with them and the shales, limestone soils, and hematitic sands are possible sources of the high readings over these units.

The Devonian through Permian rocks of the Allegheny Plateau are ranked moderate in geologic radon potential. Indoor radon measurements are generally moderate to high. Radioactivity in the Allegheny Plateau is low to moderate with locally high equivalent uranium associated with the Pocono Group and Mauch Chunk Formation. Soil permeability is variable but generally moderate.

PENNSYLVANIA

New England Province

The New England Province is ranked high in geologic radon potential. A number of studies on the correlation of indoor radon with geology in Pennsylvania have been done. The Reading Prong area in the New England Province is the most notable example because of the national publicity surrounding a particularly severe case of indoor radon. These studies found that shear zones within the Reading Prong rocks enhanced the radon potential of the rocks and created local occurrences of very high uranium and indoor radon. Several of the rock types in the Reading Prong were found to be highly uraniferous in general and they are the source for high radon levels throughout much of the province.

Piedmont

The Piedmont is underlain by metamorphic, igneous, and sedimentary rocks of Precambrian to Mesozoic age that have generally moderate to high radon potential. Rock types in the metamorphic crystalline portion of the Piedmont that have naturally elevated uranium concentrations include granitic gneiss, biotite schist, and gray phyllite. Rocks that are known sources of radon and have high indoor radon associated with them include phyllites and schists, such as the Wissahickon Formation and Peters Creek Schist, shear zones in these rocks, and the faults surrounding mafic bodies within these rocks.

Studies in the Newark Basin of New Jersey indicate that the black shales of the Lockatong and Passaic Formations and fluvial sandstones of the Stockton Formation are a significant source of radon in indoor air and in water. Where these rock units occur in Pennsylvania, they may be the source of high indoor radon as well. Black shales of the Heidlersburg Member and fluvial sandstones of the New Oxford Formation may also be sources of locally moderate to high indoor radon in the Gettysburg Basin. Diabase sheets and dikes within the basins have low eU. The Mesozoic basins as a whole, however, are variable in their geologic radon potential. The Narrow Neck area is distinctly low in radioactivity and Montgomery County, which is underlain almost entirely by Mesozoic basin rocks, has an indoor radon average less than 4 pCi/L. Other counties underlain partly by the Mesozoic basin rocks, however, have average indoor radon greater than 4 pCi/L. The Newark basin is high in radon potential whereas the Gettysburg basin is low to locally moderate. For the purposes of this report the basins have been subdivided along the Lancaster-Berks county boundary. The Newark basin comprises the Mesozoic rocks east of this county line.

Blue Ridge

The Blue Ridge Province is underlain by metasedimentary and metavolcanic rocks and is generally an area of low radon potential. A distinct low area of radioactivity is associated with the province on the map, although phyllite of the Harpers Formation may be uraniferous. Soils generally have variable permeability. The metavolcanic rocks in this province have very low uranium concentrations. It is difficult, given the constraints of the indoor radon data, to associate the high average indoor radon in counties underlain by parts of this province with specific rock units. When the indoor radon data are examined at the zip code level, it appears that most of the high indoor radon is attributable to the Valley and Ridge soils and rocks. The conclusion is that the Blue Ridge is provisionally ranked low in geologic radon potential although this cannot be verified with the presently available indoor radon data.

Ridge and Valley and Appalachian Plateaus

Carbonate rocks of the Great Valley and Appalachian Mountain section have been the focus of several studies and the carbonates in these areas produce soils with high uranium and radium contents and soil radon concentrations. In general, indoor radon in these areas is higher than 4 pCi/L and the geologic radon potential of the area is high, especially in the Great Valley where indoor radon is distinctly higher on the average than in surrounding areas. Soils developed on limestone and dolomite rock at the surface in the Great Valley, Appalachian Mountains, and Piedmont are probably sources of high indoor radon.

The clastic rocks of the Ridge and Valley and Appalachian Plateaus province, particularly the Ordovician through Pennsylvanian-age black to gray shales and fluvial sandstones, have been extensively cited in the literature for their uranium content as well as their general uranium potential. It appears from the uranium and radioactivity data and comparison with the indoor radon data that the black shales of the Ordovician Martinsburg Formation, the lower Devonian black shales, Pennsylvanian black shales of the Allegheny Group, Conemaugh Group, and Monogahela Group, and the fluvial sandstones of the Devonian Catskill and Mississippian Mauch Chunk Formation may be the source of most moderate to high indoor radon levels in the Appalachian Plateau and parts of the Appalachian Mountains section.

Only a few areas in these provinces appear to have geologically low to moderate radon potential. The Greene Formation in Greene County appears to correlate with distinctly low radioactivity. The indoor radon for Greene County averages less than 4 pCi/L for the few measurements available in the State/EPA survey.

Somerset and Cambria Counties in the Allegheny Mountain section have indoor radon averages less than 4 pCi/L, and it appears that low radioactivity and slow permeability of soils may be factors in the moderate geologic radon potential of this area. These two counties and most of the Allegheny Mountain section are underlain by Pennsylvanian-age sedimentary rocks. The radioactivity map shows low to moderate radioactivity for the Pennsylvanian-age rocks in the Allegheny Mountain section and much higher radioactivity in the Pittsburgh Low Plateau section. Most of the reported uranium occurrences in these rocks appear to be restricted to the north and west of the Allegheny Mountain section. Approximately half of the soils developed on these sediments have slow permeability and seasonally high water tables.

Coastal Plain

Philadelphia and Delaware Counties, in the southeastern corner of Pennsylvania, have average indoor radon less than 4 pCi/L and have low radioactivity. Part of Delaware County and most of Philadelphia County are underlain by Coastal Plain sediments with low uranium concentrations. Soils developed on these sediments are variable, but a significant portion are clayey with slow permeability.

Glaciated Areas of Pennsylvania

Radiometric lows and relatively lower indoor radon levels appear to be associated with the glaciated areas of the State, particularly the eastern portion of the Glaciated Low Plateau and Pocono Plateau in Wayne, Pike, Monroe, and Lackawanna Counties. Glacial deposits are problematic to assess for radon. In some areas of the glaciated portion of the United States, glacial deposits enhance radon potential, especially where the deposits have high permeability and are derived from uraniferous source rocks. In other portions of the glaciated United States, glacial deposits blanket more uraniferous rock or have low permeability and corresponding low radon potential. The northeastern corner of Pennsylvania is covered by the Olean Till, made up of 80-90 percent sandstone and siltstone clasts with minor shale, conglomerate, limestone, and crystalline clasts. A large proportion of the soils developed on this till have seasonally high water tables and poor drainage, but some parts of the till soils are stony and have good drainage and high permeability. Low to moderate indoor radon levels and radioactivity in this area may be due to the seasonally saturated ground and to the tills being made up predominantly of sandstones and siltstones with low uranium contents. A similar situation exists in the northwestern part of the State, which is covered by a wide variety of tills, predominantly the Kent Till, which contains mostly sandstone, siltstone, and shale clasts. Many of the soils in this area also have low permeabilities and seasonally high water tables. Where the tills are thinner, the western portion of the Glaciated Low Plateau has higher indoor radon and high radioactivity.

VIRGINIA

Coastal Plain

The Coastal Plain of Virginia is ranked low in geologic radon potential. Indoor radon is generally low; however, moderate to high indoor radon can occur locally and may be associated with phosphatic, glauconitic, or heavy mineral-bearing sediments. Equivalent uranium over the Tertiary units of the Coastal Plain is generally moderate. Soils developed on the Cretaceous and Tertiary units are slowly to moderately permeable. Studies of uranium and radon in soils indicate that the Yorktown Formation could be a source for elevated levels of indoor radon. The Quaternary sediments generally have low eU associated with them. Heavy mineral deposits of monazite found locally within the Quaternary sediments of the Coastal Plain may have the potential to generate locally moderate to high indoor radon.

Piedmont

The Goochland terrane and Inner Piedmont have been ranked high in radon potential. Rocks of the Goochland terrane and Inner Piedmont have numerous well-documented uranium and radon occurrences associated with granites; pegmatites; granitic gneiss; monazite-bearing metasedimentary schist and gneiss; graphitic and carbonaceous slate, phyllite, and schist; and shear zones. Indoor radon is generally moderate but significant very high radon levels occur in several areas. Equivalent uranium over the Goochland terrane and Inner Piedmont is predominantly high to moderate with areas of high eU more numerous in the southern part. Permeability of soils developed over the granitic igneous and metamorphic rocks of the Piedmont is generally moderate. Within the Goochland terrane and Inner Piedmont, local areas of low to moderate radon potential will probably be found over mafic rocks (such as gabbro and amphibolite), quartzite, and some quartzitic schists. Mafic rocks have generally low uranium concentrations and slow to moderate permeability in the soils they form.

The Carolina terrane is variable in radon potential but is generally moderate. Metavolcanic rocks have low eU but the granites and granitic gneisses have moderate to locally high eU. Soils developed over the volcanic rocks are slowly to moderately permeable. Granite and gneiss soils have moderate permeability.

The Mesozoic basins have moderate to locally high radon potential. It is not possible to make any general associations between county indoor radon averages and the Mesozoic basins as a whole because of the limited extent of many the basins. However, sandstones and siltstones of the Culpeper basin, which have been lightly metamorphosed and altered by diabase intrusion, are mineralized with uranium and cause documented moderate to high indoor radon levels in northern Virginia. Lacustrine black shales and some of the coarse-grained gray sandstones also have significant uranium mineralization, often associated with green clay clasts and copper. Equivalent uranium over the Mesozoic basins varies among the basins. The Danville basin has very high eU associated with it whereas the other basins have generally moderate eU. This radioactivity may be related to extensive uranium mineralization along the Chatham fault on the west side of the Danville basin. Localized high eU also occurs over the western border fault of the Culpeper basin. Soils are generally slowly to moderately permeable over the sedimentary and intrusive rocks of the basins.

Valley and Ridge

The Valley and Ridge has been ranked high in geologic radon potential but some areas have locally low to moderate radon potential. The Valley and Ridge is underlain by Cambrian dolomite, limestone, shale, and sandstone; Silurian-Ordovician limestone, dolomite, shale, and sandstone; and Mississippian-Devonian sandstone, shale, limestone, gypsum, and coal. Soils derived from carbonate rocks and black shales, and black shale bedrock may be sources of the moderate to high levels of indoor radon in this province. Equivalent uranium over the Valley and Ridge is generally low to moderate with isolated areas of high radioactivity. Soils are moderately to highly permeable. Studies of radon in soil gas and indoor radon over the carbonates and shales of the Great Valley in West Virginia and Pennsylvania indicate that the rocks and soils of this province constitute a significant source of indoor radon. Sandstones and red siltstones and shales are probably low to moderate in radon potential. Some local uranium accumulations are contained in these rocks.

Appalachian Plateaus

The Appalachian Plateaus Province has been ranked moderate in geologic radon potential. The plateaus are underlain by Pennsylvanian-age sandstone, shale, and coal. Black shales, especially those associated with coal seams, are generally elevated in uranium and may be the source for moderate to high radon levels. The coals themselves may also be locally elevated in uranium. The sandstones are generally low to moderate in radon potential but have higher soil permeability than the black shales. Equivalent uranium of the province is low to moderate and indoor radon is variable from low to high, but indoor radon data are limited in number.

WEST VIRGINIA

Allegheny Plateau

The Central Allegheny Plateau Province has moderate geologic radon potential overall, due to persistently moderate eU values and the occurrence of steep, well-drained soils. However, Brooke and Hancock counties, in the northernmost part of this province, have average indoor radon levels exceeding 4 pCi/L. This appears to be related to underlying Conemaugh and Monongahela Group sedimentary rocks which have elevated eU values in this area and in adjacent areas of western Pennsylvania.

The Cumberland Plateau and Mountains Province has low radon potential. The eU values for the province are low except in areas of heavy coal mining, where exposed shale-rich mine waste tends to increase values. Indoor radon levels average less than 2 pCi/L in most counties.

The Eastern Allegheny Plateau and Mountains Province has moderate radon potential overall. Locally high indoor radon levels are likely in homes on dark gray shales of Devonian age and colluvium derived from them in Randolph County. The southern part of this province has somewhat lower eU values and indoor radon averages.

Ridge and Valley Province

The southern part of the Appalachian Ridge and Valley Province in West Virginia has moderate radon potential overall. The eU signature for this province is elevated (> 2.5 ppm eU). Locally high radon potential occurs in areas of deep residual soils developed on limestones of the Mississippian Greenbrier Group, especially in central Greenbrier County, where eU values are high. Elevated levels of radon may be expected in soils developed on dark shales in this province or in colluvium derived from them.

The northern part of the Appalachian Ridge and Valley Province in West Virginia has high geologic radon potential. The soils in this area have an elevated eU signature. Soils developed on the Martinsburg Formation and on limestones and dolomites throughout the Province contain elevated levels of radon and a very high percentage of homes have indoor radon levels exceeding 4 pCi/L in this province. Karst topography and associated locally high permeability in soils increases the radon potential. Structures sited on uraniferous black shales may have very high indoor radon levels. Steep, well-drained soils developed on phyllites and quartzites of the Harpers Formation in Jefferson County also produce high average indoor radon levels.

PRELIMINARY GEOLOGIC RADON POTENTIAL ASSESSMENT OF DELAWARE

by
Linda C.S. Gundersen
U.S. Geological Survey

INTRODUCTION

The Office of Radiation Control in the Delaware Department of Health and Social Services assisted Delaware citizens in testing for indoor radon from 1985-1990 (Eichler and Wright, 1991). Of more than 7000 indoor radon measurements performed in the State, 10.5 percent of the homes tested had indoor radon levels exceeding the U.S. Environmental Protection Agency's 4 pCi/L guideline. Statewide radon levels ranged from 0.5 to 164 pCi/L and averaged 2 pCi/L. Ninety-eight percent of the testing was done by means of charcoal canister. The Delaware Geological Survey is also investigating the surface radioactivity and soil radon content of geologic units in the State (Woodruff and others, 1992).

Examination of the indoor radon data in the context of geology, soil permeability, and radioactivity suggest that some of the metamorphic and igneous rocks of the Piedmont and some sediments of the northern portion of the Atlantic Coastal Plain have moderate to locally high radon potential. Much of the Atlantic Coastal Plain in the central and southern portion of the State has low radon potential.

This is a generalized assessment of geologic radon potential of rocks, soils, and surficial deposits of Delaware. The scale of this assessment is such that it is inappropriate for use in identifying the radon potential of small areas such as neighborhoods, individual building sites, or housing tracts. Within any area of a given radon potential ranking there are likely to be areas with higher or lower radon levels than characterized for the area as a whole. Indoor radon concentrations, both high and low, can be quite localized, and there is no substitute for testing individual homes. For more information, the reader is urged to consult the Office of Radiation Control, Delaware Department of Health and Social Services, or the EPA regional office. More detailed information on state or local geology may be obtained from the state geological survey. Addresses and phone numbers for these agencies are listed in chapter 1 of this booklet.

PHYSIOGRAPHIC AND GEOGRAPHIC SETTING

Delaware lies within parts of two physiographic provinces (fig. 1). The Piedmont is underlain by igneous and metamorphic rocks with gently rolling, wooded and open uplands, averaging 250 feet in elevation, but with as much as 300 feet of local relief. The rest of Delaware is within the Atlantic Coastal Plain. The northern portion of the Atlantic Coastal Plain is characterized by gently rolling hills with minor relief, underlain by fluvial and marine sediments. The central, southern, and coastal portions of the Atlantic Coastal Plain consist of bottom land, pine woods, and marshes, which are also underlain by fluvial and marine sediments. The entire State is well drained, with a central divide postulated to be controlled by tectonic tilt of the Delmarva Peninsula (Spoljaric, 1980).

In 1990, the population of Delaware was 666,168 (U.S. Census Bureau, fig. 2). The majority of its population resides in the northernmost county of New Castle, where technological, marine, and heavy industries support the population centers of Wilmington, Newark, and New Castle. The two southern counties of Kent and Sussex are dominantly agricultural.

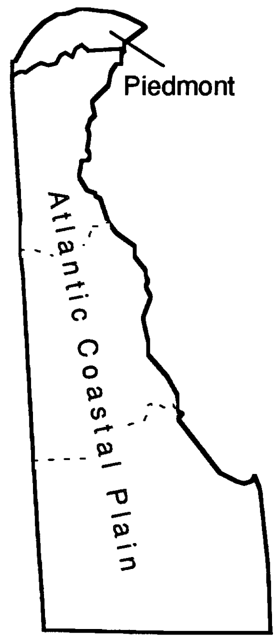

Figure 1. Physiographic areas of Delaware.

GEOLOGY AND SOILS

The following discussion of bedrock and surficial geology is condensed from Jordan (1962, 1964, 1974, 1983), Pickett and Spoljaric (1971), Woodruff (1985, 1986), Woodruff and Thompson (1972, 1975), Pickett and Benson (1977, 1983), Kraft and Carey (1980), Thompson (1980), Talley (1982, 1987), Andres (1986), Benson and Pickett (1986), Ramsey and Schenck (1990), and Wagner and others (1991). Discussion of soils is based on Richmond and others (1987) and the Soil Conservation Service county soil surveys (Mathews and Lavoie, 1970; Mathews and Ireland, 1971; and Ireland and Mathews, 1974). A generalized geologic map of Delaware is shown in figure 3, cross sections of the Coastal Plain are given in figure 4a and b, and a generalized surficial geologic map of Delaware is shown in figure 5.

The Piedmont

The Piedmont is underlain by a complex sequence of high-grade metamorphic and igneous rocks that have been folded and faulted. These crystalline rocks are generally weathered to a depth of 10 feet or more, and in some cases, depth of weathering may exceed 70 feet. Soils formed on these rocks are saprolitic and reflect the original composition of the rock. Because the crystalline rocks are so complex, the soils formed on them are also complex. The descriptions of soils presented here are generalized and do not reflect site-specific conditions that one would expect to observe in the field.

The oldest rocks in the Piedmont are Precambrian Grenville gneisses that occur along the Pennsylvania border in the core of the Mill Creek dome in the northwestern part of the Piedmont. They have been correlated with the Baltimore Gneiss and consist of quartz-feldspar gneisses, biotite schist, and minor amphibolite. Saprolite soils developed on the gneiss are sandy to silty loams and clayey, silty sands. Permeability in the sandy, silty loams ranges from moderate to moderately rapid. Deeply developed soils and soils from the micaceous schist tend to be more

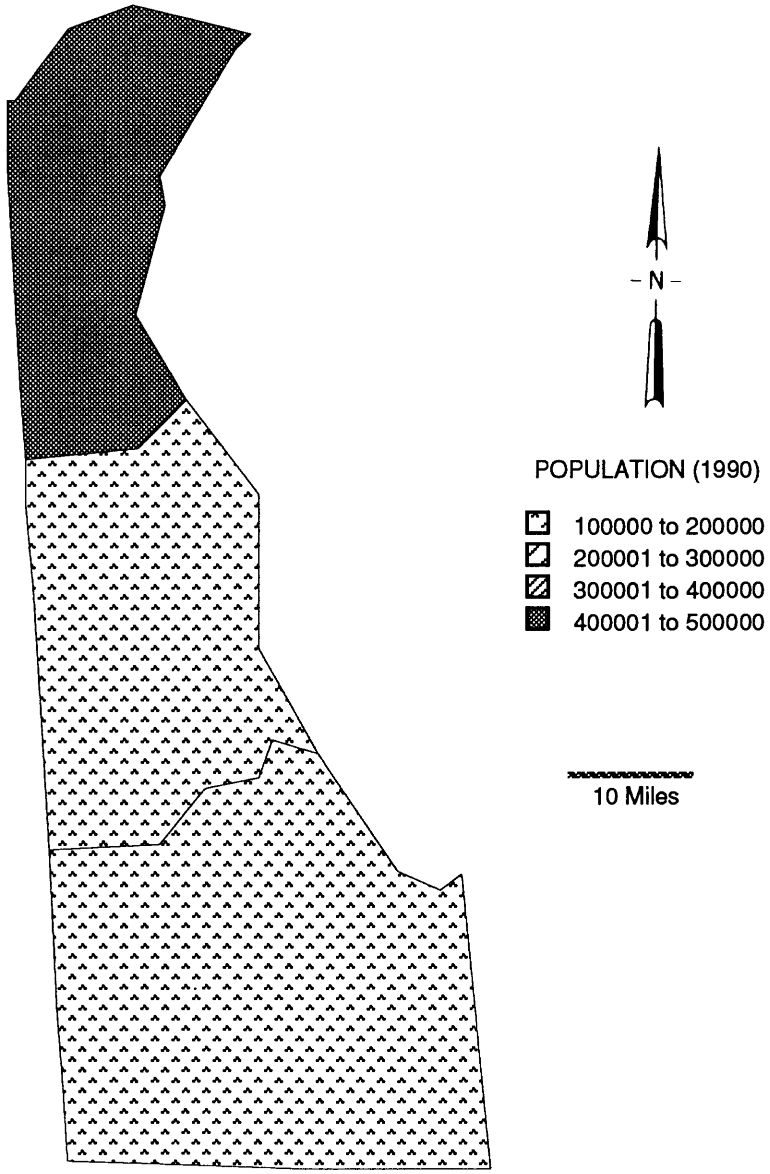

Figure 2. Population of counties in Delaware (1990 U.S. Census data).

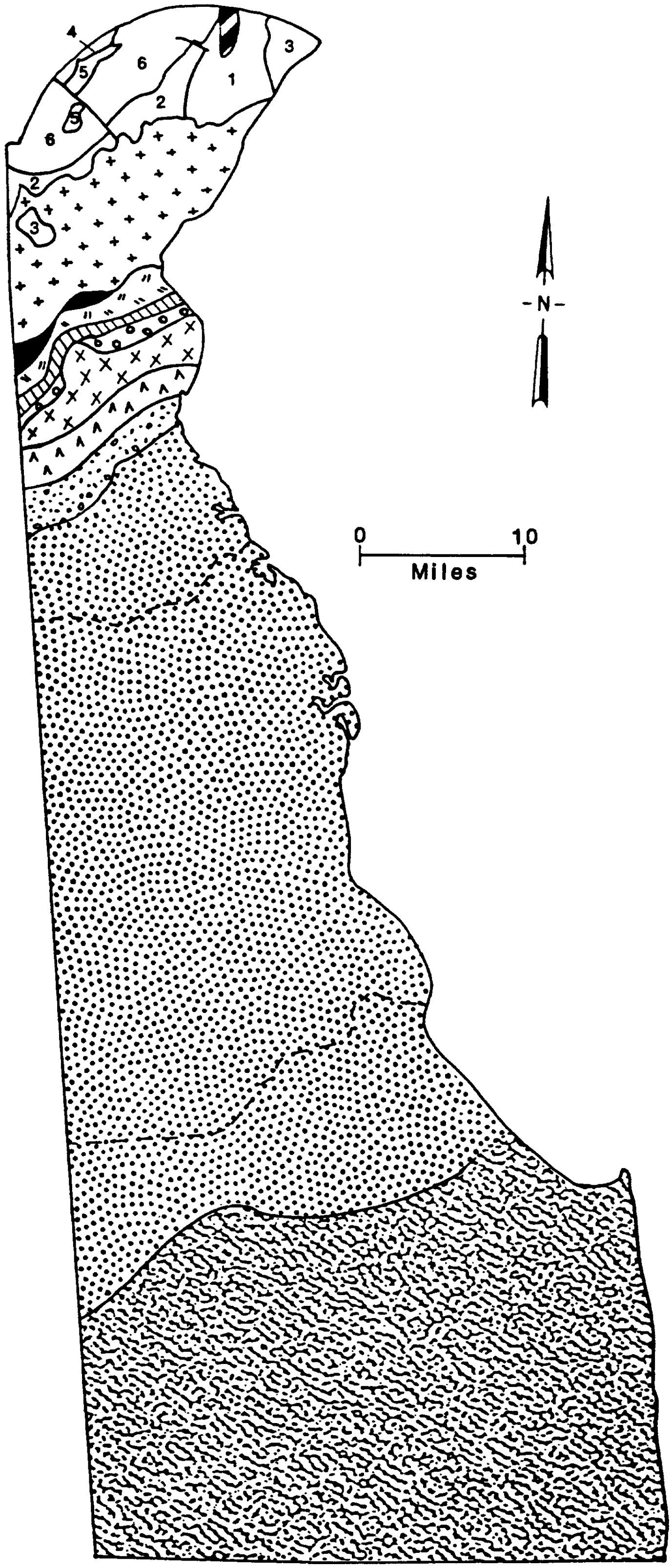

Figure 3. Generalized geologic map of Delaware showing rock units ranging in age from Precambrian to Tertiary (after Pickett, 1976). Quaternary units are shown on the surficial geologic map (fig. 5).

GENERALIZED GEOLOGIC MAP OF DELAWARE (PRECAMBRIAN-TERTIARY)
EXPLANATION

TERTIARY

PLIOCENE

Beaverdam Formation - Fairly well sorted medium sand, some gravel.

PLIOCENE?

Bryn Mawr Formation - Red and brown quartz sand with silt, clay and fine gravel (in Piedmont).

MIOCENE-PLIOCENE(?)

Chesapeake Group - Bluish gray silt with quartz sand and some shell beds.

PALEOCENE-EOCENE(?)

Vincentown Formation - Green, gray and reddish-brown fine to coarse, highly quartzose glauconitic sand with some silt.

CRETACEOUS-PALEOCENE

Hornerstown Formation - Green, gray and reddish-brown fine to medium, silty, highly glauconitic sand and sandy silt.

CRETACEOUS

Mount Laurel -Monmouth Formations - Gray, green and red-brown, glauconitic fine to medium, quartz sand with some silt.

Matawan Group

Marshalltown Formation - Dark greenish-gray, massive, very glauconitic silty, fine sand.

Englishtown Formation - Light gray and rust brown, well sorted micaceous sand with thin interbedded layers of dark gray silty sand; abundant fossil burrows.

Merchantville Formation - Dark gray to dark blue micaceous, glauconitic sandy silt and silty fine sand.

Magothy Formation - White and buff quartz sand with beds of gray and black clayey silt.

Potomac Formation - Variegated silts and clays with beds of quartz sand.

PRECAMBRIAN-PALEOZOIC

6 **Wissahickon Formation** - Gneiss, schist, amphibolite, and minor serpentine.

5 **Setters Formation & Cockeysville Marble of the Lower Glenarm Series** - Quartz - mica schist and dense white crystalline marble.

4 **Baltimore Gneiss** - Feldspathic biotite gneiss and minor schist.

3 **Anorthosite** - Andesine anorthosite and anorthositic gabbro.

2 **James Run Formation** - Amphibolite; hypersthene gneiss and minor pelitic gneiss.

1 **Wilmington Complex** - Hypersthene-bearing felsic gneiss, minor amphibolite, with gabbro, norite, and anorthosite plutons.

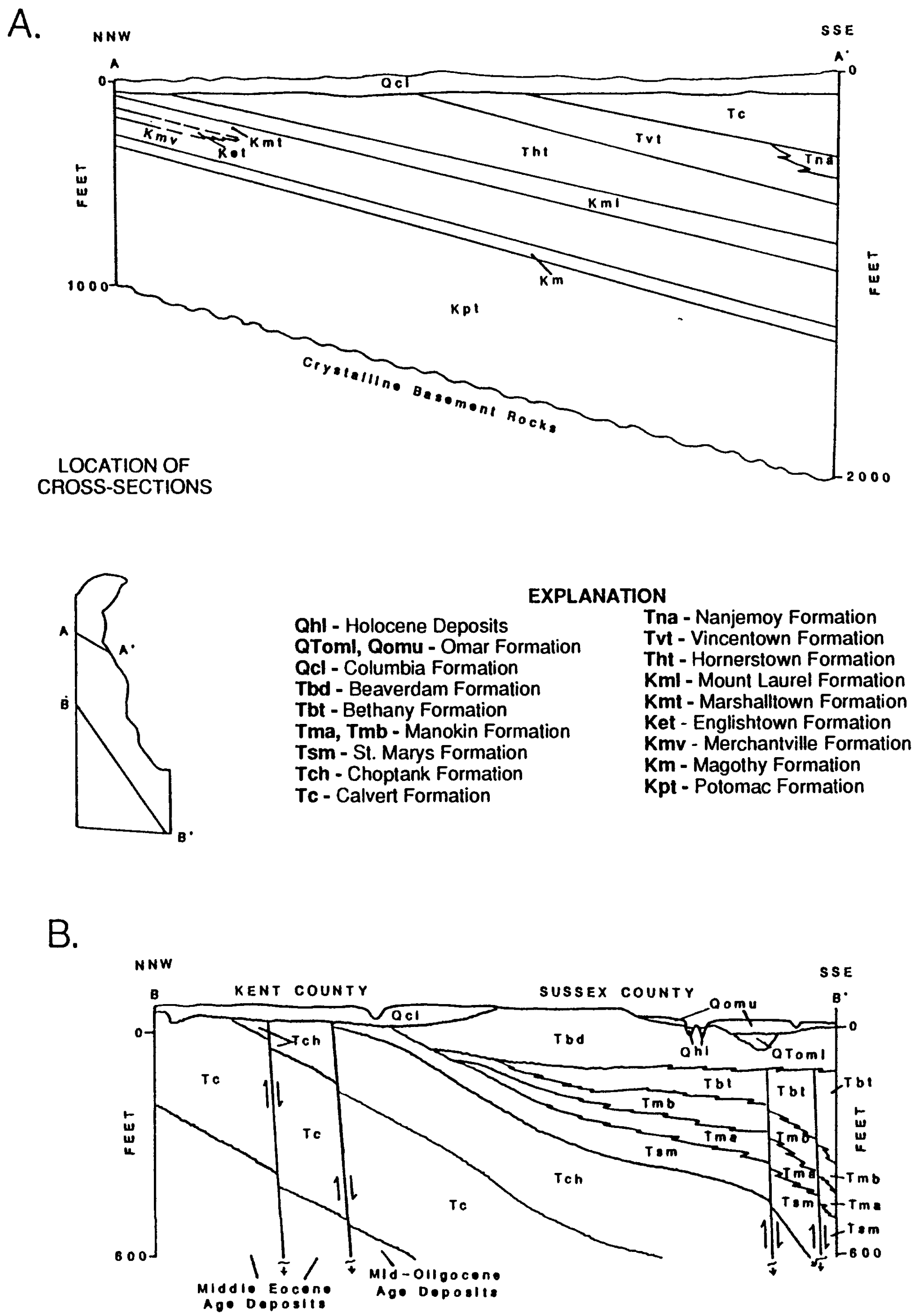

Figure 4. Diagrammatic geologic cross-sections of (A) the Middletown-Odessa area, New Castle County (after Pickett and Spoljaric, 1971), and (B) Kent and Sussex counties, southern Delaware (after Ramsey and Schenck, 1990).

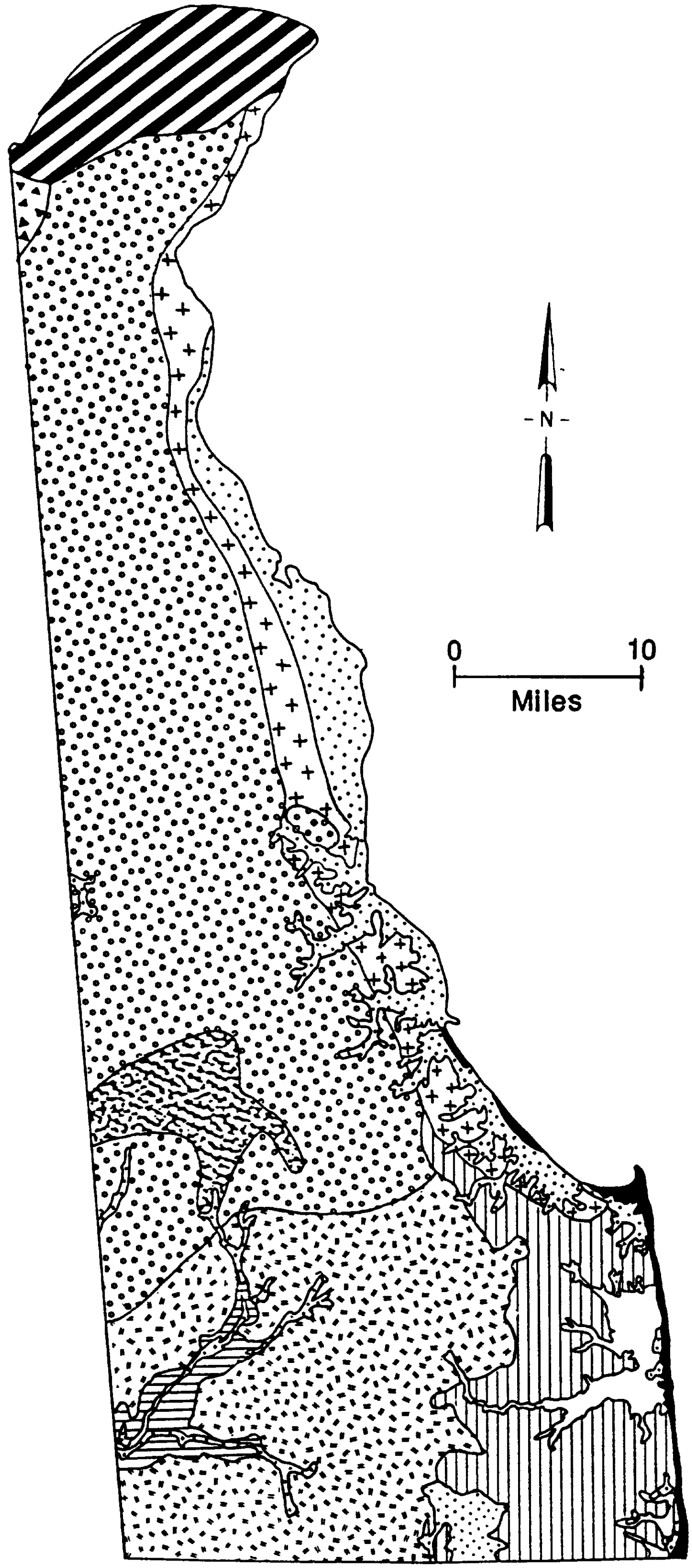

Figure 5. Generalized surficial geologic map of Delaware (after Richmond and others, 1987, and Ramsey and Schenck, 1990).

GENERALIZED SURFICIAL GEOLOGIC MAP OF DELAWARE
EXPLANATION
(After Richmond and others, 1987, and Ramsey and Schenck, 1990)

HOLOCENE

Beach, Barrier, and Spit Deposits - White to gray, fine to coarse sand with scattered gray silty clay beds. Well sorted, laminated, and crossbedded, mostly quartz, includes some organic matter and shells.

Swamp and Saline-Marsh Deposits - Interbedded dark-gray, black, or greenish-gray silty clay to clayey fine sand and carbonaceous clay; dark-brown to black organic debris, muck, and local peat, mixed with muck composed of fine sand, silt and kaolinitic clay. Commonly bioturbated; local marl in calcareous clay at depth.

PLEISTOCENE

Alluvial and Estuarine Sand and Silt - White to light reddish-brown medium to coarse sand, gravelly sand, gravel, silty clay, and organic-rich silty clay. Sand commonly crossbedded. Fossiliferous in places (Delaware Bay deposits).

Alluvial Gravelly Sand - Gray to brown, fine to medium sand, gravelly sand, clayey silt, and silty clay. Both sand and gravel are chiefly quartz. Deposit is poorly sorted, thin to medium bedded, and locally crossbedded. Capped in places by well-sorted fine sand associated with dunes.(Nanticoke deposits).

Beach and Marine Sand, Silt and Clay - White to tan to bluish gray silty fine sand, clayey silt, silty clay, and fine to coarse sand. Heterogeneous; lithologic changes occur over short distances laterally and vertically. Contains scattered shell beds (Omar Formation).

Sandy and Silty Decomposition Residuum - Tan to dark gray silty and clayey sand and sandy silt (Staytonville unit).

Sandy Decomposition Residuum - Orange-red, reddish-brown, tan, light gray, or white sandy loam that grades downward into medium to coarse feldspathic sand with minor gravel and silt; with reddish-brown or orange-brown iron oxide stains. Residuum is chiefly on broad upland surfaces (Columbia Formation).

QUATERNARY AND TERTIARY

Sandy Clay Saprolite and Alluvium - Red, yellowish-red, strong-brown , yellow, light-gray, or greenish-gray slightly clayey sand to sandy clay. Clays are mixed smectite and kaolinite in saprolite. Where source rocks are more felsic, clay is predominantly kaolinite. Sand is principally feldspar and quartz, with biotite, hornblende, and micaceous clay in more mafic varieties.

Micaceous Saprolite and Alluvium - Red, reddish-brown, strong-brown, yellowish-red, or gray, micaceous, clayey to slightly clayey sand to clayey sandy silt. Clay is kaolinite and lesser amounts of gibbsite. Mica mostly weathered to micaceous clay and (or) kaolinite near ground surface.

TERTIARY

Sand and Sandy Decomposition Residuum - Pale white, buff, or greenish-gray, medium sand with scattered beds of coarse sand, gravelly sand, and silty clay. Unit fines upwards; contains rare glauconite. Residuum is chiefly on broad upland surfaces (Beaverdam Formation).

clayey and have slow to moderate permeability. Soils derived from amphibolite are clayey loams to clayey silts and silty, sandy clays that are slowly to moderately permeable.

The Baltimore Gneiss is unconformably overlain by the Setters Formation and Cockeysville Marble of the Lower Glenarm Series. The Setters Formation comprises thin lenses of quartzitic mica schist and is very limited in exposure. The Cockeysville Marble is a calcitic to locally dolomitic, coarse-grained marble that underlies the Hockessin-Yorklyn Valley and Pleasant Valley near Newark. Where soils are well developed, the marble weathers to form silty clays and clayey loams of slow permeability. Steeper slopes of the marble tend to have soils that are less deep and stony soils of moderate permeability that vary from sandy loam to silty clay.

Much of the western part of the Piedmont is underlain by the Wissahickon Formation, consisting of quartzitic to micaceous, felsic schists and gneisses, amphibolite, and small areas of serpentinite and granitic pegmatite. Soils developed on the quartzitic schist are sandy to silty loams and clayey, silty sands with moderate to moderately rapid permeability. Soils developed on the micaceous schist tend to be more clayey and have slow to moderate permeability. Soils derived from amphibolite and serpentinite are clayey loams to silty clays with slow permeability. Lying in an elongate belt between the Wissahickon Formation and the Wilmington Complex is the James Run (?) Formation (fig. 3). Interpretation and distribution of this rock type is the subject of debate. The James Run (?) Formation as shown on the map of Pickett (1976) in figure 3 is similar to the distribution of the James Run (?) Formation in Thompson (1980). On the geologic maps of Woodruff and Thompson (1972, 1975) these rocks are included in the Wilmington Complex. They are described in the western Piedmont as felsic and mafic gneiss with minor pelitic schist. The mafic and felsic gneisses may also contain hornblende and hypersthene. In the eastern Piedmont, they are described as hornblende-plagioclase gneiss interlayered with smaller amounts of pyroxene-bearing felsic gneiss, amphibolite, and quartz-feldspar gneiss (Woodruff and Thompson, 1975). Wagner and others (1991) show the James Run Formation only in the southwesternmost corner of the Piedmont in contact with a small body of granitic gneiss. They place most of the western felsic and mafic gneisses in the Wissahickon Formation and include the eastern hornblende- and pyroxene-bearing gneisses in the Wilmington Complex.

The Wilmington Complex underlies much of the eastern third of the Piedmont. It comprises hypersthene-bearing felsic gneiss, minor amphibolite, and small plutons. Two of the largest plutons are in the eastern and southeastern portions of the Wilmington Complex. The Arden Pluton has been described as anorthosite, noritic anorthosite, norite, and minor charnockite by Woodruff and Thompson (1975), and as a granodiorite-norite-charnockite by Wagner and others (1991). The other major pluton is the Bringhurst Gabbro, which underlies part of the city of Wilmington and consists of gabbro and norite. The felsic rocks of the Wilmington Complex form silty sands and sandy loams of moderate to moderately rapid permeability. The mafic rocks of the Wilmington Complex (gabbro, amphibolite) form silty clays and clayey loams with slow permeability.

The Coastal Plain

The Coastal Plain consists of relatively unconsolidated Cretaceous and Tertiary sediments that are unconformably overlain by Tertiary, Quaternary, and Holocene sediments (fig. 4). At the surface, the Cretaceous portion of the Coastal Plain consists of the fluvial and marine sediments of the Potomac and Magothy Formations, Matawan Group, and the Mount Laurel (Monmouth) Formation. Other units exist in the subsurface and are shown in figure 4. Only surface units are described in this section.

The Potomac Formation consists of fluvial channel sands with variegated, locally lignitic, silt and clay deposited in an alluvial plain. Iron oxide concretions and cements are common. The Magothy Formation consists of quartz sands and lignitic, gray and black clayey silt of estuarine and marginal deltaic origin. The Matawan Group is subdivided into the Marshalltown, Englishtown, and Merchantville Formations. Downdip, the lithologies in these three formations grade into a single unit and the Matawan Group is changed to formation rank. It consists predominantly of marine silty sands and sandy silt with abundant glauconite. The Mount Laurel Formation (also known as the Monmouth in the subsurface) is made up of glauconitic silty sands and silt. Glauconite may locally comprise more than 80 percent of the sediment in the Matawan Group and Mount Laurel Formation (Spoljaric, 1980). These Cretaceous units are generally exposed in some of the major river drainages, canals, and estuaries, as well as where the overlying Quaternary sediments are absent. The fluvial sands of the Potomoc Formation tend to have moderate to moderately rapid permeability. Marine sands with abundant glauconite or sands that have abundant iron-oxide content tend to be more clayey and have slow to moderate permeability. Silt and fine sandy sediments are slowly to moderately permeable and the clays (except where dry and fractured) are slowly permeable.

The oldest part of the Tertiary sequence exposed at the surface is the glauconitic sands and sandy silts of the Rancocas Group, consisting of the Hornerstown and Vincentown Formations. Soils derived from these formations are sandy to clayey loams with slow to moderate permeability. The rest of the Tertiary sequence exposed at the surface, the Chesapeake Group, includes the Calvert and Choptank Formations. The Calvert Formation is predominantly fine sand with shelly interbeds. The Choptank Formation consists of several fining-upward sequences varying from shelly sand to sandy, clayey silt. These deposits generally lack glauconite. Soils formed on the Chesapeake Group typically have slow to moderately rapid permeability. Other Tertiary units exist in the subsurface of the Coastal Plain and are shown in figure 4.

Quaternary and late Tertiary sediments, where present, vary from 5 to 100 feet in thickness and blanket much of the Atlantic Coastal Plain (fig. 5). The Quaternary fluvial deposits in the northern and central portion of the Atlantic Coastal Plain are called the Columbia Formation, and they unconformably overlie the older Cretaceous and Tertiary sediments. They consist of rusty-weathering, feldspathic quartz sands with gravel and silt beds that are derived primarily from older units to the northeast and north. The Staytonville unit is a silty to clayey sand and sandy silt that overlies the Columbia and is exposed in a limited area in southwestern Kent County near the county line. The Staytonville unit's relationship to the Columbia Formation is not known. The Columbia Formation overlaps an older fluvial unit in southern Delaware, the Pliocene Beaverdam Formation. This unit is siltier than the Columbia Formation, is partly unconformable with older Tertiary units, and crops out only in Sussex County. The Beaverdam Formation is predominantly sand with some gravelly sand and silty clay layers. The sand has a silt matrix in the upper half of the unit. In southeastern Delaware, the Tertiary-Quaternary Omar Formation overlies the Beaverdam Formation. It consists of silty fine sand, clayey silt and silty clay, and fine to coarse sand. The upper Omar Formation is the principal part of the unit exposed at the surface; the lower part of the Omar Formation is restricted to a paleovalley cut into the Beaverdam Formation. Permeability of the Quaternary sediments is generally moderate to moderately rapid, but areas of slow permeability exist in more clay-rich or water-saturated sediments. In the Nanticoke River Valley, deposits of silty clay, gravelly sand, and fine- to medium-grained sand are termed the Nanticoke deposits and are Quaternary in age. In Delaware Bay, Quaternary deposits of sand, minor gravel, silty clay, and organic-rich silty clay comprise the Delaware Bay deposits. Shoreline deposits of Holocene age dominate in southeasternmost Delaware and along the Atlantic coastline. These sediments include: organic rich silty clay and sand of marsh and swamp deposits; fine to coarse, white quartz sand and silty clay beds found in the present day beach, barrier, and spit deposits; and organic-rich silty clay and clayey silty sand in present day lagoon and estuary deposits.

RADIOACTIVITY

An aeroradiometric map of Delaware (fig. 6) was compiled from spectral gamma-ray data acquired during the U.S. Department of Energy's National Uranium Resource Evaluation (NURE) program (Duval and others, 1989). For the purposes of this assessment, low equivalent uranium (eU) is defined as less than 1.5 parts per million (ppm) of uranium , moderate eU is defined as 1.5–2.5 ppm, and high eU is defined as greater than 2.5 ppm. Low radioactivity appears to be associated with most of the Atlantic Coastal Plain sediments. Moderate eU is found in parts of the central and northern portions of the State associated with the Piedmont and parts of the Coastal Plain. There are no areas of high radioactivity on the map. The pattern of radioactivity over the Coastal Plain in figure 6 cannot be readily correlated with any specific geologic units.

A recent study of radon and radioactivity in part of the Coastal Plain by the Delaware Geological Survey (Woodruff and others, 1992) used portable gamma radiation detectors to survey the surface areas underlain by glauconitic sediments in southern New Castle County. They found that, despite the cover of Columbia Formation, ranging from 10 to 70 feet thick, gamma-ray measurements over subcrops of the glauconite-rich Mount Laurel Formation and Rancocas Group displayed typically higher radioactivity (72-139 counts per second, cps) than the non-glauconitic deposits of the Chesapeake Group (60–80 cps) to the south. The highest gamma radiation measurements were associated with the Hornerstown Formation (130–140 cps). They measured uranium concentrations ranging from 0.8–114 ppm with an average of 8.2 ppm in samples of the Mount Laurel Formation and Rancocas Group, and ranging from 0.6–4.9 ppm with an average of 1.89 ppm (J.H. Talley, written commun., 1993) in the Columbia Formation. Soil radon measurements by Woodruff and others (1992) in the Columbia Formation ranged from 53.9–419.1 pCi/L in areas underlain by glauconitic sediments and 25.7–259.9 pCi/L in areas underlain by non-glauconitic sediments; however, the authors do not feel that the differences in the radon concentrations are statistically significant. The authors suggested that gamma radiation and, possibly, radon gas from the glauconitic sediments beneath the Columbia Formation, were contributing to the natural radioactivity measured at and near the surface.

INDOOR RADON DATA

During the period from November, 1985, to June, 1990, the Office of Radiation Control in the Delaware Department of Health and Social Services assisted homeowners and others in testing for indoor radon, and compiled test data to map indoor radon levels in the State. Results of this study are presented in a report by Eichler and Wright (1991). This data set includes all 150 public schools in Delaware and more than 30 private schools. Ninety-eight percent of the tests were done by charcoal canister. The average indoor radon level for the more than 7000 tests in the State survey was 2 pCi/L. Table 1 summarizes the data by zip code. Figures 7a and b are maps of the average indoor radon and percent of indoor radon measurements exceeding 4 pCi/L, plotted by zip code centroid—each point is located in the center of the zip code area. These zipcode maps show

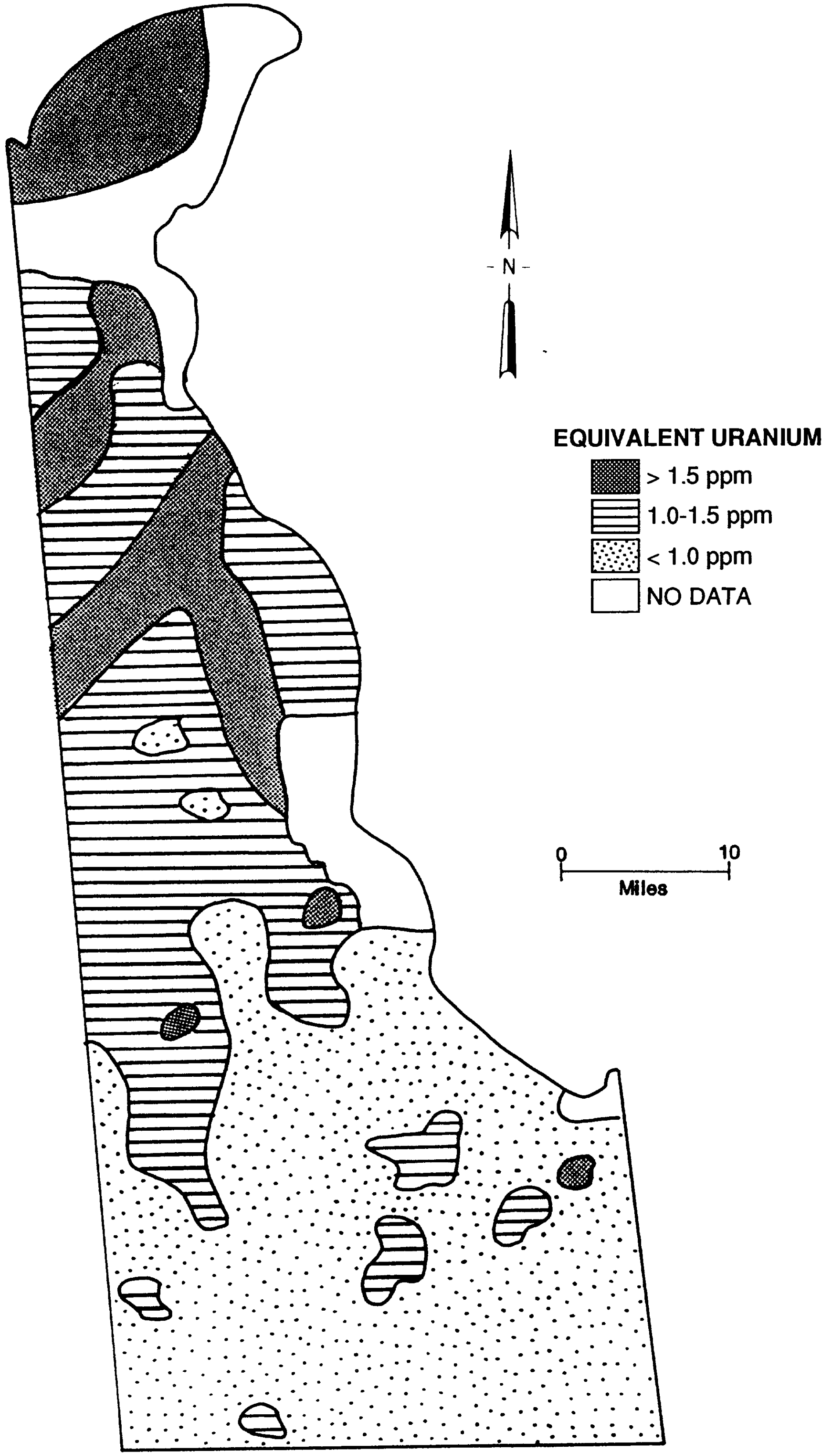

Figure 6. Aerial radiometric map of Delaware (after Duval and others, 1989).

TABLE 1. Screening indoor radon data complied by the Delaware Department of Public Health for homes tested during the period 1986-1990. Data represent 2-7 day charcoal canister measurements. Units for all columns of radon data are pCi/L.

ZIP CODE	CITY	COUNTY	NO. OF MEAS.	AVERAGE	MEDIAN	GM	STD	MAX	%>4 pCi/L	%>20 pCi/L
19701	BEAR	NEW CASTLE	140	1.8	1.3	1.3	1.9	15.8	11	0
19702	NEWARK	NEW CASTLE	175	1.5	1.0	1.1	1.5	13.4	4	0
19703	CLAYMONT	NEW CASTLE	132	1.8	1.3	1.3	1.5	7.5	11	0
19706	DEL. CITY	NEW CASTLE	33	1.0	0.6	0.9	0.7	3.0	0	0
19707	HOCKESSIN	NEW CASTLE	352	2.4	1.6	1.7	2.5	17.5	15	0
19708	KIRKWOOD	NEW CASTLE	5	0.9	0.5	0.8	0.6	1.7	0	0
19709	MIDDLETOWN	NEW CASTLE	240	3.0	2.0	2.0	4.0	38.9	19	1
19710	MONTCHANIN	NEW CASTLE	15	1.7	1.5	1.4	1.1	4.2	7	0
19711	NEWARK	NEW CASTLE	821	2.7	1.5	1.5	7.5	163.9	14	1
19713	NEWARK	NEW CASTLE	197	1.5	0.9	1.0	1.6	13.1	5	0
19714	NEWARK	NEW CASTLE	2	2.7	2.7	2.6	0.2	2.8	0	0
19715	NEWARK	NEW CASTLE	4	1.7	1.8	1.6	0.6	2.4	0	0
19720	NEW CASTLE	NEW CASTLE	269	1.7	1.3	1.2	1.8	21.0	7	0
19730	ODESSA	NEW CASTLE	47	3.2	2.0	2.0	3.1	13.0	30	0
19731	PORT PENN	NEW CASTLE	13	1.2	0.5	0.9	1.4	5.4	8	0
19732	ROCKLAND	NEW CASTLE	6	1.7	1.5	1.3	1.2	3.2	0	0
19733	ST. GEORGES	NEW CASTLE	5	2.9	2.2	2.5	1.9	6.2	20	0
19734	TOWNSEND	NEW CASTLE	106	1.6	1.0	1.1	1.8	9.6	9	0
19735	YORKLYN	NEW CASTLE	1	0.8	0.8	0.8	***	0.8	0	0
19736	YORKLYN	NEW CASTLE	15	2.3	1.3	1.4	3.3	13.3	7	0
19800	WILMINGTON	NEW CASTLE	2	0.5	0.5	0.4	0.3	0.7	0	0
19801	WILMINGTON	NEW CASTLE	39	1.5	1.1	1.2	1.1	5.6	3	0
19802	WILMINGTON	NEW CASTLE	114	1.7	1.1	1.2	1.6	10.2	9	0
19803	WILMINGTON	NEW CASTLE	688	2.1	1.6	1.5	1.8	12.3	14	0
19804	WILMINGTON	NEW CASTLE	171	1.9	1.7	1.4	1.4	6.5	8	0
19805	WILMINGTON	NEW CASTLE	194	1.6	1.0	1.0	3.0	37.2	6	1
19806	WILMINGTON	NEW CASTLE	78	1.6	1.1	1.2	1.3	7.4	5	0
19807	WILMINGTON	NEW CASTLE	178	2.2	1.7	1.6	1.9	12.8	13	0
19808	WILMINGTON	NEW CASTLE	572	2.2	1.6	1.6	2.3	26.5	13	0
19809	WILMINGTON	NEW CASTLE	234	2.1	1.5	1.5	1.9	13.0	13	0
19810	WILMINGTON	NEW CASTLE	691	2.6	1.8	1.8	2.7	40.5	19	0
19901	DOVER	KENT	295	1.6	1.2	1.1	1.4	9.5	6	0
19930	BETHANY	SUSSEX	21	0.7	0.5	0.6	0.4	2.0	0	0
19931	BETHAL	SUSSEX	3	1.0	1.0	0.9	0.4	1.4	0	0
19933	BRIDGEVILLE	SUSSEX	49	1.0	0.8	0.9	0.5	3.3	0	0
19934	CAMDEN	KENT	58	1.1	0.9	0.9	0.9	5.5	3	0
19936	CHESWOLD	KENT	5	0.9	0.5	0.8	0.5	1.5	0	0
19938	CLAYTON	KENT	48	1.1	0.8	0.9	1.0	6.0	2	0
19939	DAGSBORO	SUSSEX	32	1.5	0.5	0.8	3.1	17.1	6	0
19940	DELMAR	SUSSEX	24	0.8	0.5	0.7	0.4	2.1	0	0
19941	ELLENDALE	SUSSEX	7	0.6	0.5	0.6	0.4	1.5	0	0
19942	FARMINGTON	KENT	1	0.5	0.5	0.5	***	0.5	0	0

TABLE 1 (continued). Screening indoor radon data for Delaware.

ZIP CODE	CITY	COUNTY	NO. OF MEAS.	AVERAGE	MEDIAN	GM	STD	MAX	%>4 pCi/L	%>20 pCi/L
19943	FELTON	KENT	52	1.1	0.9	0.9	1.1	8.0	2	0
19944	FENWICK IS.	SUSSEX	7	0.5	0.5	0.5	0.0	0.5	0	0
19945	FRANKFORD	SUSSEX	32	0.8	0.5	0.7	0.7	3.5	0	0
19946	FREDERICA	KENT	20	1.5	0.9	1.1	1.3	4.3	10	0
19947	GEORGETOWN	SUSSEX	70	0.9	0.5	0.7	0.8	5.1	1	0
19950	GREENWOOD	KENT	34	1.4	0.8	0.9	1.7	9.3	6	0
19951	HARBESON	SUSSEX	12	0.9	0.5	0.8	0.6	1.8	0	0
19952	HARRINGTON	KENT	38	0.8	0.5	0.7	0.7	4.6	3	0
19953	HARTLY	KENT	17	0.8	0.5	0.7	0.6	2.6	0	0
19954	HOUSTON	KENT	16	1.1	0.8	0.9	0.6	2.1	0	0
19955	KENTON	KENT	1	0.5	0.5	0.5	***	0.5	0	0
19956	LAUREL	SUSSEX	52	0.9	0.5	0.7	0.8	4.7	2	0
19958	LEWES	SUSSEX	88	1.1	0.7	0.8	0.9	5.9	1	0
19960	LINCOLN	SUSSEX	27	0.9	0.5	0.7	0.8	4.1	4	0
19961	LITTLE CREK	KENT	1	2.1	2.1	2.1	***	2.1	0	0
19962	MAGNOLIA	KENT	28	1.6	1.2	1.2	1.4	6.3	7	0
19963	MILFORD	SUSSEX	87	1.5	1.0	1.1	1.2	7.0	3	0
19964	MARYDEL	KENT	6	0.7	0.7	0.7	0.2	1.1	0	0
19966	MILLSBORO	SUSSEX	64	0.9	0.5	0.7	0.6	3.0	0	0
19968	MILTON	SUSSEX	55	1.0	0.6	0.8	0.8	5.0	2	0
19969	NASSAU	SUSSEX	3	1.5	1.0	1.3	1.0	2.7	0	0
19970	MILLVILLE	SUSSEX	50	0.8	0.5	0.7	0.5	2.3	0	0
19971	REHOBOTH	SUSSEX	63	1.2	0.7	0.9	1.2	8.1	3	0
19973	SEAFORD	SUSSEX	105	1.1	0.8	0.9	1.0	5.2	3	0
19975	SELBYVILLE	SUSSEX	36	0.5	0.5	0.5	0.2	1.7	0	0
19977	SMYRNA	KENT	99	1.6	1.0	1.2	1.6	11.7	6	0
19979	VIOLA	NEW CASTLE	3	1.2	1.5	1.0	0.6	1.5	0	0
19980	WOODSIDE	KENT	1	0.5	0.5	0.5	***	0.5	0	0

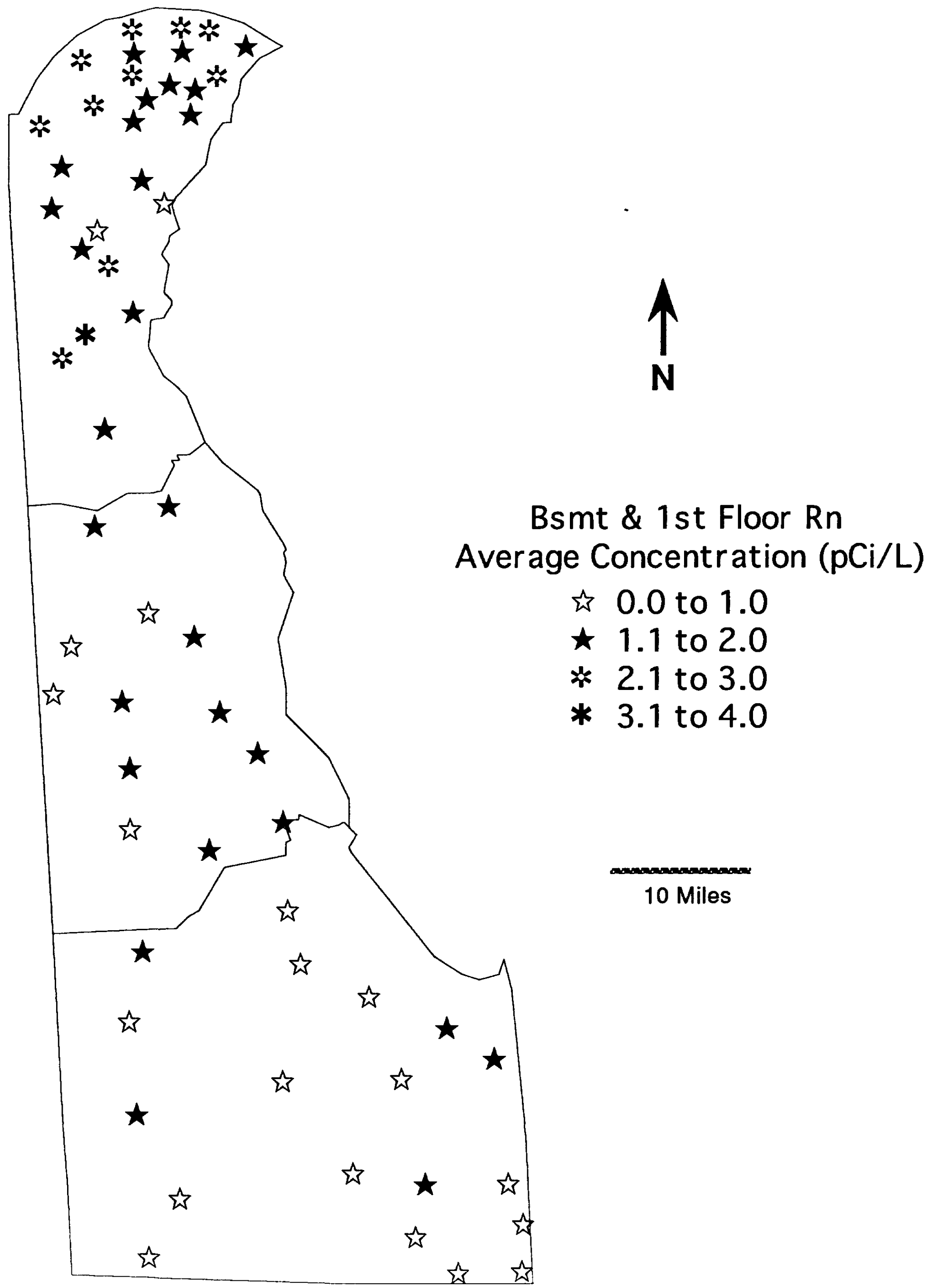

Figure 7a. Average indoor radon levels of homes sampled in each zip code area, plotted by zip code centroid. Points are plotted only for those zip code areas containing 5 or more measurements. Points representing the average indoor radon reading are plotted at the center of each zip code area. Data compiled by the Delaware Department of Public Health for homes tested between 1986-1990 (see Table 1).

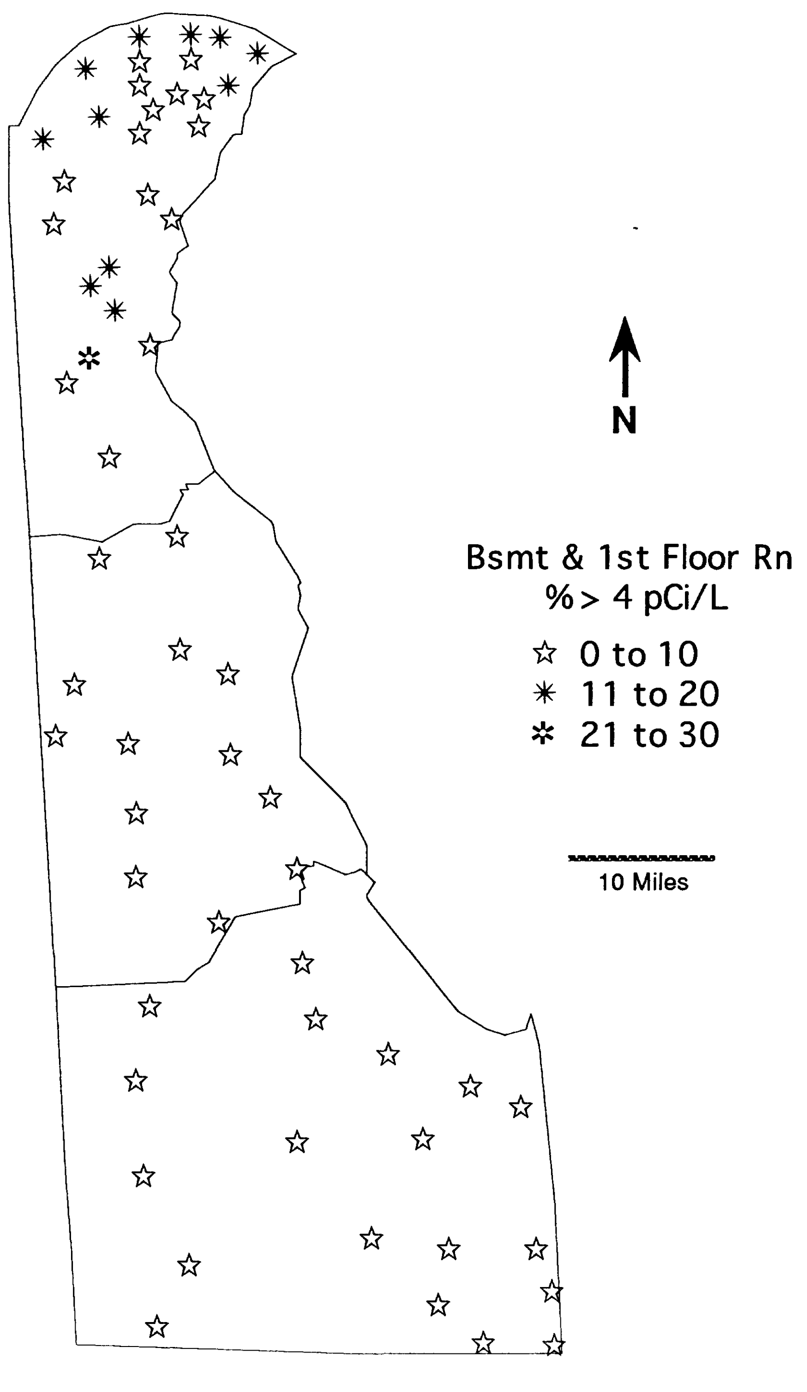

Figure 7b. Percent of homes tested with indoor radon measurements greater than 4 pCi/L, plotted by zip code centroid. Points are plotted only for those zip code areas with 5 or more measurements. Points representing the percent of readings greater than 4 pCi/L are plotted at the center of each zip code area. Data compiled by the Delaware Department of Public Health for homes tested between 1986-1990 (see Table 1).

data only for those zipcodes with 5 or more indoor radon readings. Figure 8 is a map of counties for reference. Figure 9 shows the frequency distribution of individual indoor radon measurements by county. In general, the indoor radon measurements were highest in New Castle County and lowest in Sussex County. New Castle County had 16 measurements exceeding 20 pCi/L whereas Kent and Sussex Counties had no readings over 20 pCi/L.

GEOLOGIC RADON POTENTIAL

An examination of aerial radioactivity, geologic, and indoor radon data, and radioactivity surveys conducted by the Delaware Geological Survey (Woodruff and others, 1992) allows us to make some observations about the geologic radon potential of the State. It appears that the Piedmont and northern portion of the Atlantic Coastal Plain have the highest geologic radon potential. Average indoor radon in the Piedmont varies from low (<2 pCi/L) to moderate (2-4 pCi/L). Individual readings within the Piedmont can be locally very high (> 20 pCi/L). This is not unexpected when a regional-scale examination of the Atlantic coastal states shows that the Piedmont is consistently an area of moderate to high radon potential. Much of the western Piedmont in Delaware is underlain by the Wissahickon Formation, which is predominantly schist. Soils developed on this schist have generally moderate permeability. This formation is moderate to locally high in geologic radon potential. Studies of equivalent schists in the Piedmont of Maryland (Gundersen and others, 1988) indicate that these rocks can have uranium concentrations of 3–5 ppm, especially where faulted. The soils developed on these schists can also have soil-gas radon concentrations greater than 1000 pCi/L. The Wilmington Complex and James Run Formation in the central and eastern portions of the Delaware Piedmont are variable in radon potential. In these units, the felsic gneiss and schist may contribute to the elevated radon levels, whereas mafic rocks such as amphibolite and gabbro, and quartz-poor rocks such as charnockite and diorite, are probably lower in radon potential. The soils developed on the felsic rocks also tend to have higher permeability than the soils developed on the mafic rocks. The average indoor radon (fig. 7a) is distinctly lower in parts of the Wilmington Complex than in surrounding areas, particularly in zipcode areas underlain by the Bringhurst Gabbro and the Arden pluton. Plotting of individual indoor radon readings may better delineate specific geologic units; however, given the present format of the data, this is not possible.

Studies of radon and uranium in Coastal Plain sediments in New Jersey (Gundersen and others, 1991) and Maryland (Reimer and others, 1991) suggest that glauconitic marine sediments equivalent to those in the northern portion of the Delaware Coastal Plain can generate elevated levels of indoor radon. Central New Castle County is underlain by glauconitic marine sediments of Cretaceous and Tertiary age that have moderate to locally high geologic radon potential. Aerial radiometric data indicate that moderate concentrations of uranium occur in rocks and soils associated with the Piedmont and parts of the Coastal Plain of northern Delaware. Chemical analyses of Cretaceous and Tertiary glauconitic marine sediments and fluvial sediments of the Columbia Formation performed by the Delaware Geological Survey indicate that variable but generally moderate concentrations of uranium occur, averaging 1.89 ppm or greater. The permeability of soils in these areas is variable but generally moderate to high, allowing radon gas to move readily through the soil. Data from the State indoor radon survey for New Castle County indicates that areas underlain by the non-glauconitic Cretaceous fluvial sediments have lower average indoor radon levels than the glauconitic parts of the upper Cretaceous and lower Tertiary sequence to the south. Kent County and all of Sussex County are underlain by quartz-dominated

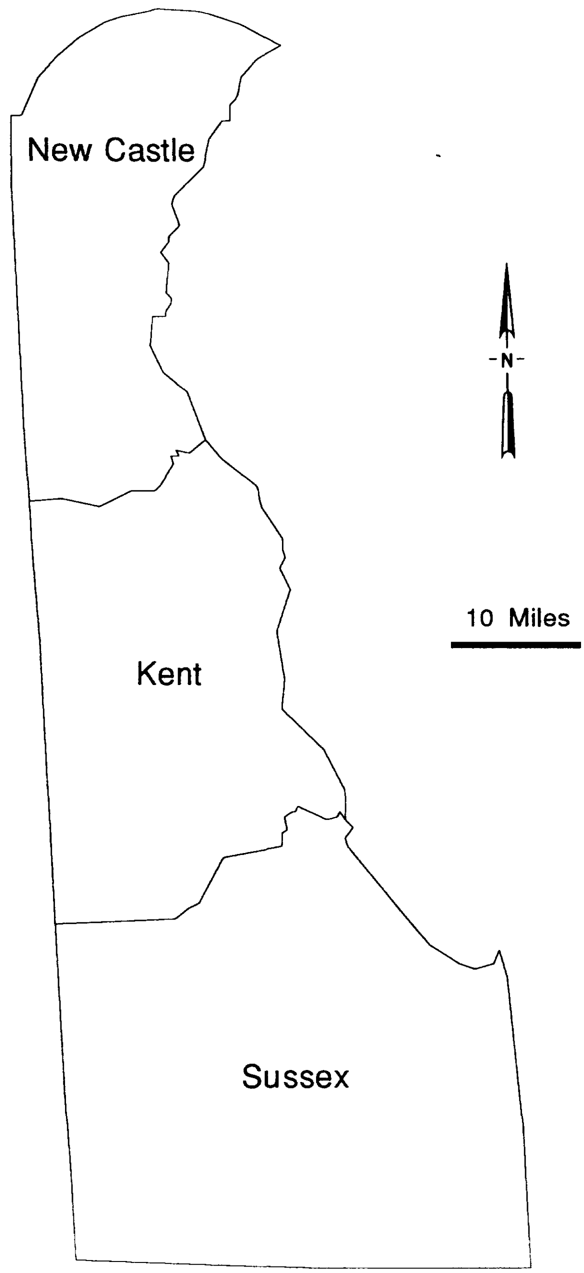

Figure 8. Counties in Delaware.

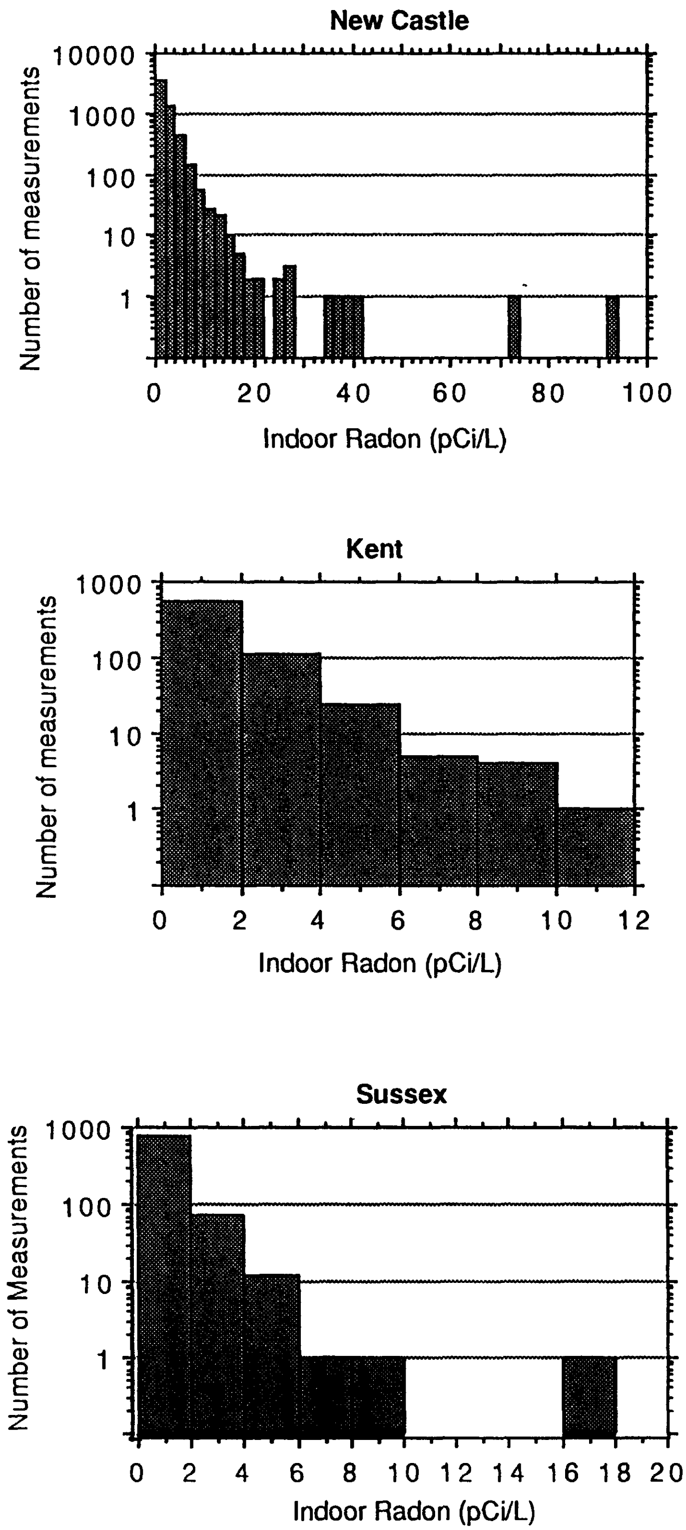

Figure 9. Histograms showing frequency distribution of indoor radon readings by county in Delaware. A log-scale vertical axis was used for ease of presentation. In order to better distinguish lower values on the graph, the histogram for New Castle County excludes a single reading of 163.9 pCi/L. Data compiled by the Delaware Department of Health and Social Services from indoor radon tests performed between 1986 and 1990 (see Table 1).

sands, silts, gravels, and clays that have low geologic radon potential. These sediments are low in radioactivity and generally have a small percentage of homes with indoor radon levels greater than 4 pCi/L.

SUMMARY

For the purpose of this assessment, Delaware has been divided into 3 geologic radon potential areas and each area assigned a Radon Index (RI) and a Confidence Index (CI) score (Table 2) using the information outlined in the sections above (please see the introduction chapter to this report for a detailed explanation of the indexes). The RI is a relative measure of radon potential based on geology, soils, radioactivity, architecture, and indoor radon. The CI is a measure of the confidence of the RI assessment based on the quality and quantity of the data used to assess geologic radon potential.

New Castle County has generally moderate but variable radon potential. Northern New Castle County is underlain by the metamorphic and igneous rocks of the Piedmont that have moderate radon potential, but that may be locally high or low, as discussed in the previous section. Central New Castle County is underlain in part by glauconitic marine sediments of Cretaceous and Tertiary age that have moderate to locally high geologic radon potential. Aerial radiometric data indicate that moderate concentrations of uranium occur in rocks and soils associated with the Piedmont and parts of the Coastal Plain of northern Delaware. Chemical analyses (Woodruff and others, 1992) of Cretaceous and Tertiary glauconitic marine sediments and fluvial sediments of the Columbia Formation indicate that moderate concentrations of uranium, generally averaging 1.89 ppm or greater, occur. The permeability of soils in these areas is variable but generally moderate to high, allowing radon gas to move readily through the soil. Data from the State indoor radon survey also indicate that these areas of New Castle County have the highest percentage of homes with elevated indoor radon as well as the highest indoor radon concentrations found in the State. Kent County and all of Sussex County are underlain by quartz-dominated sands, silts, gravels, and clays that have low geologic radon potential. These sediments are low in radioactivity and generally have a low percentage of homes with indoor radon levels greater than 4 pCi/L.

This is a generalized assessment of the State's geologic radon potential and there is no substitute for having a home tested. The conclusions about radon potential presented in this report cannot be applied to individual homes or building sites. Indoor radon levels, both high and low, can be quite localized, and within any radon potential area there will likely be areas with higher or lower radon potential than assigned to the area as a whole. Any local decisions about radon should not be made without consulting all available local data. For additional information on radon and how to test, contact your State radon program or EPA regional office. More detailed information on state or local geology may be obtained from the state geological survey. Addresses and phone numbers for these agencies are listed in chapter 1 of this booklet.

TABLE 2. Radon Index and Confidence Index scores for Delaware.

	(1) Piedmont		(2) Coastal Plain Upper Cretaceous and lower Tertiary glauconitic marine sediments		(3) Coastal Plain Cretaceous, Tertiary, Quaternary quartzitic fluvial and marine sediments	
FACTOR	RI	CI	RI	CI	RI	CI
INDOOR RADON	2	2	2	2	1	2
RADIOACTIVITY	2	2	2	2	1	2
GEOLOGY	2	2	2	2	1	2
SOIL PERM.	2	3	2	3	2	3
ARCHITECTURE	3	-	2	-	2	-
GFE POINTS	0	-	0	-	0	-
TOTAL	11	9	10	9	7	9
	Mod	Mod	Mod	Mod	Low	Mod

RADON INDEX SCORING:

Radon potential category	Point range	Probable screening indoor radon average for area
LOW	3-8 points	< 2 pCi/L
MODERATE/VARIABLE	9-11 points	2 - 4 pCi/L
HIGH	> 11 points	> 4 pCi/L

Possible range of points = 3 to 17

CONFIDENCE INDEX SCORING:

LOW CONFIDENCE	4 - 6 points
MODERATE CONFIDENCE	7 - 9 points
HIGH CONFIDENCE	10 - 12 points

Possible range of points = 4 to 12

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PRELIMINARY GEOLOGIC RADON POTENTIAL ASSESSMENT OF MARYLAND

by
Linda C.S. Gundersen
U.S. Geological Survey

INTRODUCTION

A random sampling of indoor radon in 1126 homes in Maryland was conducted for the State/EPA Residential Radon Survey during the winter of 1991. Indoor radon was measured by charcoal canister and the average for the State was 3.1 pCi/L. Twenty percent of these indoor radon measurements exceeded the EPA guideline of 4 pCi/L. The Maryland State Department of the Environment has also collected more than 37,000 indoor radon measurements from Maryland residents and commercial vendors since 1986. Examination of these data in the context of geology, soil parameters, and radioactivity suggest that many of the soils and rocks of the Piedmont and Great Valley have the potential to produce high levels of indoor radon (> 4 pCi/L). Soils and rocks of the Allegheny Plateau, Valley and Ridge, and the western shore of the Coastal Plain have moderate to locally high radon potential. Soils and rocks of the Blue Ridge and Eastern Shore of the Coastal Plain have relatively low geologic radon potential.

This is a generalized assessment of geologic radon potential of rocks, soils, and surficial deposits of Maryland. The scale of this assessment is such that it is inappropriate for use in identifying the radon potential of small areas such as neighborhoods, individual building sites, or housing tracts. Any localized assessment of radon potential must be supplemented with additional data and information from the locality. Within any area of a given radon potential ranking, there are likely to be areas with higher or lower radon levels than characterized for the area as a whole. Indoor radon levels, both high and low, can be quite localized, and there is no substitute for testing individual homes. Elevated levels of indoor radon have been found in every State, and EPA recommends that all homes be tested. For more information, the reader is urged to consult the local or State (1-800-872-3666) radon program or EPA regional office. More detailed information on state or local geology may be obtained from the state geological survey. Addresses and phone numbers for these agencies are listed in chapter 1 of this booklet.

PHYSIOGRAPHIC AND GEOGRAPHIC SETTING

The physiography of Maryland (fig. 1) is in part a reflection of the underlying bedrock geology (fig. 2a, 2b). Maryland has three major physiographic regions: the Appalachian Province, the Piedmont Province, and the Coastal Plain Province. Each of these provinces is subdivided into several smaller regions (fig. 1). The Coastal Plain Province covers approximately one half of Maryland and is subdivided into the dissected rolling plain of the Western Shore and the nearly flat Eastern Shore. Elevations range from sea level to 400 feet at the Fall Line. The Fall Line is actually a zone where the sediments of the Coastal Plain are thinnest and overlap onto the crystalline rocks of the Piedmont Province. Across this zone, there is a striking change in the water velocity of rivers and streams; falls and rapids characterize the streams of the Piedmont. West of the Fall Line lies the rolling hills of the Piedmont, which is divided into lowlands and uplands. The Piedmont uplands is underlain by crystalline igneous and metamorphic rocks, and the Piedmont lowlands are underlain by sedimentary and igneous rocks of the Frederick Valley and Mesozoic basins. The Appalachian Province lies to the west of the Piedmont. It is subdivided into four distinct subdivisions, and it is underlain by folded and faulted sedimentary and igneous rocks.

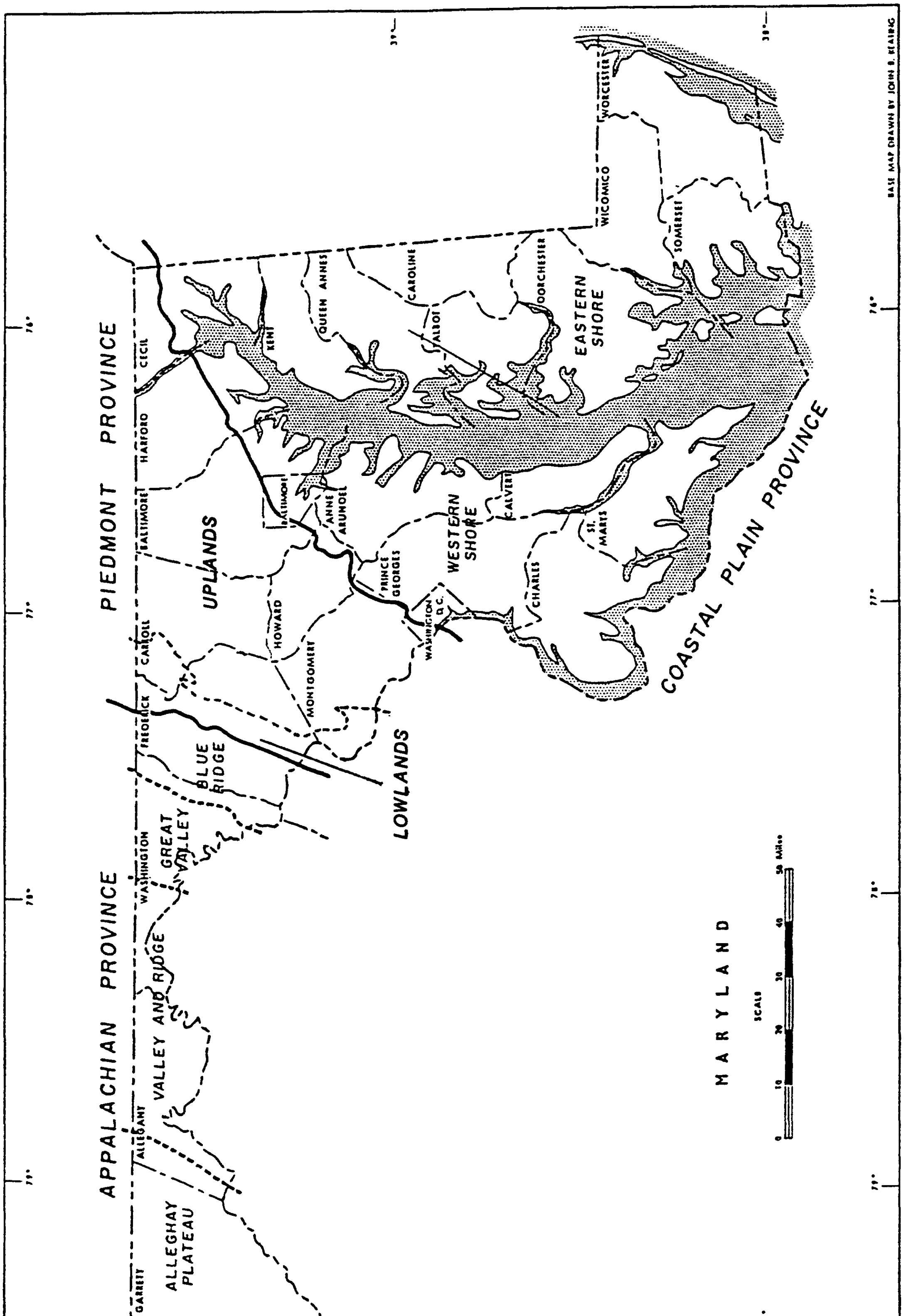


Figure 1. Physiographic/geologic provinces and subdivisions of Maryland (after Vokes, 1957, and Thornbury, 1965).

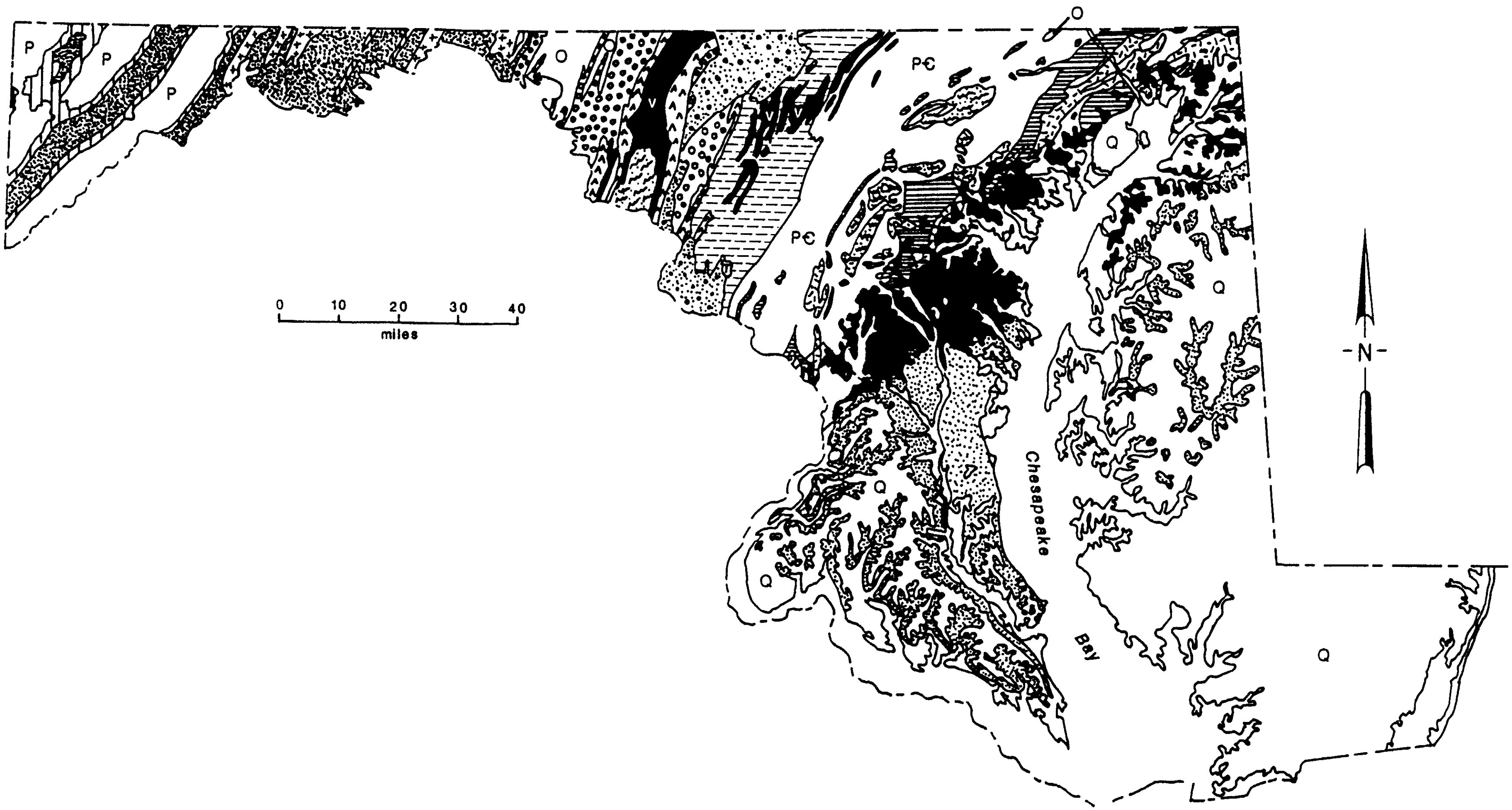


Figure 2a. Generalized geologic map of Maryland (after Maryland Geological Survey, 1967).

GENERALIZED GEOLOGIC MAP OF MARYLAND
EXPLANATION

Q — QUATERNARY—sand, silt, gravel, clay, and peat

TERTIARY—sand, clay, silt, greensand, and diotomaceous earth

CRETACEOUS—sand, gravel, silt, and clay

TRIASSIC—red shale, red sandstone, and conglomerate, intruded by diabase dikes and sills (indicated by T)

P — PERMIAN & PENNSYLVANIAN—clyclic sequences of shale, siltstone, sandstone, clay, limestone, and coal

MISSISSIPPIAN—red beds, shale, siltstone, sandstone, and limestone

DEVONIAN—shale, siltstone, sandstone, limestone, and chert

SILURIAN—shale, mudstone, sandstone, and limestone

O — ORDOVICIAN—limestone, dolomite, shale, siltstone, and red beds. Slate and conglomerate in northern Hartford County

CAMBRIAN—limestone, dolomite, shale, and sandstone

PALEOZOIC GRANITIC ROCKS—quartz diorite to granite intrusive rocks and diamictite

PALEOZOIC BASIC IGNEOUS ROCKS—intrusive rocks; gabbro, serpentine

CAMBRIAN TO PRECAMBRIAN (?)—(South Mountain area) quartzite, sandstone, shale, and phyllite

PRECAMBRIAN (?)—(South Mountain area and western Piedmont) metabasalt, metarhyolite, marble, and phyllite

PRECAMBRIAN (?)—(Westem Piedmont) tuffaceous and non-tuffaceous phyllite, slate, and quartzite

P€ — PRECAMBRIAN-PALEOZOIC (?)—(Eastern Piedmont) schist, metagraywacke, quartzite, diamictite, marble, and metavolcanic rocks

PRECAMBRIAN BASEMENT COMPLEX—gneiss, migmatite, and augen gneiss

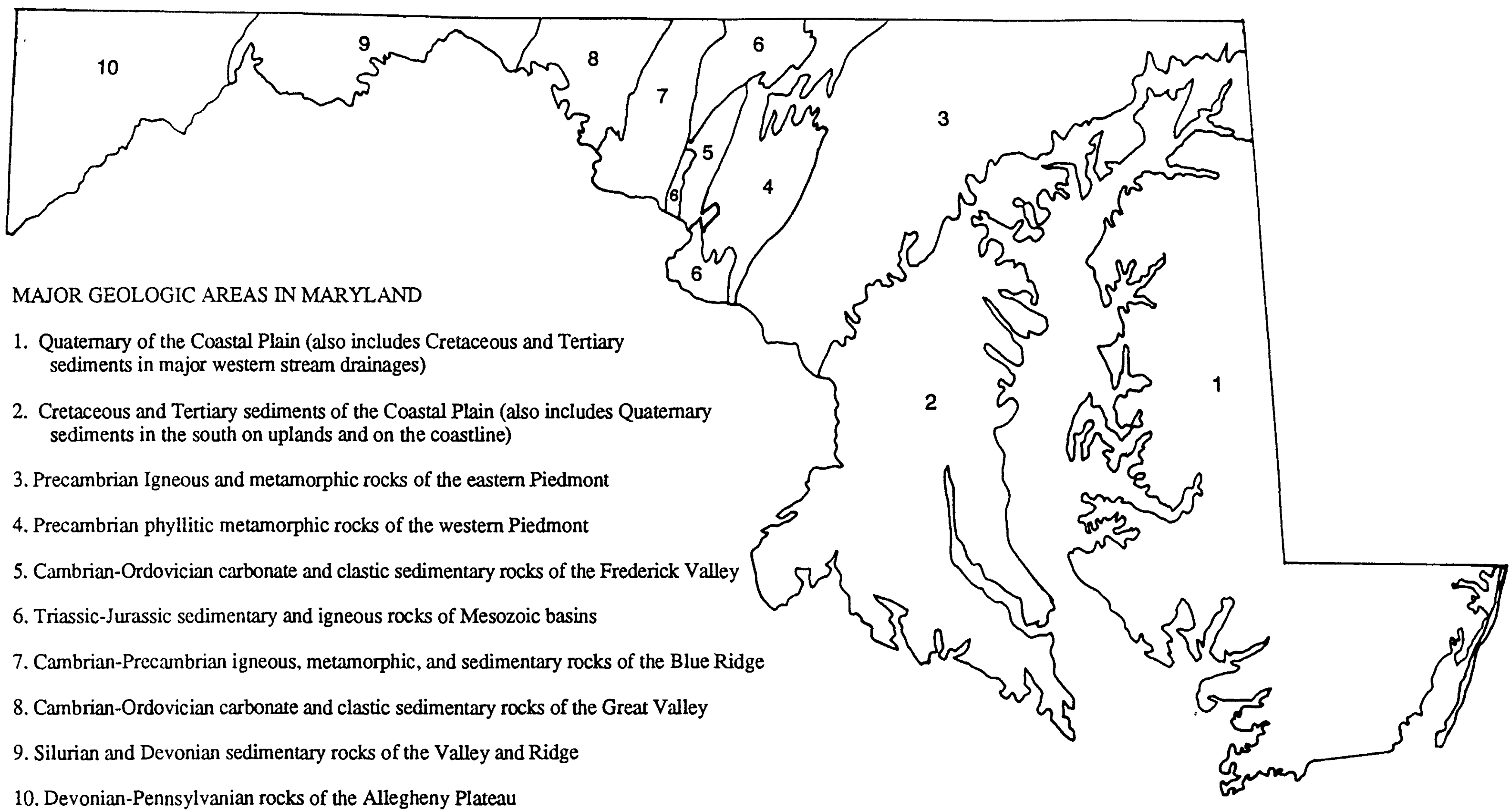


Figure 2b. Major geologic areas in Maryland.

The Blue Ridge has rugged topography, with ridges made of resistant quartzite and valley floors underlain by metavolcanic rocks. West of the Blue Ridge lies the Great Valley, which is underlain by limestones and shales and has a rolling to nearly level topography. The Valley and Ridge bounds the western side of the Great Valley and has steep ridges of resistant sandstone and deep valleys underlain by limestone and shale. The westernmost part of Maryland is in the Allegheny Plateau, a broad upland crossed by mountain ranges. The highest elevation in Maryland, 3360 feet above sea level, is in this province. Sedimentary rocks, which include several coal deposits, underlie the Allegheny Plateau.

Maryland's climate is continental in the western regions to humid subtropical in the east. Average annual precipitation is similar throughout the State, averaging about 44 inches (fig. 3). In 1990 Maryland's population was 4,781,468, with 80 percent of the population living in urban centers (fig. 4). Population density is approximately 442 per square mile.

GEOLOGIC SETTING

The geology of Maryland is complex, ranging from unconsolidated sands and clays to granites, marbles, limestones, and volcanic rocks. Names of rock formations and the way rocks are grouped have changed with time. This description of the geology tries to convey the major rock types of an area, especially as they pertain to the radon problem. Descriptions in this report are derived from the following references: Hopson (1964), Cleaves and others (1968), Reinhardt (1974), Edwards (1986, 1988), Hansen and Edwards (1986), Higgins and Conant (1990), and Smoot (1991). A general geologic map is given in figure 2a and general geologic areas and terminology are defined in figure 2b. This terminology will be used throughout this report. It is suggested that the reader refer to the more detailed state geologic map (Cleaves and others, 1968) as well as the numerous detailed geologic maps available from the Maryland Geological Survey (1992).

The Coastal Plain

The Coastal Plain Province is underlain by relatively unconsolidated fluvial and marine sediments forming a wedge of strata that thickens to the east. The Coastal Plain is divided into an inner belt of Cretaceous- and early Tertiary-age sediments and an outer belt of younger Tertiary- and Quaternary-age units. The Lower Cretaceous units are composed of fluvial sediments including quartz sand, gravel, and clay, whereas the Upper Cretaceous through Quaternary sediments are largely marine in origin and include calcareous clays and silts, glauconitic clays, silts, and sands, micaceous clays, silts, and fine sands, and finally, the young coastal deposits of beach, lagoon, and marsh environments that dominate the shoreline.

The oldest and most extensive Cretaceous-age rocks are the Potomac Group, composed of interbedded quartz gravels, quartzitic argillaceous sands, and variegated silts and clays. The younger Cretaceous sediments crop out in narrow belts from north and west of Annapolis to Washington, D.C., and along drainages in the northern part of the Eastern Shore. Overlying the Potomac Group is the Magothy Formation, consisting of white, cross-bedded, lignitic sands, gray silty clays, and ferruginous quartz gravels. The Matawan Formation overlies the Magothy Formation and is characterized by fine-grained, glauconitic, micaceous sand and silt. The Severn Formation forms the top of the Cretaceous section and consists of fine- to coarse-grained, glauconitic, micaceous sand with a basal gravel.

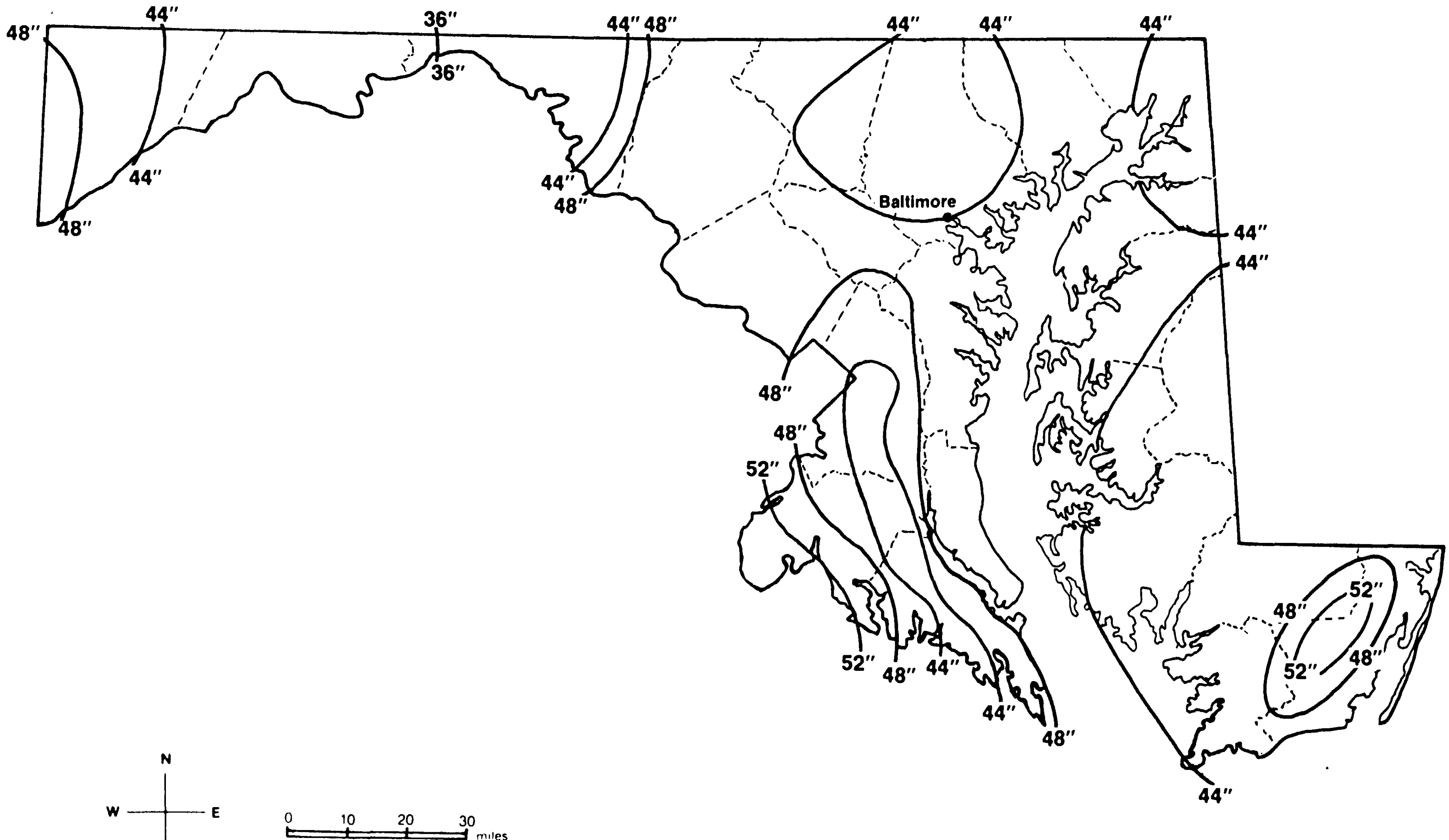


Figure 3. Average annual precipitation in Maryland (from Facts on File, 1984).

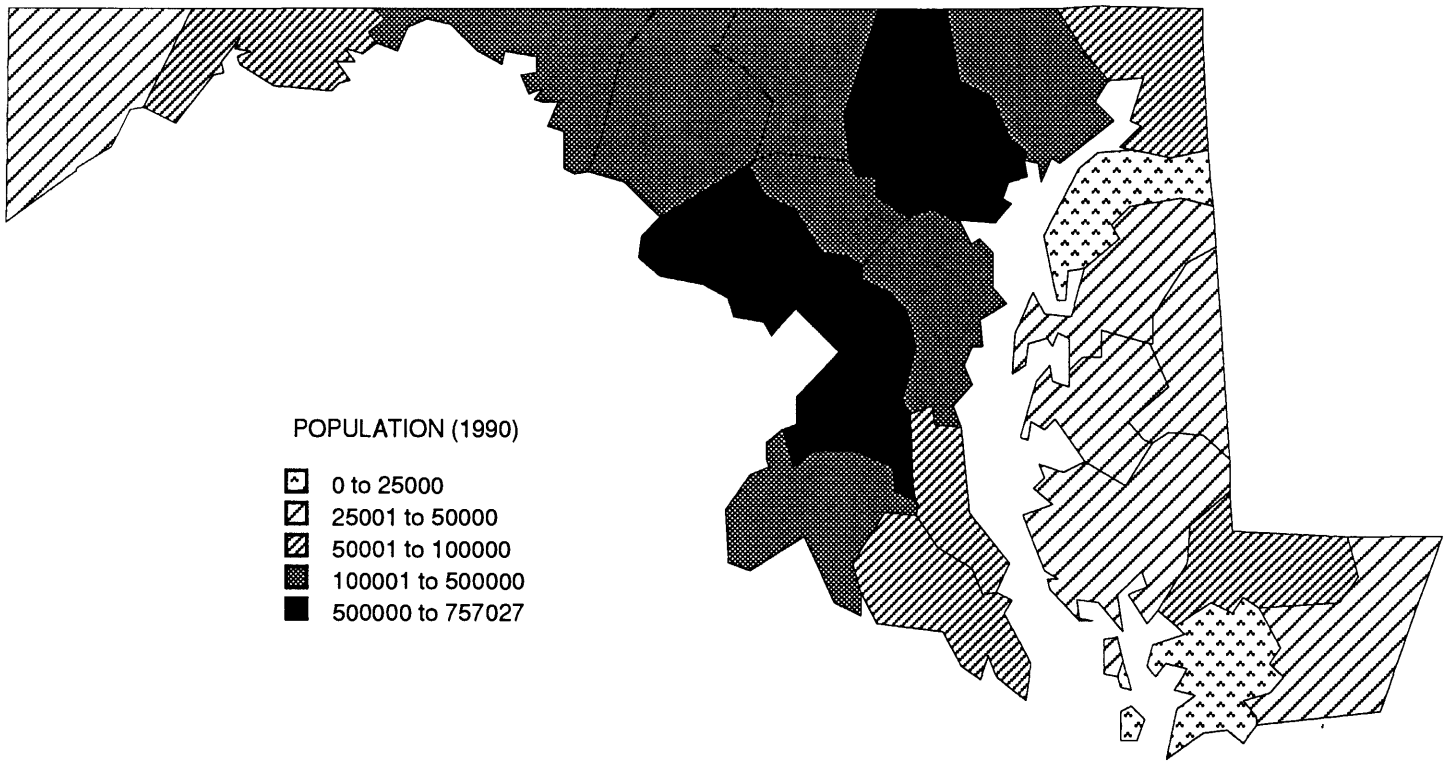


Figure 4. Population of counties in Maryland (1990 U.S. Census data).

Tertiary-age rocks of the Coastal Plain crop out for the most part on the Western Shore and along major drainages in the central and northern parts of the Eastern Shore. The base of the Tertiary section is the Pamunkey Group, consisting of the Brightseat, Aquia, Marlboro, and Nanjemoy Formations. These sediments form a wide band from Washington, D.C. to Annapolis. The Brightseat consists of fine- to coarse-grained, micaceous and locally glauconitic sand with locally indurated calcareous beds and phosphatic pebbles and fossils. The glauconitic, fossiliferous sands of the Aquia Formation overlie the Brightseat Formation. These sands contain as much as 70 percent glauconite. The Marlboro Clay consists of pink to gray clay with lenses of fine white sand. The Nanjemoy Formation is characterized by fine- to medium-grained, argillaceous, glauconitic sands with minor clay. Overlying the Pamunkey Group is the Chesapeake Group, consisting of the Calvert, Choptank, and St. Marys Formations. The Calvert Formation crops out extensively in the central portion of the Western Shore. The base of the Calvert is a diatomaceous clay with fine argillaceous sand overlain by interbedded fine grained argillaceous sand, shelly sand, carbonaceous clay, and sandy clay. Sand is locally cemented to form sandstone. The Calvert is succeeded by the quartzose, fine-grained sand, silt, shelly sand, and sandstone of the Choptank Formation. The St. Marys Formation is a sandy clay and fine-grained sand that crops out predominantly in the southern part of the Western Shore.

The youngest Tertiary rocks in Maryland occur in the subsurface or are of questionable age. The end of Tertiary time and beginning of Quaternary time was a period of deposition and erosion, including the deposition of very coarse-grained sand and gravel that formed upland deposits of the Western Shore (McCarten, 1990). Quartzose, cross-bedded sand and gravel, and minor silt and clay of Tertiary age form upland deposits on the Eastern Shore. Quaternary deposits occurring in lowlands and along shorelines include quartzose gravel, sand, silt and clay, peat, marsh muds, and shell-bearing clays and sands.

<u>The Piedmont</u>

For the purposes of this assessment, the Piedmont of Maryland is subdivided into an eastern and western part (fig. 2b), each underlain by a distinctive sequence of rocks. The Precambrian-Cambrian (?) crystalline rocks of the western Piedmont consist of phyllite and schist with thin interbeds of quartzite, and a major belt of metabasalt with minor marble and volcanic phyllite. To the west of these rocks lie the Paleozoic carbonates, shales, and fine sandstones of Frederick Valley and the sandstones, siltstones, shales, conglomerates, and diabase dikes of the Mesozoic Basins. Rocks of the eastern Piedmont are exposed in a large structure called the Baltimore-Washington anticlinorium. In the core of the anticlinorium is the Precambrian Baltimore Gneiss, surrounded by younger, Paleozoic metasedimentary schist and marble of the Glenarm Supergroup. The anticlinorium is flanked by mafic and ultramafic rocks of the Baltimore Mafic Complex, metavolcanic rocks of the James Run Formation, and various bodies of diamictite, granitic plutons, and metagraywacke. A more detailed description of the Piedmont from east to west is given in the following paragraphs.

Metamorphosed volcanic rocks, including greenstone, greenschist, amphibolite, and felsite of the James Run Formation, crop out in several large irregular areas along the Fall Line, especially north of the Susquehanna River. Numerous isolated bodies of granitic gneiss and granite plutons also crop out along the eastern edge of the Piedmont. The Aberdeen metagabbro, consisting of metagabbro and amphibolite, underlies a large area of eastern Harford County, in the area of Havre de Grace. To the west of these mafic rocks is a wide band of generally granitic rocks, including granitic gneiss, granofels, schist, felsite, and metagraywacke of the Port Deposit Gneiss, James

Run Formation, the Conowingo Diamictite, and several unnamed rock units that extend from the northeast corner of the State south to Baltimore. The Port Deposit Gneiss is a deformed complex of extrusive and shallow intrusive rocks, predominantly biotite-diorite in composition, that is locally sheared. The James Run Formation is a complicated sequence of metavolcanic rocks ranging in composition from mafic to felsic as described above. The Conowingo Diamictite is a metasedimentary rock with abundant grains and pebbles of quartz, as well as clasts, blocks, and slabs of other rock types including quartzite, gneiss, schist, graywacke, and amphibolite. The Baltimore Mafic Complex lies west of the Conowingo Diamictite and east of the Baltimore Gneiss domes and the Glenarm Supergroup, cropping out from northern Cecil County to southwest of Baltimore and the Patuxent River. The Baltimore Mafic Complex is composed of gabbro, serpentinite, amphibolite, and talc schist. The Precambrian Baltimore Gneiss is exposed in several large domes through Baltimore and Howard Counties and comprises biotite-quartz-feldspar gneiss, biotite hornblende gneiss, and amphibolite. Paleozoic rocks of the lower Glenarm Supergroup unconformably overlie the Baltimore Gneiss and consist of the Setters Formation, a quartzite interbedded with mica schist, and the Cockeysville Marble, which overlies the Setters Formation and consists of metadolomite, calc-silicate schist and marble, and calcite marble. The Cockeysville Marble is overlain by the areally extensive pelitic schist of the Loch Raven Schist and the Oella Formation that comprise the upper Glenarm Supergroup (formerly termed the lower pelitic schist of the Wissahickon Formation). To the west of the gneiss domes and the Glenarm Supergroup is the diamictite of the Sykesville Formation, and extensive areas of metagraywacke and schist (formerly mapped as Wissahickon) with isolated bodies of mafic rocks and granitic plutons.

The crystalline rocks of the western Piedmont are distinctly different from the rocks of the eastern Piedmont. The western Piedmont crystalline rocks are dominated by schist and phyllite of the Gillis, Marburg, Urbana, and Ijamsville Formations, and metavolcanic rocks of the Sams Creek Formation. The Gillis crops out in a wide band from southwestern Montgomery County north to Mt. Airy and to the west and north through eastern Frederick County into southern Carroll County. It is composed of interbedded green chloritic phyllite, gray graphitic phyllite, metasiltstone, and metagraywacke with white vein quartz. The Marburg Schist crops out to the north of the Gillis and is a fine-grained muscovite-chlorite schist interbedded with quartzite. Around Linwood is a small mass of crystalline, schistose limestone and calcareous slate called the Silver Run Limestone Member of the Marburg Schist. The Urbana Formation crops out west of the Gillis and extends north to New London. It is composed of gray to green chloritic phyllite interbedded with siltstone, quartzite, and marble. The Sams Creek Formation crops out in sinuous bands within the phyllites and schists from Hyattstown northeast to the state line. The Sams Creek Formation consists of massive to schistose metabasalt with minor phyllite and quartzite. The Wakefield Marble Member of the Sams Creek Formation forms thin bands in association with the metabasalt.

The crystalline rocks of the Piedmont are bounded on the west by the Gettysburg and Culpeper basins and by carbonate and clastic rocks of the Frederick Valley. The Frederick Valley is underlain by locally deformed and metamorphosed Cambrian-Ordovician clastic and carbonate rocks. The base of the Cambrian sequence is the Araby Formation, consisting of locally phyllitic siltstone, silty shale, and argillaceous sandstone. It forms a narrow ridge on the east side of the valley. At the top of the Araby is the highly deformed Cash Smith Formation, a gray to black phyllitic shale and calcareous shale with limestone nodules. The Frederick Formation overlies the Cash Smith Formation and is the most areally extensive unit of the Frederick Valley. It consists of three members: the thin bedded, locally sandy, limestone, dolomite, and minor shale of the Rocky

Springs Station Member; the laminated limestone of the Adamstown Member; and the fossiliferous, laminated, locally silty and sandy, limestone and dolomite of the Lime Kiln Member. The Ordovician Grove Formation overlies the Frederick Formation and consists of fossiliferous limestone and dolomite with minor sandstone.

Late Triassic-early Jurassic continental sedimentary and igneous rocks of the Newark Supergroup occur in parts of two half-graben basins (Mesozoic basins) that form a north-south belt across the central part of the State. The southern corner of the Gettysburg basin extends south from Pennsylvania. The strata dip westward to the border fault and are folded into broad synclines separated by faults. The basal Triassic New Oxford Formation forms a belt that thins to the south along the southeastern margin of the basin. The New Oxford Formation consists of fluvial arkosic sandstone, siltstone, and conglomerate. It is more conglomeratic along its basal contact with older rocks on the southeastern margin of the basin. The New Oxford in Maryland is overlain by Triassic Gettysburg Formation, which comprises the rest of the basin fill. The lower part of the Gettysburg Formation consists of fluvial red siltstones with thin arkosic sandstones. The upper part of the Gettysburg Formation consists of lacustrine red and black shales and siltstones. The lower part of this portion of the Gettysburg Formation contains more frequent occurrences of black shale and is called the Heidlerburg Member.

South of the Gettysburg basin, the northernmost part of the Culpeper basin extends into Virginia. The Culpeper strata also dip westward toward the border fault and are part of a broad syncline that extends into Virginia, but they are cut by numerous north-northeast trending faults. The basal Manassas Sandstone is a fluvial arkosic sandstone, siltstone, and conglomerate. The Manassas Sandstone is overlain by the Balls Bluff Siltstone, which in Maryland consists of fluvial siltstones and thin arkosic sandstones similar to the lower Gettysburg Formation. Along the western faulted margin of both basins, all of the formations intertongue with conglomerates containing clasts of the older rocks immediately outside of the basin. In the Culpeper basin, the conglomerates derived from Paleozoic limestones adjacent to the border are called the Leesburg Conglomerate Member of the Balls Bluff Siltstone. The sedimentary rocks in both basins are intruded by Jurassic diabase dikes and sheets.

The Appalachian Province

The Appalachian Province is bounded on the east by Precambrian to Cambrian metamorphic rocks of the Blue Ridge. The Great Valley, Valley and Ridge, and Allegheny Plateau comprise a sequence of marine and fluvial sedimentary rocks folded into distinct ridges and valleys. The rocks range from Cambrian to Permian in age, with limestone and shale forming the valleys and more resistant sandstones forming the prominent ridges.

The South Mountain Anticlinorium dominates the Blue Ridge and forms prominent mountains just west of the Mesozoic basins. It is cored by Precambrian granodiorite and biotite granite gneiss that crop out in the Middletown Valley, which lies between South Mountain and Catoctin Mountain in the southern part of the area. Overlying the Precambrian basement is a thin discontinuous unit named the Swift Run Formation, a coarse-grained quartzite interbedded with phyllite, tuffaceous slate, and minor marble. This in turn is overlain by the Precambrian-Cambrian Catoctin Metabasalt, which underlies most of the area. It is composed of metabasalt layers with minor metarhyolite, meta-andesite, and tuffaceous phyllite. Epidote alteration is common. In the north, the metabasalt is overlain by metarhyolite and associated pyroclastic sediments. A thick sequence of Cambrian-Ordovician clastic and carbonate sediments overlies the volcanic sequence and includes thin conglomerate of the Loudoun Formation, which is overlain by a thick layer of the ridge-forming quartzite of the Weverton Formation and followed by phyllite of the Harpers Formation. This sequence is repeated on both the east and west sides of the anticlinorium. On the west side of South Mountain, the sequence continues with the Antietam Formation overlying the Harpers. This unit is succeeded by the Tomstown Dolomite as the section passes into the Great Valley.

West of South Mountain, the Tomstown Dolomite is succeeded by the thin-bedded siltstone, shale, sandstone, and dolomite of the Waynesboro Formation. A sequence of Cambrian through Ordovician limestones and shales follows and underlies most of eastern Washington County and the Great Valley. This sequence includes the argillaceous limestone, shale, and dolomite of the Elbrook Limestone, the argillaceous limestone, minor conglomerate, shale, and sandstone of the Conococheague Limestone, the dolomite, limestone, and conglomerate of the Stonehenge Limestone, the thick cherty dolomite and limestone of the Rockdale Run Formation, and the cherty dolomite of the Pinesburg Station Dolomite. These last three units are gathered into the Beekmantown Group. The Beekmantown Group is followed by Ordovician limestones of the St. Paul Group, including the Row Park Limestone and the New Market Limestone. The St. Paul Group is overlain by the Chambersburg Limestone at the top of the Ordovician carbonate sequence. West of Hagerstown, a fault separates the carbonate sequence form a wide band of Ordovician shales, siltstones, and graywackes known as the Martinsburg Formation. West of this wide band of Martinsburg, the carbonate units and Martinsburg Formation are tightly folded into thin bands and faulted. Just west of Clear Spring, the North Mountain Fault separates the Great Valley from younger sedimentary rocks of Silurian and Devonian age. Folded Silurian and Devonian sedimentary rocks underlie most of Allegany County and western Washington County and comprise the Valley and Ridge in Maryland. Silurian rocks are exposed in several major folds in central Washington County and eastern and western Allegany County. At the base of the Silurian section is the Tuscarora Sandstone, which consists of thin to thick-bedded orthoquartzite that crops out most extensively in western Allegany County. The Tuscarora is overlain by the Clinton Group, including the interbedded gray shales and sandstones of the Rose Hill Formation, the quartzite and calcareous quartzite of the Keefer Sandstone, and the calcareous, gray Rochester Shale. The Clinton Group is overlain by the McKenzie Formation, consisting of gray shales and argillaceous limestone which grade into interbedded red shales and sandstones to the west. The interbedded red siltstone, shale, and sandstone of the Bloomsburg Formation and limestone, dolomite, and shale of the Wills Creek Formation occur extensively in the synclines. They are overlain by the thick limestone, dolomitic limestone, calcareous shale, and sandstone of the Tonoloway Limestone.

At the top of the Silurian section and base of the Devonian section are the Keyser Limestone, comprising calcarenite, limestone, and shale, and the Helderberg Formation, consisting of limestone with minor shale and sandstone. These rocks underlie only small areas in this province. The Devonian Oriskany Group overlies, and, in places, intertongues with the Helderberg Formation and crops out in wide bands in western Washington and Allegany Counties. The Oriskany Group comprises the black shales and bedded cherts of the Shriver Chert and calcareous quartzite and limestone of the Oriskany Sandstone. The Devonian Needmore Shale Overlies the Oriskany and crops out extensively in southern Allegheny County and central and western Washington County. It consists of black shale and argillaceous limestone which is succeeded by the black carbonaceous and pyritic Marcellus Shale, and the dark gray shale, siltstone, and fine sandstone of the Mahantango Formation. Overlying the Mahantango is the thin, gray, laminated Harrell Shale, the thick gray shale and siltstone of the Brallier Formation, the sandy shale, graywacke, and conglomeratic sandstones of the Scherr and Foreknobs Formations. Broad bands of Devonian Hampshire Formation crop out in Allegany and Garrett Counties. It consists of interbedded red and green mudstone, siltstone, sandstone, and shale. In western Allegany County, it is followed by thin bands of Mississippian sedimentary rocks and marks the beginning of the Allegheny Plateau. The Allegheny Plateau is underlain by folded Devonian to Permian sedimentary rocks. At the base of the Mississippian is the Rockwell Formation, consisting of cross-bedded sandstone and conglomerate interbedded with gray and red shale, mudstone, and siltstone. It also includes arkosic sandstone, conglomerate, shale, and thin coal beds. Sandstone, conglomerate, shale, and coal comprise the overlying Purslane Sandstone. The Greenbrier Formation consists of narrow belts of red calcareous shale and sandstone interbedded with argillaceous limestone. It is overlain by the red and green shale, mudstone, and crossbedded sandstone of the Mauch Chunk Formation, which also forms relatively narrow belts. Overlying the Mauch Chunk are the Pennsylvanian Pottsville and Allegheny Formations, consisting of a cyclic sequence of interbedded sandstone, siltstone, mudstone, shale and coal beds with a conglomeratic quartz sandstone at the base. These two formations crop out extensively in wide belts throughout the Allegheny Plateau. Overlying the Allegheny Formation is the Conemaugh Formation, which is composed of gray and brown mudstone, shale, siltstone, and sandstone with several coal beds. Broad bands of Conemaugh Formation underlie approximately a third of the Allegheny Plateau. The Monongahela Formation overlies the Conemaugh and comprises interbedded mudstone, argillaceous limestone, shale, sandstone, and coal beds. The Permian Dunkard Group overlies the Monongahela and consists of red and green shale, siltstone and sandstone with thin lenticular beds of argillaceous limestone and coal.

SOILS

Soils in Maryland include Ultisols, Alfisols, Inceptisols, and Histosols (U.S. Soil Conservation Service, 1987). Ultisols are mineral soils with a horizon containing an appreciable amount of translocated clay (but they do not contain fragipans) and they often have a moist or wet substratum. Ultisols occur mainly in the Coastal Plain and Piedmont. Alfisols are mineral soils with clayey subsurface horizons or fragipans, and may contain plinthite (iron-rich horizons) or calcic horizons in the subsurface. Alfisols cover large parts of the Piedmont and the Blue Ridge. Inceptisols are described as soils with weakly developed horizons in which materials have been altered or removed and they may contain horizons of accumulated silica, iron, or bases, but they generally do not have clayey subsurface horizons. These soils cover most of the Appalachian Province. Histosols are organic soils such as peats or mucks which occur locally along coastlines or in river valleys (Soil Survey Staff, 1975). Figure 5 is a generalized soil map of Maryland. The reader is urged to consult State soil maps and reports and U.S. Soil Conservation Service county soil surveys for more detailed information.

Coastal Plain Soils

The Coastal Plain is covered by poorly drained to somewhat well-drained soils on the more dissected and rolling western shore, and mostly poorly drained soils on the nearly flat Eastern Shore (Miller, 1967). Deep, poorly to well-drained, fine and very fine sand with minor amounts of glauconite occur on rolling uplands in the southern part of the western shore (fig. 5). These soils are weakly to moderately well developed and have slightly to moderately clayey subsoils. Shallow to moderately deep, poorly drained to moderately well drained, sandy and silty soils with

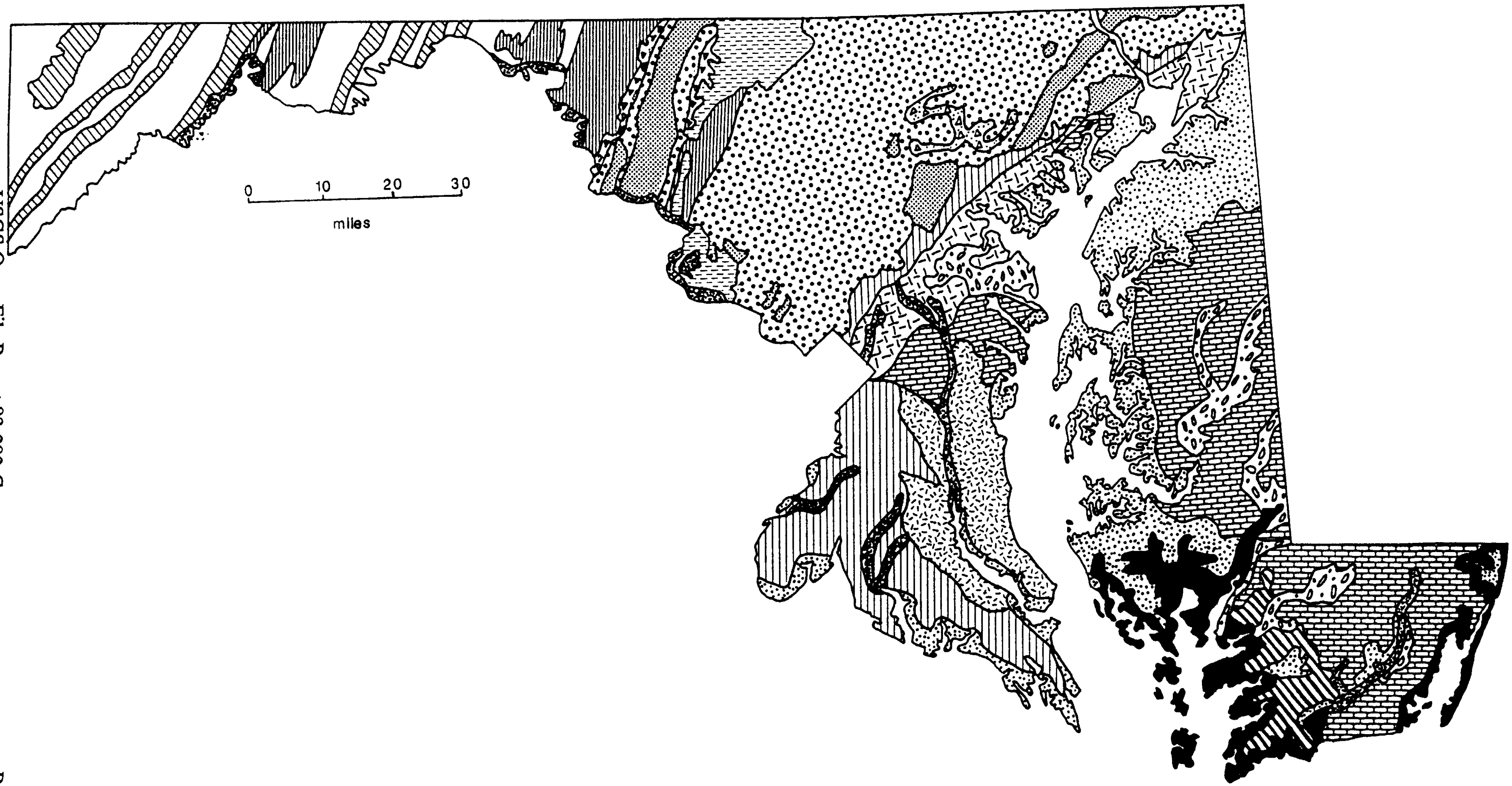


Figure 5. Generalized soil map of Maryland (after Miller, 1967).

EXPLANATION FOR THE GENERALIZED SOILS MAP OF MARYLAND

SOILS FORMED FROM SEDIMENTARY ROCKS

Shallow to moderately deep, moderately well drained to excessively drained, sandy loam, silt loam, and silty clay loam formed in residuum from gray acid shale, sandstone, and alluvium; *mostly moderate permeability, clayey soils developed on shales have lower permeability*

Shallow to moderately deep, well drained to excessively drained, stony, silty and sandy soils formed in residuum from red and gray acid shale, siltstone, and sandstone; *moderate to locally high permeability.*

Shallow to deep, poorly to moderately drained, clayey, silty, and sandy soils developed on red shale, siltstone, and sandstone; *low to moderate permeability*

In valleys, deep, well drained, silt loams, some with with clayey substrata, formed in residuum from limestones, calcareous shale, and interbedded limestone and shale; *low to moderate permeability.* Along valley slopes, includes soils developed on colluvium from sandstone and shale; *mostly moderate permeability*

SOILS FORMED FROM IGNEOUS AND METAMORPHIC ROCKS

Deep, somewhat poorly drained to well drained, silty soils with clayey substrata or fragipans, formed on residuum from metabasalt (greenstone), schist, gneiss, diabase, and locally, quartzite; *low permeability*

In the western part, shallow, well to excessively drained, skeletal, silt loams formed on residuum from hard schist and phyllite; *moderate to high permeability.*
In the eastern part, shallow to moderately deep, poorly to well drained, clayey sandy soils with clayey substrata developed from soft mica schist; *low to locally moderate permeability*

Deep, well drained, gravelly to stony soils formed on colluvium of crystalline rocks; *high permeability*

Deep, well drained silty to gravelly soils formed on colluvium of schist and limestone; *moderate to high permeability*

SOILS FORMED FROM UNCONSOLIDATED COASTAL PLAIN SEDIMENTS

Very deep, poorly drained to excessively drained, sandy, silty, and clayey soils formed on sandy and silty deposits (contains moderate amounts of glauconite on Western Shore); *moderate to high permeability*

Very deep, sandy, excessively drained to locally poorly drained soils formed on nearly level to steep uplands of the Coastal Plain; *locally moderate to mostly high permeability*

Deep, well drained, fine and very fine sand with minor amounts of glauconite; *moderate permeability*

Shallow to moderately deep, poorly drained to moderately well drained, sandy and silty soils with fragipans and clayey subsoils, overlying older gravelly and sandy sediments; *low to moderate permeability*

Deep, generally poorly drained, silt loams and clay loams with clayey B horizons and commonly high water tables; *low permeability*

Deep, very poorly drained, silty soils in low-lying areas; *moderate permeability*, typically wet

Deep, well drained, clayey soils on higher uplands of the Coastal Plain; *low permeability*

Organic-rich soils of tidal marshes; commonly flooded

SOILS FORMED FROM ALLUVIAL MATERIALS

Deep, clayey, silty, sandy, and gravelly soils developed on alluvial sediments; upland alluvial soils and soils of old, high terraces of the Potomac River are generally moderately well to well drained; alluvial soils of the Coastal Plain are more poorly drained; *permeability is variable depending on parent lithology* fragipans and clayey subsoils that overlie older gravelly and sandy sediments cover the southern and western Coastal Plain. These soils are slowly permeable and are subject to seasonally high water tables due to clay fragipans that form at 15-25 inches depth. Deep, well-drained, clayey, red soils cover higher uplands of the Coastal Plain. The subsoil clay separates into distinct blocks, giving these soils low to locally moderate permeability. Some of the soils in this map unit contain considerable amounts of sand, although the matrix of the soil is dominantly clay.

Very deep, poorly drained to excessively drained, sandy and silty soils cover much of the Eastern Shore of the Coastal Plain (fig. 5). These yellow and brown soils are common to much of the Coastal Plain region of the Mid-Atlantic States (Miller, 1967). Where these soils are formed on rolling topography, they are moderately to well-drained; however, they tend to have high water tables in flatter areas. Soils of this map unit on the Western Shore are silty and clayey soils containing moderate amounts of glauconite. Deep, generally poorly drained silt loams and clay loams with slowly permeable B horizons and commonly high water tables are extensive on the Eastern Shore (fig. 5). Some of these soils have distinctive mottling, indicating that they remain wet for considerable periods of time during the year. Soils in the southern part of the Coastal Plain are deep, very poorly drained, silty soils in low-lying areas, and organic-rich soils of tidal marshes. The silty soils overlie moderately to highly permeable sands and silts, but because they are low-lying, these and the adjacent tidal marshes are typically wet throughout the year.

Piedmont Soils

Soils of the Piedmont are formed primarily on igneous and metamorphic rocks, except for the sedimentary rocks that underlie the Frederick Valley. Shallow to moderately deep, well-drained to excessively drained, silty and sandy soils form in residuum of red Triassic shale, siltstone, and sandstone. The red soils have a distinct, red clayey B horizon and they are generally more poorly drained than the gray soils in this area (Miller, 1967). Shallow to moderately deep, well-drained, silt loams formed on residuum from mica schist, phyllite, quartzose schist, and quartzite cover most of the Piedmont province (fig. 5). Soils formed on relatively soft mica schist saprolites in the eastern half of the province are well developed and contain 20-25 percent clay in the subsoil (Miller, 1967). Soils in the western Piedmont are formed on more resistant schist and phyllite and are generally shallow, skeletal, poorly developed, silty or loamy throughout the profile, and generally well- to excessively drained. Deep, well-drained, gravelly to stony soils formed on colluvium of quartzite, quartzitic schist, and phyllite occur on the eastern and western slopes of Catoctin Mountain. These soils are gravelly to stony, poorly developed, excessively drained, and highly permeable. Colluvial soils formed mainly from schist are found in the eastern Piedmont just north of Baltimore. These deep, well-drained, silty to gravelly soils occur at the base of slopes, and they locally contain fragments of limestone parent material.

Appalachian Province Soils

Soils of the Appalachian province are shallow to moderately deep, moderately well drained to excessively drained, sandy loam, silt loam, and silty clay loam formed in residuum from gray acid shale, sandstone, and siltstone. These soils have generally low to moderate permeability and are common in the Allegheny Plateau and Valley and Ridge provinces. Deep, well-drained, silt loams, some with clayey substrata, formed in residuum from limestones, calcareous shale, and interbedded limestone and shale cover most of the Great Valley, Frederick Valley, and areas underlain by cherty limestones in the western Valley and Ridge (fig. 5). These soils have a slowly permeable, plastic clay subsoil and are acidic because most of the carbonates have been leached from the soil profile (Miller, 1967). In the Valley and Ridge, these soils are typically well drained because they occur on steep slopes and limestone-capped ridgetops. Deep, somewhat poorly drained to well drained, silty soils with slowly permeable, clayey substrata, formed on residuum from metabasalt, schist, gneiss, diabase, and quartzite, are found in the Blue Ridge province.

RADIOACTIVITY

An aeroradiometric map of Maryland (fig. 6) was compiled from spectral gamma-ray data acquired during the Department of Energy's National Uranium Resource Evaluation (NURE) program (Duval and others, 1989). For the purposes of this report, low equivalent uranium (eU) on the map is defined as less than 1.5 parts per million (ppm), moderate equivalent uranium is defined as 1.5-2.5 ppm, and high equivalent uranium is defined as greater than 2.5 ppm. Low eU appears to be associated with the Blue Ridge metavolcanic and metasedimentary rocks, Jurassic diabase in the western Piedmont, and the Quaternary sediments of the Eastern Shore. Low to moderate eU covers much of the Allegheny Plateau, the Tertiary and Cretaceous sediments of the Coastal Plain, and parts of the Valley and Ridge. High eU areas in the State appear to be associated with Cambrian and Ordovician sediments of the Great Valley; Precambrian, Cambrian, and Triassic igneous, metamorphic, and sedimentary rocks of the western Piedmont; and metamorphic and igneous rocks of the eastern Piedmont.

The NURE reports for the Harrisburg Quadrangle (LKB Resources, 1978), the Baltimore Quadrangle (Texas Instruments Incorporated, 1978a), the Cumberland Quadrangle (Texas Instruments Incorporated, 1980), and the Washington Quadrangle (Texas Instruments Incorporated, 1978b) indicate that high to moderate eU is associated with particular geologic units along the flightlines of the aerial radiometric survey. Rock units with high eU include: Precambrian schists and Baltimore Gneiss of the Piedmont; the Precambrian-Cambrian Harpers Formation; the Cambrian Elbrook Limestone, Waynesboro Formation, Kinzers Formation, Tomstown, and Weverton Formations; the Ordovician Chambersburg Limestone, Martinsburg Formation, and Rockdale Run Formation; the Silurian Tonoloway, Keyser, and Wills Creek Formations and the Clinton Group; the Devonian Hampshire Formation and Hamilton Group; the Pennsylvanian Monongahela Formation; and the Tertiary Calvert Formation.

INDOOR RADON

Indoor radon data from 1126 homes sampled in the State/EPA Residential Radon Survey conducted in Maryland during the winter of 1991 are shown in map format in figure 7 and statistically in Table 1. A map with county names is also included for reference (fig. 8). Indoor radon was measured by charcoal canister. The maximum value recorded in the survey was 139.6 pCi/L in Carroll County. The average for the State was 3.1 pCi/L and 19.9 percent of the homes tested had indoor radon levels exceeding 4 pCi/L. Notable counties include Calvert, Carroll, Frederick, Howard, and Washington Counties, in which the average indoor radon for the county was ≥ 4 pCi/L. The State of Maryland compiled data from volunteers, the University of Pittsburgh Radon Project (Cohen, 1990), and commercial vendors to produce a non-random data set of more than 37,000 data points (State of Maryland, 1989). These data are presented in Table 2 for comparison with the State/EPA data. Non-random (volunteer) indoor radon data tend to be biased toward higher values compared to randomly sampled surveys because it is more likely that many of the data points are from homeowners that tested their homes after receiving word of a nearby high value. Four percent of the homes in this dataset had indoor radon levels exceeding 20 pCi/L and

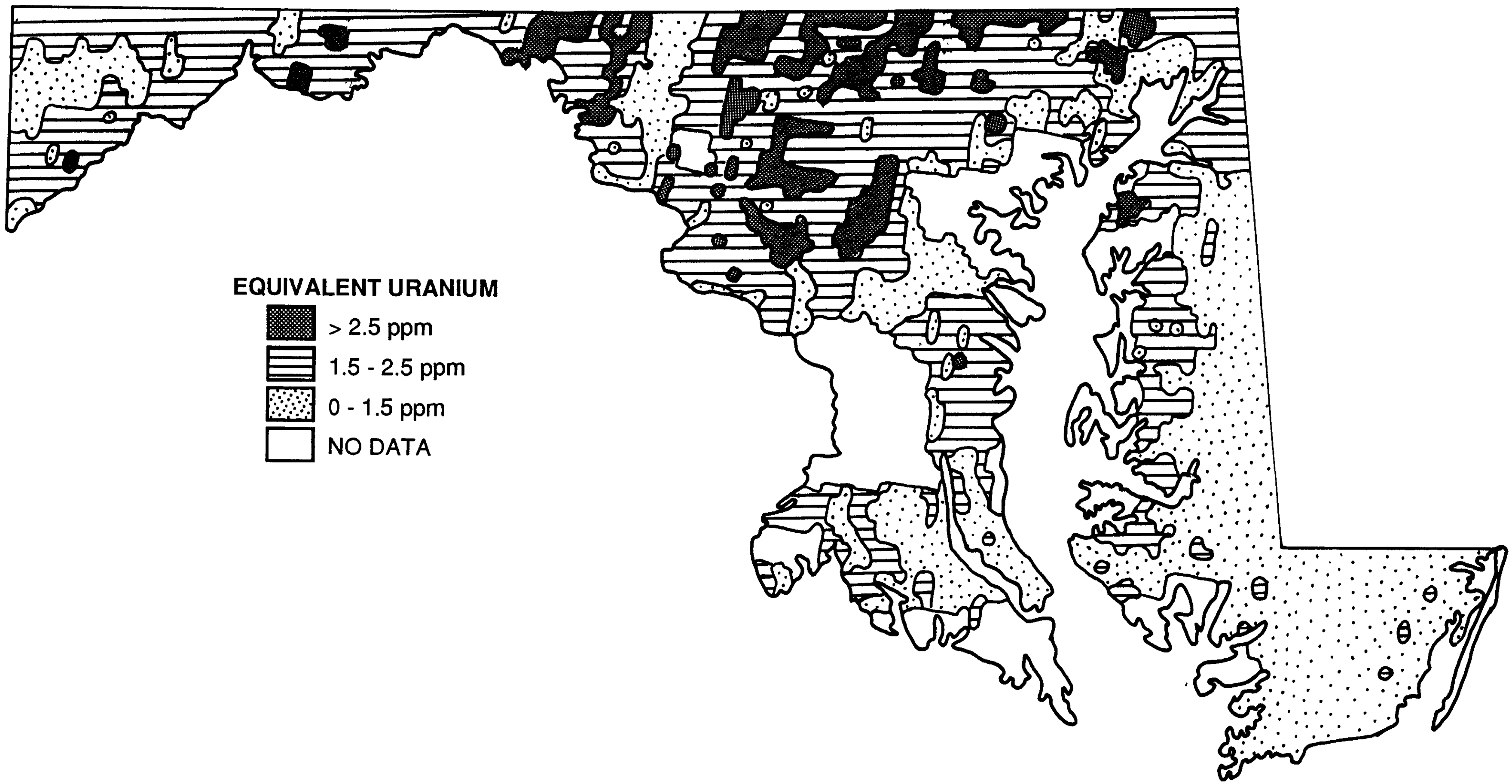
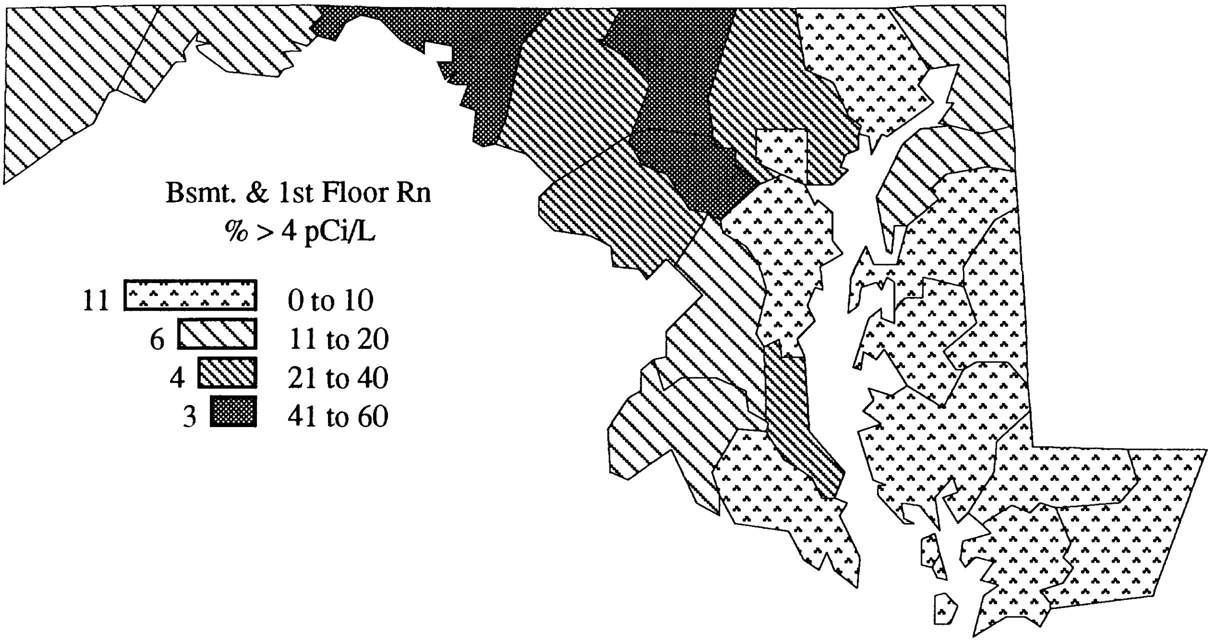


Figure 6. Aerial radiometric map of Maryland (after Duval and others, 1989).



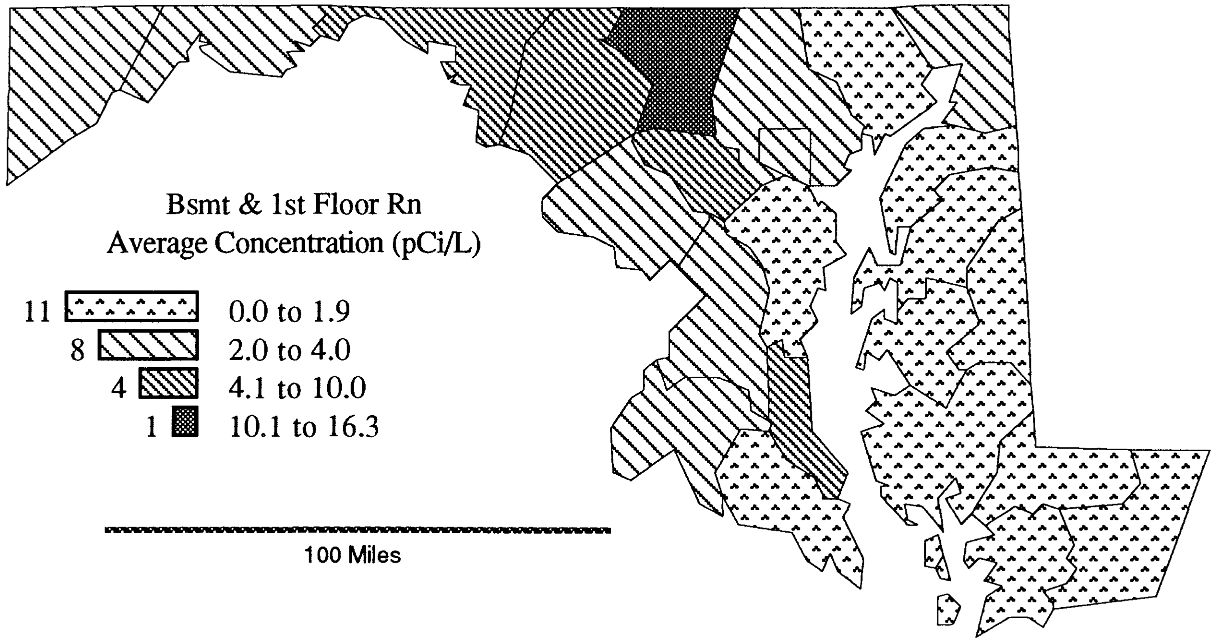


Figure 7. Screening indoor radon data from the EPA/State Residential Radon Survey of Maryland, 1990-91, for counties with 5 or more measurements. Data are from 2-7 day charcoal canister tests. Histograms in map legends show the number of counties in each category. The number of samples in each county (See Table 1) may not be sufficient to statistically characterize the radon levels of the counties, but they do suggest general trends. Unequal category intervals were chosen to provide reference to decision and action levels.

TABLE 1. Screening indoor radon data from the EPA/State Residential Radon Survey of Maryland conducted during 1990-91. Data represent 2-7 day charcoal canister measurements from the lowest level of each home tested.

COUNTY	NO. OF MEAS.	MEAN	GEOM. MEAN	MEDIAN	STD. DEV.	MAXIMUM	%>4 pCi/L	%>20 pCi/L
ALLEGANY	74	2.7	1.3	1.3	5.8	46.0	12	1
ANNE ARUNDEL	86	1.6	0.8	1.0	2.2	13.2	6	0
BALTIMORE	40	2.3	1.0	1.0	2.8	10.8	23	0
BALTIMORE CITY	79	2.1	0.5	0.4	7.4	63.2	8	1
CALVERT	16	4.9	1.4	1.1	9.4	37.9	31	6
CAROLINE	23	0.4	0.2	0.2	0.6	2.8	0	0
CARROLL	16	16.3	5.5	6.3	33.7	139.6	50	13
CECIL	61	2.1	1.1	1.3	2.4	11.2	15	0
CHARLES	19	2.6	0.6	0.4	7.3	32.1	16	5
DORCHESTER	18	0.2	0.1	0.1	0.4	1.5	0	0
FREDERICK	96	5.3	2.7	2.7	6.8	35.8	40	4
GARRETT	31	3.6	1.2	1.4	7.5	40.4	19	3
HARFORD	27	1.7	1.0	0.9	2.0	8.4	7	0
HOWARD	30	5.4	3.3	3.4	4.8	18.0	43	0
KENT	16	1.1	0.3	0.2	2.0	6.5	13	0
MONTGOMERY	101	3.1	1.7	1.8	3.9	26.1	24	1
PRINCE GEORGE'S	126	2.0	1.0	1.1	2.7	18.7	13	0
QUEEN ANNE'S	19	0.4	0.2	0.2	0.9	4.0	0	0
SOMERSET	17	0.2	0.1	0.1	0.7	2.8	0	0
ST. MARY'S	15	1.1	0.6	0.9	1.1	4.0	0	0
TALBOT	25	0.4	0.2	0.1	0.6	2.5	0	0
WASHINGTON	115	8.1	4.9	5.3	8.4	63.7	59	6
WICOMICO	50	0.2	0.2	0.1	0.4	1.3	0	0
WORCESTER	26	0.1	0.1	0.0	0.3	1.1	0	0

Table 2. Maryland Radon Data Summary. The minimum, maximum, and average radon levels in pCi/l are presented for each county with at least 100 data points. An asterisk (*) highlights those jurisdictions with less than 100 data points, indicating insufficient data to characterize the radon situation in those jurisdictions. Compare the county average with the State average of 5.32 pCi/l.

(from State of Maryland, 1989)

Code	County	# Tests	Minimum pCi/l	Maximum pCi/l	Avg pCi/l
01	Allegany	152	.05	48.00	5.23
03	Anne Arundel	1599	.05	313.00	4.10
05	Baltimore	594	.05	270.30	7.62
07*	Balto. City	70	.05	13.00	
09	Calvert	317	.05	52.00	5.40
11*	Caroline	6	.30	5.80	
13	Carroll	1140	.05	482.90	15.06
15*	Cecil	52	.05	49.00	
17	Charles	577	.05	76.00	2.72
19*	Dorchester	7	.05	5.00	
21	Frederick	1978	.05	491.00	11.20
23*	Garrett	45	.60	36.10	
25	Harford	230	.05	87.30	7.24
27	Howard	2512	.05	895.30	8.61
29*	Kent	2	.05	2.50	
31	Montgomery	20356	.05	376.90	4.67
33	Prince Georges	6516	.05	209.00	2.41
35*	Queen Anne's	28	.10	11.00	
37	Saint Marys	260	.05	22.00	2.03
39*	Somerset	1	6.70	6.70	
41*	Talbot	38	.20	6.70	
43	Washington	612	.05	679.80	12.64
45*	Wicomico	5	.40	2.10	
47*	Worcester	2	.40	.90	

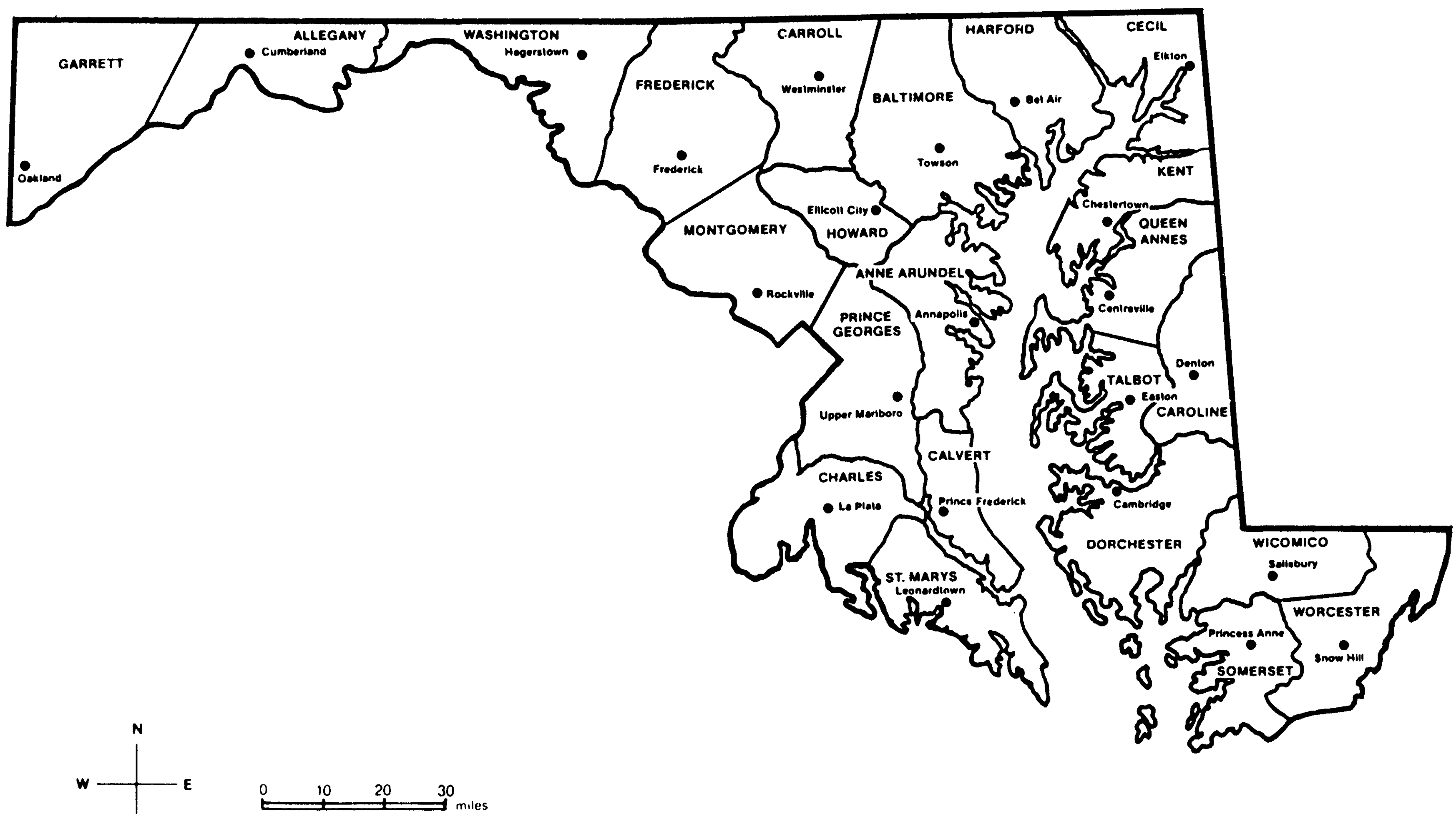


Figure 8. Maryland counties (from Facts on File, 1984).

29 percent of the homes tested had indoor radon levels between 4 and 20 pCi/L. Carroll, Frederick, and Washington Counties had indoor radon averages greater than 10 pCi/L. Charles, Prince George's, and Saint Mary's Counties, all located in the Coastal Plain, had indoor radon averages less than 4 pCi/L.

GEOLOGIC RADON POTENTIAL

Coastal Plain Province

The Western Shore has been ranked moderate to locally high in geologic radon potential and the Eastern Shore has been ranked low in radon potential. The Coastal Plain Province is underlain by relatively unconsolidated fluvial and marine sediments that are variably phosphatic and glauconitic on the Western Shore and dominated by quartz in the Eastern Shore. Radioactivity in the Coastal Plain is moderate over parts of the Western Shore sediments, particularly in the Upper Cretaceous and Tertiary sediments of Prince George's, Anne Arundel, and northern Calvert Counties. Moderate radioactivity also appears to be associated with the Cretaceous and Tertiary sediments of the Eastern Shore where these sediments are exposed in major drainages in Kent, Queen Anne's, and Talbot Counties. Soil radon studies in Prince George's County (Otton, 1992; Reimer, 1988; Reimer and others, 1991) indicate that soils formed from the locally phosphatic, carbonaceous, or glauconitic sediments of the Calvert, Aquia, and Nanjemoy Formations can produce significantly high radon (average soil radon > 1500 pCi/L). Otton (1992) indicates that the Cretaceous Potomac Group had generally moderate levels of soil radon, averaging 800-900 pCi/L, and the Tertiary-Cretaceous Brightseat Formation and Monmouth Group had average soil radon of 1300 pCi/L. Permeability in the Western Shore is variably low to moderate with some high permeability in sandier soils. Well-developed clayey B horizons with low permeability are common. Indoor radon from the State/EPA Residential Radon Survey is variable among the counties of the Western Shore and indoor radon levels are generally low to moderate, with Calvert County having a high average (4.9 pCi/L, but only 16 measurements in the county). The Maryland radon data summary (Table 2) indicates moderate to high average indoor radon for most of the Western Shore counties. For this assessment we have ranked part of the Western Shore as high in radon potential, including Calvert County, southern Anne Arundel County, and eastern Prince George's County. This area has the highest radioactivity, high indoor radon, and significant exposure of Tertiary rock units. The part of the Western Shore ranked moderate consists of Quaternary sediments with low radon potential, Cretaceous sediments with moderate radon potential, and lesser amounts of Tertiary sediments with high radon potential. The Quaternary sediments of the Eastern Shore have low radioactivity associated with them and are generally quartzose and thus low in uranium. Heavy-mineral concentrations within these sediments may be very local sources of uranium. Indoor radon appears to be generally low on the Eastern Shore with only a few measurements over 4 pCi/L reported.

Piedmont Province

Gneisses and schists in the eastern Piedmont, phyllites in the western Piedmont, and Paleozoic metasedimentary rocks of the Frederick Valley have been ranked high in geologic radon potential. Sedimentary and igneous rocks of the Mesozoic basins have been ranked moderate in radon potential. Radioactivity in the Piedmont is generally moderate to high. Indoor radon is moderate to high in the eastern Piedmont and nearly uniformly high in the western Piedmont. Permeability is low to moderate in soils developed in the mica schists and gneisses of the eastern

Piedmont, Paleozoic sedimentary rocks of the Frederick Valley, and igneous and sedimentary rocks of the Mesozoic Basins. Permeability is moderate to high in the soils developed on the phyllites of the western Piedmont. The Maryland Geological Survey has conducted a comparison of the geology of Maryland with the Maryland radon data summary in Table 2. They report (State of Maryland, 1989) that most of the Piedmont rocks, with the exception of ultramafics, can generate indoor radon readings exceeding 4 pCi/L. Their data indicate that the phyllites of the western Piedmont have much higher radon potential than the schists in the east. Ninety-five percent of the homes built on phyllites of the Gillis Formation had indoor radon measurements greater than 4 pCi/L, and 47 percent of the measurements were greater than 20 pCi/L. In comparison, 80 percent of the homes built on the schists and gneiss of the Loch Raven and Oella Formations had indoor radon readings greater than 4 pCi/L, but only 9 percent were greater than 20 pCi/L. Studies by Gundersen and others (1988), Mose and others (1988a, b), and Mose and Mushrush (1988a, b, c) support this conclusion.

Szarzi and others (1990) have also shown that the phyllites in Frederick County yield the highest average soil-gas radon when compared to the other rock types, and that soils derived from limestone and shale, and some of the Triassic sedimentary rocks, in the Frederick Valley may be significant sources of radon (500-2000 pCi/L in soils). In Maryland, Gundersen and others (1988) noted high uranium concentrations in fluvial crossbeds of the upper Manassas Sandstone containing gray carbonaceous clay intraclasts and drapes. Similar lithologic associations are common in the upper New Oxford Formation. Black shales and gray sandstones of the Heidlersburg Member are similar to uranium-bearing strata in the Culpeper basin in Virginia. Black shales in the overlying Gettysburg Formation may also be locally uranium rich. The lower New Oxford Formation, the lower Manassas Sandstone, the lower Gettysburg Formation, and the Balls Bluff Siltstone in Maryland are not likely to have significant concentrations of uranium except where altered by diabase intrusives and/or faulted. The diabase bodies are low in radon potential. Because of the highly variable nature of the Triassic sediments and the amount of area the rocks cover with respect to the county boundaries, it is difficult to say with confidence whether the high indoor radon in Montgomery, Frederick, and Carroll Counties is partly attributable to the Triassic sediments.

Appalachian Province

The Appalachian Province is divided into the Blue Ridge, Great Valley, Valley and Ridge, and Allegheny Plateau. Each of these areas is underlain by a distinct suite of rocks with a particular radon potential. The Blue Ridge is ranked low in radon potential but may be locally moderate to high. The Catoctin volcanic rocks that underlie a significant portion of the Blue Ridge have low radioactivity, yield low soil radon (Szarzi and others, 1990) and have low soil permeability. The quartzite and conglomerates overlying the Catoctin also have low radioactivity and low soil radon (Szarzi and others, 1990). Further, the Pennsylvania Topographic and Geologic Survey (J. Barnes and R. Smith, upub. data) calculated the median uranium content of 80 samples of Catoctin metabasalt and metadiabase (measured by delayed neutron activation) and found it to be less than 0.5 ppm. The Harpers Formation phyllite yields high soil radon (1000 pCi/L), has higher surface radioactivity than the surrounding rocks (Szarzi and others, 1990), and is a potential source of radon. The Precambrian gneiss that crops out in the Middletown Valley of the southern Blue Ridge appears to have moderate radioactivity associated with it and yielded some high soil-gas radon in Szarzi and others' (1990) study. It is difficult, given the constraints of the indoor radon data, to associate the high average indoor radon in the part of Frederick County underlain by parts of this province with the actual rocks. The Blue Ridge is provisionally ranked low in geologic radon potential, but this cannot be verified with the present indoor radon data.

Carbonates and black shales in the Great Valley in Maryland have been ranked high in radon potential. Radioactivity is moderate to high over the Great Valley in Washington County. Washington County has more than a hundred indoor radon measurements, has an average indoor radon of 8.1 pCi/L in the State/EPA Survey, and more than half of the readings are greater than 4 pCi/L. To the north in Pennsylvania, carbonate rocks of the Great Valley and Appalachian Mountain section have been the focus of several studies (van Assendelft and Sachs, 1982; Gross and Sachs, 1982; Greeman and Rose, 1990; Luetzelschwab and others, 1989), and the carbonates in these areas produce soils with high uranium and radium contents that generate high radon concentrations. In general, indoor radon levels in these areas are more than 4 pCi/L. Soils developed from carbonate rocks are often elevated in uranium and radium. Carbonate soils are derived from the dissolution of the $CaCO_3$ that makes up the majority of the carbonate rock. When the $CaCO_3$ has been dissolved away, the soils are enriched in the remaining impurities, predominantly base metals, including radionuclides. Studies in the carbonates of the Great Valley in West Virginia suggest that the deepest, most mature soils have the highest radium and radon concentrations (Schultz and others, 1992). Rinds containing high concentrations of uranium and uranium-bearing minerals can be formed on the surfaces of rocks affected by $CaCO_3$ dissolution and karstification. Karst and cave morphology is also thought to promote the flow and accumulation of radon. Schultz and others (1992) also measured high radon in soils and high indoor radon in homes over the black shales of the Martinsburg Formation.

The Silurian and Devonian rocks of the Valley and Ridge have been ranked moderate to locally high in geologic radon potential. Indoor radon measurements from the State/EPA Residential Radon Survey in Allegany County have an average of 2.7 pCi/L and 12 percent of the 74 measurements were greater than 4 pCi/L. In the Maryland radon data summary (Table 2) the average for Allegeny County was 5.23 pCi/L and 30 percent of the 152 measurements were greater than 4 pCi/L. Bedford County, Pennsylvania, which is adjacent to Allegeny County and is underlain by the same rock types, has a high indoor radon average in the State/EPA survey. Soil permeability is variable but is generally moderate. Radioactivity in the Valley and Ridge is moderate to locally high. The Tonoloway, Keyser, and Wills Creek Formations and Clinton and Hamilton Groups have high equivalent uranium associated with them in the NURE aeroradiometric data. The shales, limestone soils, and hematitic sands are possible sources of these high readings.

The Devonian through Permian rocks of the Allegheny Plateau have been ranked moderate in geologic radon potential. Indoor radon measurements from the State/EPA survey for Garrett County have an average of 3.5 pCi/L for the 31 measurements taken in the county. Radioactivity in the Allegheny Plateau is low to moderate. Soil permeability is variable but is generally moderate. The NURE report for the Harrisburg Quadrangle (LKB Resources, 1978) reports high equivalent uranium associated with the Pocono Group and Mauch Chunk Formation.

Van Assendelft and Sachs (1982) list an extensive table of indoor radon and associated geologic units in Pennsylvania that may be applicable to equivalent units in Maryland. It appears from the uranium and radioactivity data and comparison with the indoor radon data that the Cambrian-Ordovician limestone soils, the black shales of the Ordovician Martinsburg Formation, the early Devonian black shales, Pennsylvanian black shales of the Allegheny Group, Conemaugh Group, and Monongahela Group, and the fluvial sandstones of the Devonian Hampshire and Mississippian Mauch Chunk Formations may be sources of moderate to high indoor radon levels in the Appalachian Province.

SUMMARY

For the purpose of this assessment, Maryland has been divided into ten geologic radon potential areas and each area assigned a Radon Index (RI) and a Confidence Index (CI) score using the information outlined in the sections above (Table 3). The RI is a relative measure of radon potential based on geology, soils, radioactivity, architecture, and indoor radon. The CI is a measure of the confidence of the RI assessment based on the quality and quantity of the data used to assess geologic radon potential (please see the introduction chapter to this regional booklet for a detailed explanation of the RI and CI). The geologic radon potential areas are shown in figure 9.

Geology, soil permeability, indoor radon, and radioactivity data for Maryland suggest that many of the soils and rocks of the Piedmont and Great Valley have the potential to produce moderate (2-4 pCi/L) to high (> 4 pCi/L) levels of indoor radon. Soils and rocks of the Allegheny Plateau, Valley and Ridge, and the Western Shore of the Coastal Plain are generally moderate in radon potential but can be locally high in geologic radon potential. Soils and rocks of the Blue Ridge and Eastern Shore of the Coastal Plain are relatively low in radon potential.

This is a generalized assessment of the State's geologic radon potential and there is no substitute for having a home tested. The conclusions about radon potential presented in this report cannot be applied to individual homes or building sites. Indoor radon levels, both high and low, can be quite localized, and within any radon potential area there will likely be areas with higher or lower radon potential than assigned to the area as a whole. Any local decisions about radon should not be made without consulting all available local data. For additional information on radon and how to test, contact your State radon program or EPA regional office. More detailed information on state or local geology may be obtained from the state geological survey. Addresses and phone numbers for these agencies are listed in chapter 1 of this booklet.

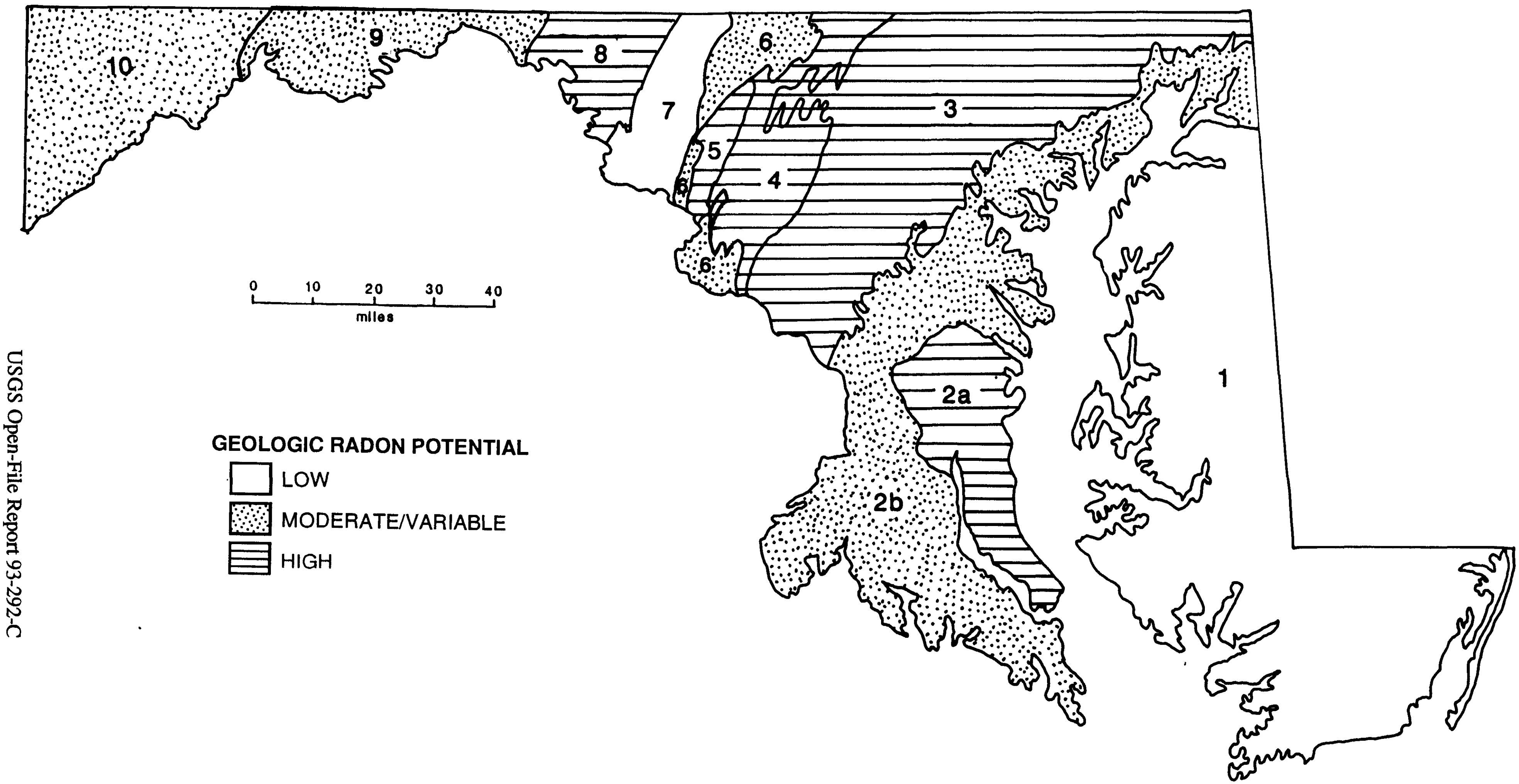


Figure 9. Geologic radon potential areas of Maryland. Refer to Table 3 for RI and CI scores of areas.

TABLE 3. RI and CI scores for geologic radon potential areas of Maryland. See figure 9 for locations of areas.

FACTOR	(2b) Western Shore, Cretaceous Quaternary, minor Tertiary RI	CI	(1) Eastern Shore Quaternary RI	CI	(3) Eastern Piedmont schist and gneiss RI	CI	(2a) Western Shore Tertiary RI	CI
INDOOR RADON	2	2	1	2	3	3	3	3
RADIOACTIVITY	2	2	1	2	2	3	2	3
GEOLOGY	2	3	1	3	2	3	3	3
SOIL PERM.	2	3	2	3	2	3	2	3
ARCHITECTURE	2	-	2	-	3	-	2	-
GFE POINTS	0	-	0	-	0	-	0	-
TOTAL	10	10	7	10	12	12	12	12
RANKING	Mod	High	Low	High	High	High	High	High

FACTOR	(4) Western Piedmont Phyllite RI	CI	(7) Blue Ridge igneous and sedimentary RI	CI	(8)Great Valley/(5) Frederick Valley carbonates and clastics RI	CI
INDOOR RADON	3	3	1?	1?	3	3
RADIOACTIVITY	2	3	1	3	2	3
GEOLOGY	2	3	1	2	3	3
SOIL PERM.	3	3	2	3	2	3
ARCHITECTURE	3	-	3	-	3	-
GFE POINTS	2	-	0	-	0	-
TOTAL	15	12	8	9	13	12
RANKING	High	High	Low	Mod	High	High

FACTOR	(9)Valley and Ridge Silurian and Devonian RI	CI	(10) Allegheny Plateau RI	CI	(6) Mesozoic Basins Culpeper/Gettysburg basins RI	CI
INDOOR RADON	2	2	2	3	2?	1
RADIOACTIVITY	2	3	2	3	2	3
GEOLOGY	2	2	2	3	2	3
SOIL PERM.	2	3	2	3	2	3
ARCHITECTURE	3	-	3	-	3	-
GFE POINTS	0	-	0	-	0	-
TOTAL	11	10	11	12	11	10
RANKING	Mod	High	Mod	High	Mod	High

RADON INDEX SCORING:

Radon potential category	Point range	Probable screening indoor radon average for area
LOW	3-8 points	< 2 pCi/L
MODERATE/VARIABLE	9-11 points	2 - 4 pCi/L
HIGH	> 11 points	> 4 pCi/L

Possible range of points = 3 to 17

CONFIDENCE INDEX SCORING:

LOW CONFIDENCE	4 - 6 points
MODERATE CONFIDENCE	7 - 9 points
HIGH CONFIDENCE	10 - 12 points

Possible range of points = 4 to 12

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PRELIMINARY GEOLOGIC RADON POTENTIAL ASSESSMENT OF PENNSYLVANIA

by
Linda C.S. Gundersen and Joseph P. Smoot
U.S. Geological Survey

INTRODUCTION

This is a generalized assessment of geologic radon potential of rocks, soils, and surficial deposits of Pennsylvania. The scale of this assessment is such that it is inappropriate for use in identifying the radon potential of small areas such as neighborhoods, individual building sites, or housing tracts. Any localized assessment of radon potential must be supplemented with additional data and information from the locality. Within any area of a given radon potential ranking, there are likely to be areas with higher or lower radon levels than characterized for the area as a whole. Indoor radon levels, both high and low, can be quite localized, and there is no substitute for testing individual homes. Elevated levels of indoor radon have been found in every State, and EPA recommends that all homes be tested. For more information on radon, the reader is urged to consult the local or State radon program or EPA regional office. More detailed information on state or local geology may be obtained from the state geological survey. Addresses and phone numbers for these agencies are listed in chapter 1 of this booklet.

PHYSIOGRAPHIC AND GEOGRAPHIC SETTING

The physiography of Pennsylvania (fig. 1) is in part a reflection of the underlying bedrock geology (fig. 2). Pennsylvania is divided into seven major physiographic provinces: the New England, the Piedmont, the Blue Ridge, the Ridge and Valley, the Appalachian Plateaus, the Central Lowland, and the Atlantic Coastal Plain. Several of these provinces are subdivided into smaller regions (fig. 1) which will be referred to throughout this report.

The New England Province is underlain by metamorphic rocks of Precambrian age and is an area of steep rolling hills and valleys. Elevation varies from 90 to over 300 meters above sea level and local relief is several hundred meters. The Piedmont Province is subdivided into the Piedmont Upland, Piedmont Lowland, and Gettysburg-Newark Lowland sections. The Piedmont Upland is underlain by metamorphic, igneous, and sedimentary rocks of Precambrian and Paleozoic age. Low rolling hills with elevation varying between 60 and 150 m above sea level characterize the southern part of the region, whereas in the northern part, the topography is similar to that of the New England Province with elevations over 250 m. The Piedmont Lowland is underlain by carbonate rocks of Paleozoic age with relatively low relief varying between 120 and 150 m in elevation. The Gettysburg-Newark Lowland consists of northeast-trending low hills and valleys underlain by Triassic siltstone, shale, and sandstone. Elevation is between 60 and 150 m above sea level. Triassic conglomerates and Jurassic diabase sheets form locally steeper topography, with elevations over 300 m.

The Blue Ridge Province is an area of steep mountains underlain by metamorphic rocks of Precambrian and Cambrian age and having elevations from 200 to 600 m. The Ridge and Valley Province consists of parallel ridges and valleys with an arcuate north-northeast trend. Ridges are underlain by sandstone and conglomerate, whereas valleys are underlain by shales and limestones. The Ridge and Valley is subdivided into the Great Valley and Appalachian Mountain sections. The Great Valley is a broad area of low relief underlain by carbonate rocks, sandstones, and shales. Carbonate areas have elevations generally between 120 and 150 m above sea level, whereas areas

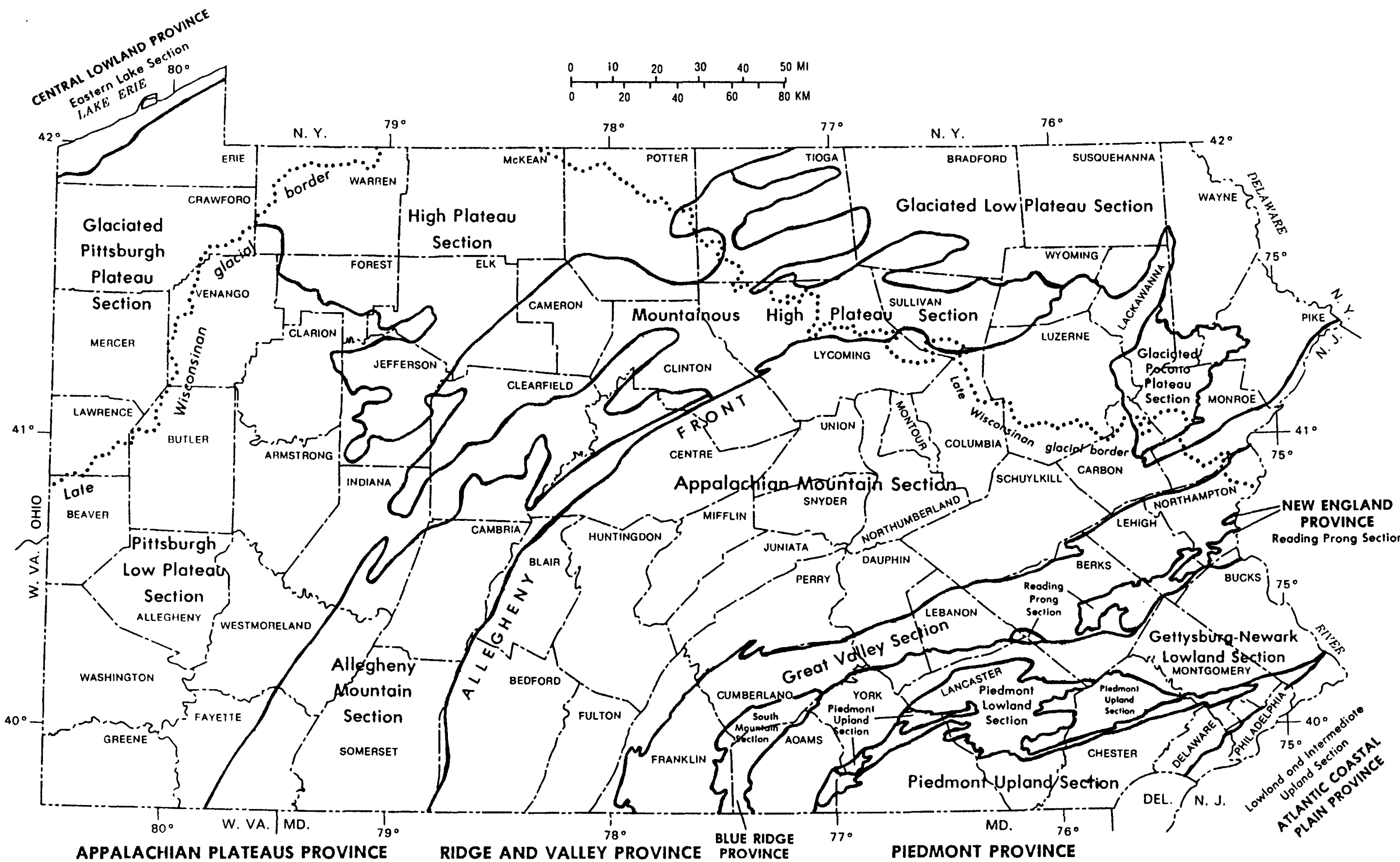


Figure 1. Physiographic provinces of Pennsylvania (from Berg and others, 1989).

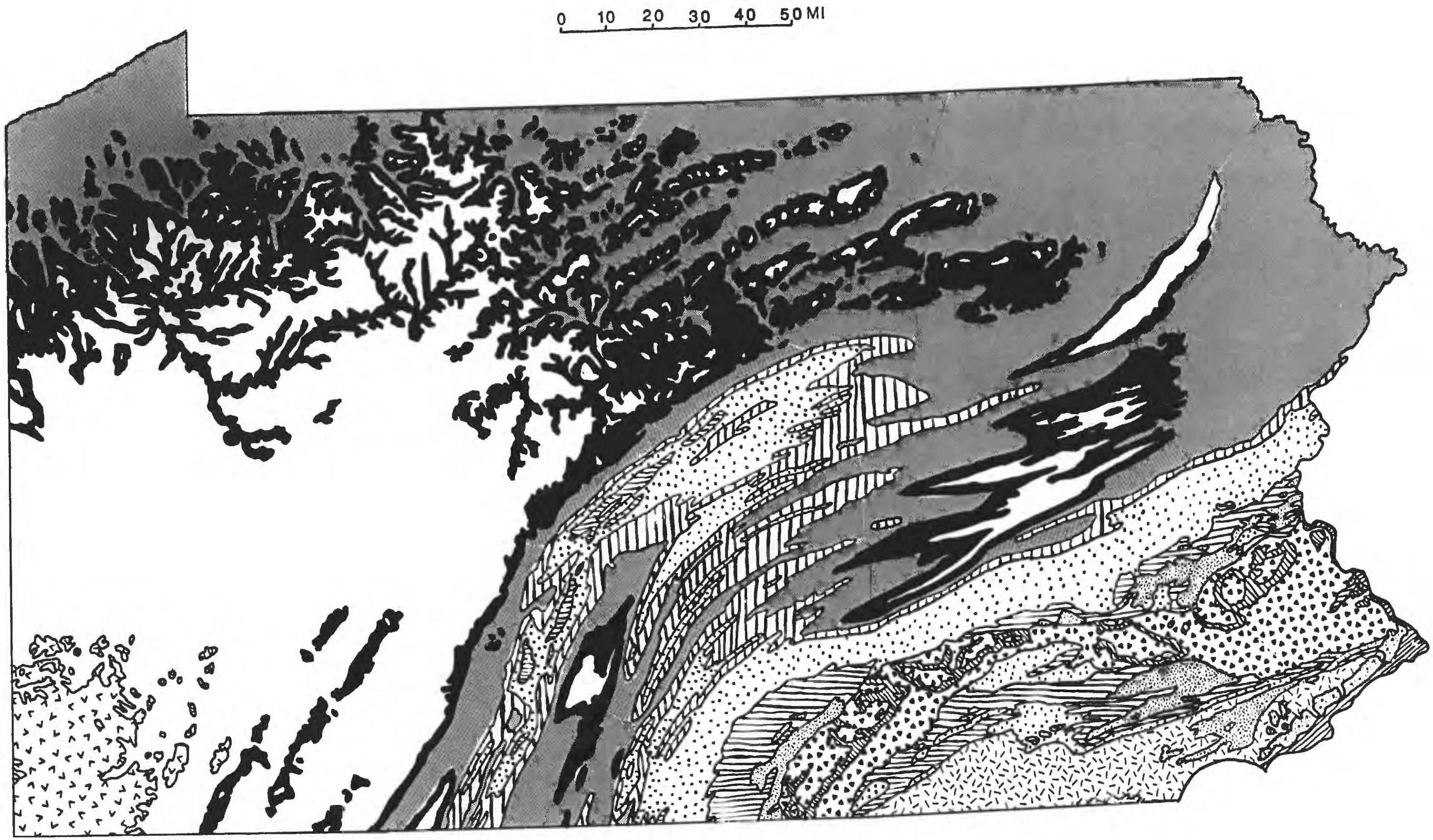
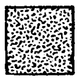


Figure 2. Generalized geologic map of Pennsylvania (from Pennsylvania Topographic and Geologic Survey, 1990).

Explanation, Pennsylvania General Geologic Map

Precambrian



Reading Prong section - granitic gneiss with small areas of hornblende gneiss, graphitic gneiss, and marble of sedimentary origin.

Blue Ridge province - metarhyolite, metabasalt and greenstone.

Piedmont province - hornblende and pyroxene felsic gneiss with small areas of mafic hornblende gneiss of sedimentary origin in northern Chester County and intermixed granodiorite, quartz monzonite, gabbroic, and graphitic gneisses and pods of anorthosite in southern Chester and Delaware counties.

Lower Paleozoic

Metasedimentary and meta-igneous rocks includes: Setters Quartzite; Cockeysville Marble; Wissahickon Fm., schist, phyllite, and metavolcanics; Peters Creek Schist; and smaller units of anorthosite, granitic gneiss, mafic gneiss, and serpentinite.

Cambrian

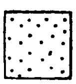
Piedmont province - Quartzite and phyllite including the Chickies, Harpers, and Antietem Formations, overlain by dolomite and limestone with minor shale including the Vintage, Kinzers, Ledger, Zooks Corner, Buffalo Springs, Snitz Creek, Schaefferstown, and Millbach Formations.

Great Valley and Reading Prong area - Quartzite and feldspathic sandstone of the Hardyston Formation overlain by dolomite and minor limestone of the Leithsville and Allentown Formations.

Great Valley and Blue Ridge province area - Quartzite, phyllite, and slate of the Weverton, Loudon, Harpers, and Antietam Formations overlain by dolomite, limestone, and minor shale of the Tomstown, Waynesboro, Elbrook, Zullinger, and Shady Grove Formations.

Appalachian Mountain section - limestone, dolomite, and minor shale of the Pleasant Hill, Warrior, and Gatesburg Formations.

Ordovician



Piedmont province - Limestone and dolomite with minor phyllite of the Conestoga, Stonehenge, Epler, Ontelaunee, Annville, Hershey, and Meyerstown Formations overlain by shale and phyllitic shale with minor argillaceous sandstone and quartz sandstone of the Cocalico Formation.

Eastern Great Valley section - Dolomite and limestone of the Rickenbach, Epler, Ontelaunee, and Jacksonburg Formations overlain by gray shale and graywacke of the Martinsburg Formation.

Central Great Valley section - Limestone and dolomite of the Stonehenge, Rickenbach, Epler, Ontelaunee, Annville, Hershey, and Meyerstown Formations overlain by shale, graywacke, and minor limestone of the Hamburg sequence and the Martinsburg Formation.

Western Great Valley section - Limestone and dolomite of the Stonehenge, Rockdale Run, Pinesburg Station Formations, St. Paul Group, and Chambersburg Formation overlain by gray shale and graywacke of the Martinsburg Formation.

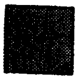
Appalachian Mountain section - Limestone, dolomite, argillaceous limestone and minor shale of the Stonehenge, Larke, Nittany, Axemann, Bellefonte, Loysburg, Hatter, Snyder, Benner, and Coburn Formations overlain by gray shale and siltstone of the Reedsville Formation and sandstone, siltstone, conglomerate and shale of the Bald Eagle and Juniata Formations.

Silurian

Eastern Appalachian Mountain section north of Great Valley - Sandstone and conglomerate of the Shawangunk Formation overlain by red siltstone, shale, and sandstone of the Bloomsburg Formation, and limestone, dolomite, and shale of the Poxono Island, Bossardville, and Decker Formations.

West-Central Appalachian Mountain section - Orthoquartzite and conglomerate of the Tuscarora Formation overlain by green to gray shale and ferruginous sandstone of the Clinton Group and interbedded gray to green shale, limestone, and dolomite of the Mifflintown, Bloomsburg, and Wills Creek Formations.

Devonian



Eastern Appalachian Mountain section - Limestone, argillaceous limestone, gray siltstone and shale, and siliceous sandstone of the Coeymans and New Scotland Formations, Minisink Limestone, Port Ewen Shale, Shriver Chert, Ridgeley, Esopus, and Schoharie Formations, and Palmerton Sandstone and Buttermilk Falls Limestone overlain by black carbonaceous shales and gray shales, siltstones and fine sandstones of the Marcellus, Mahantango, and Trimmers Rock Formations and finally the red and intermittently gray sandstone, siltstone and shale of the Catskill Formation.

West-Central Appalachian Mountain section - limestone and minor shale of the Tonoloway and Keyser Formations overlain by gray siltstone, argillaceous limestone, shale, and quartz sandstone of the

Oldport and Onondaga Formations, overlain by carbonaceous shales, siltstones, and sandstones of the Marcellus, Mahantango, Trimmers Rock, Brallier, Harrell, Scherr, and Foreknobs Formations and finally red and intermittently gray sandstone, siltstone and shale of the Catskill Formation.

Eastern Appalachian Plateaus province - Gray sandstone, siltstone, and mudstone of the Lock Haven Formation overlain by red and intermittently gray sandstone, siltstone and shale of the Catskill Formation.

Western Appalachian Plateaus province- Gray shale, siltstone, and sandstone of the upper Northeast Shale, Girard Shale, Chadakoin and Venango Formations.

Mississippian

Eastern Appalachian Mountain section - Buff sandstone, siltstone, and conglomerate of the Spechty Kopf and Pocono Formations overlain by red siltstone, sandstone, and shale with minor gray sandstone of the Mauch Chunk Formation.

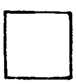
Western Appalachian Mountain section - Buff sandstone, siltstone, conglomerate, and minor carbonaceous shale of the Rockwell and Pocono Formations overlain by red siltstone, sandstone, shale, and minor gray sandstone of the Mauch Chunk Formation.

Northeastern Appalachian Plateaus province - Greenish -gray fine-grained sandstone with minor red shale of the Huntley Mountain Formation overlain by buff sandstone and conglomerate of the Burgoon Sandstone, overlain by red siltstone, sandstone, shale, and minor gray sandstone of the Mauch Chunk Formation.

Allegheny Mountain section - Buff argillaceous sandstone and green shale of the Rockwell and Oswayo Formations overlain by buff sandstone and conglomerate of the Burgoon Sandstone, then by red siltstone, sandstone, shale and minor gray sandstone of the Mauch Chunk Formation.

Northwestern Appalachian Plateaus province - Gray siltstone, shale, and sandstone of the Riceville Formation, Berea and Corry Sandstones, Cuyahoga Group, and Shenango Formation.

Pennsylvanian



Appalachian Mountain section - Gray conglomerate, sandstone, siltstone, and shale with anthracite coal beds of the Pottsville Group and Llewellyn Formation.

Appalachian Plateaus province - Gray sandstone and conglomerate with minor shale and coal beds of the Pottsville Group overlain by cyclic gray sandstone, shale, limestone, and coal of the Allegheny Group, then cyclic shale, siltstone, sandstone, red beds and minor limestone and coal of the Conemaugh Group, and finally cyclic limestone, shale, sandstone, and coal of the Monongahela Group.

Permian

Pittsburgh Low Plateau section - Cyclic sequences of sandstone, shale, limestone, and coal of the Waynesburg, Washington, and Greene Formations.

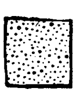
Triassic-Jurassic

Eastern Gettysburg-Newark Lowland section - Fluvial arkosic sandstone, siltstone, and conglomerate of the Stockton Formation overlain by cyclic red and black lacustrine shales and siltstones with lithic and arkosic sandstone and conglomerate of the Lockatong Formation and Brunswick Group. Jurassic tholeiitic Jacksonwald basalt in the upper part of the Brunswick Group and Jurassic diabase dikes and sheets intrude the sedimentary rocks.

Central Gettysburg-Newark Lowland section - Fluvial arkosic sandstone, siltstone, and conglomerate of the Stockton and New Oxford Formations overlain by quartose fluvial conglomeratic sandstone of the Hammer Creek Formation.

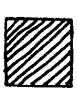
Western Gettysburg-Newark Lowland section - Fluvial arkosic sandstone, siltstone, and conglomerate of the New Oxford Formation overlain by red and black lacustrine shales and siltstones with lithic, arkosic sandstone and conglomerate of the Gettysburg Formation. Jurassic tholeiitic basalts in the upper Gettysburg Formation and Jurassic diabase dikes and sheets intrude the sedimentary rocks.

Tertiary



Reddish brown gravelly sand of the Bryn Mawr Formation is overlain by reddish brown sand with minor gravel and silt of the Pensauken and Bridgeton Formations.

Quaternary



Gravelly sand with minor silt and clay beds of the Trenton Gravel.

underlain by the clastic part of the sequence may vary between 120 and 270 m in elevation, with sandstone forming the highest ridges. The Appalachian Mountains are characterized by steep, tightly folded ridges of sandstone and deep valleys of shale and limestone. Relief on the scale of several hundred meters is common, with elevations up to 760 m above sea level. The abrupt transition from the Appalachian Mountain fold belt to the Appalachian Plateaus is called the Allegheny Front.

The Appalachian Plateaus Province is a broad, high-elevation plateau that is sharply dissected by dendritic drainages. It is subdivided into the Allegheny Mountain, Mountainous High Plateau, High Plateau, Pittsburgh Low Plateau, Glaciated Pittsburgh Plateau, Glaciated Low Plateau, and Glaciated Pocono Plateau sections. The Allegheny Mountain and Mountainous High Plateau consist of parallel ridges similar to those of the Appalachian Mountain section, but broader and more dissected by dendritic drainages. Relief in these areas varies between 500 and 900 m. The High Plateau is characterized by a broad plateau with elevations up to 760 m, with relief on the scale of hundreds of meters produced by dendritic drainages. The Pittsburgh Low Plateau, Glaciated Pittsburgh Plateau, and Glaciated Low Plateau are all physiographically similar, with dendritic valleys producing relief on the scale of hundreds of meters, but maximum elevations are on the order of 500 m. The Glaciated Pittsburgh Plateau and Glaciated Low Plateau are differentiated from the Pittsburgh Low Plateau by the presence of glacial features. The Glaciated Pocono Plateau is similar to the Mountainous High Plateau but has glacial features superimposed on it.

The Eastern Lakes section of the Central Lowlands Province is an area of low relief, sloping toward Lake Erie. It is underlain by Devonian shales and ranges from about 230 m elevation to about 180 m at the shore of Lake Erie. The Atlantic Coastal Plain Province is underlain by unconsolidated sediments that are mostly Tertiary and Quaternary in age and produce low, flat hills dissected by southeast-trending stream drainages. The hills vary from about 37 to 3 meters in elevation.

Pennsylvania has a seasonal, temperate climate with warm, humid summers and cool and snowy winters. Average temperature ranges from 22° F in January to 68° F in July with slightly warmer temperatures in the southern portion of the State. Precipitation averages about 1016 mm (40 in) per year statewide (fig. 3), varying between 860 and 1270 mm (34 and 50 in) regionally, and is fairly well distributed throughout the year. In 1990, the population of Pennsylvania was 11,881,643, with 69 percent of the population living in urban areas (fig. 4). The population density is approximately 265 persons per square mile.

GEOLOGIC SETTING AND SOILS

The following discussion of geology and soils is derived from Berg (1980), Cunningham and others (1977), Geyer and Wilshusen (1982), and Richmond and Fullerton (1991, 1992). A general geologic map for reference is given in figure 2. It is suggested, however, that the reader refer to the State Geologic Map of Pennsylvania by Berg (1980) or the Atlas of Preliminary Geologic Quadrangle Maps of Pennsylvania by Berg and Dodge (1981). A generalized soil map of Pennsylvania is given in figure 5.

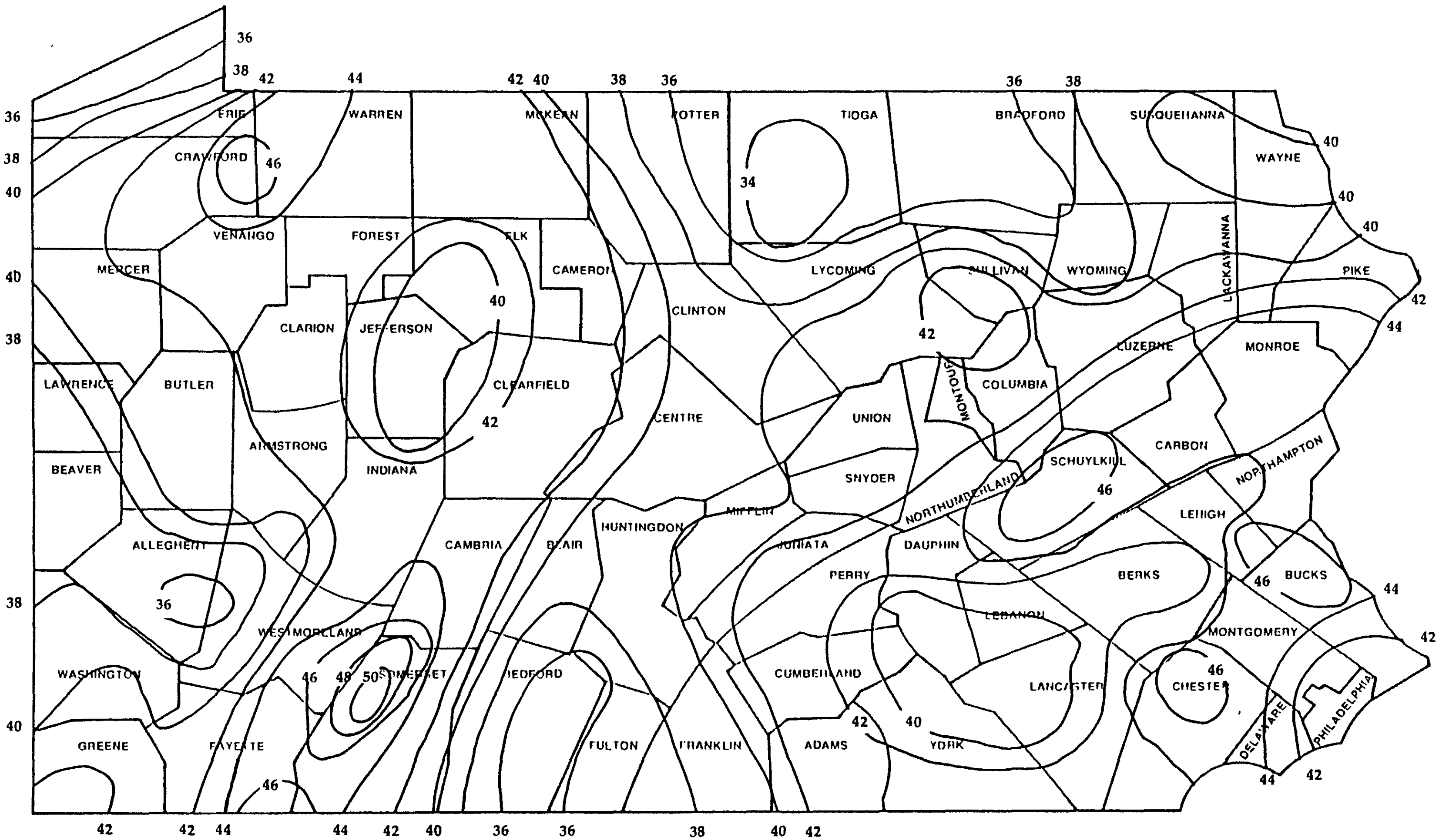


Figure 3. Average annual precipitation in Pennsylvania, in inches (from Cunningham and others, 1977).

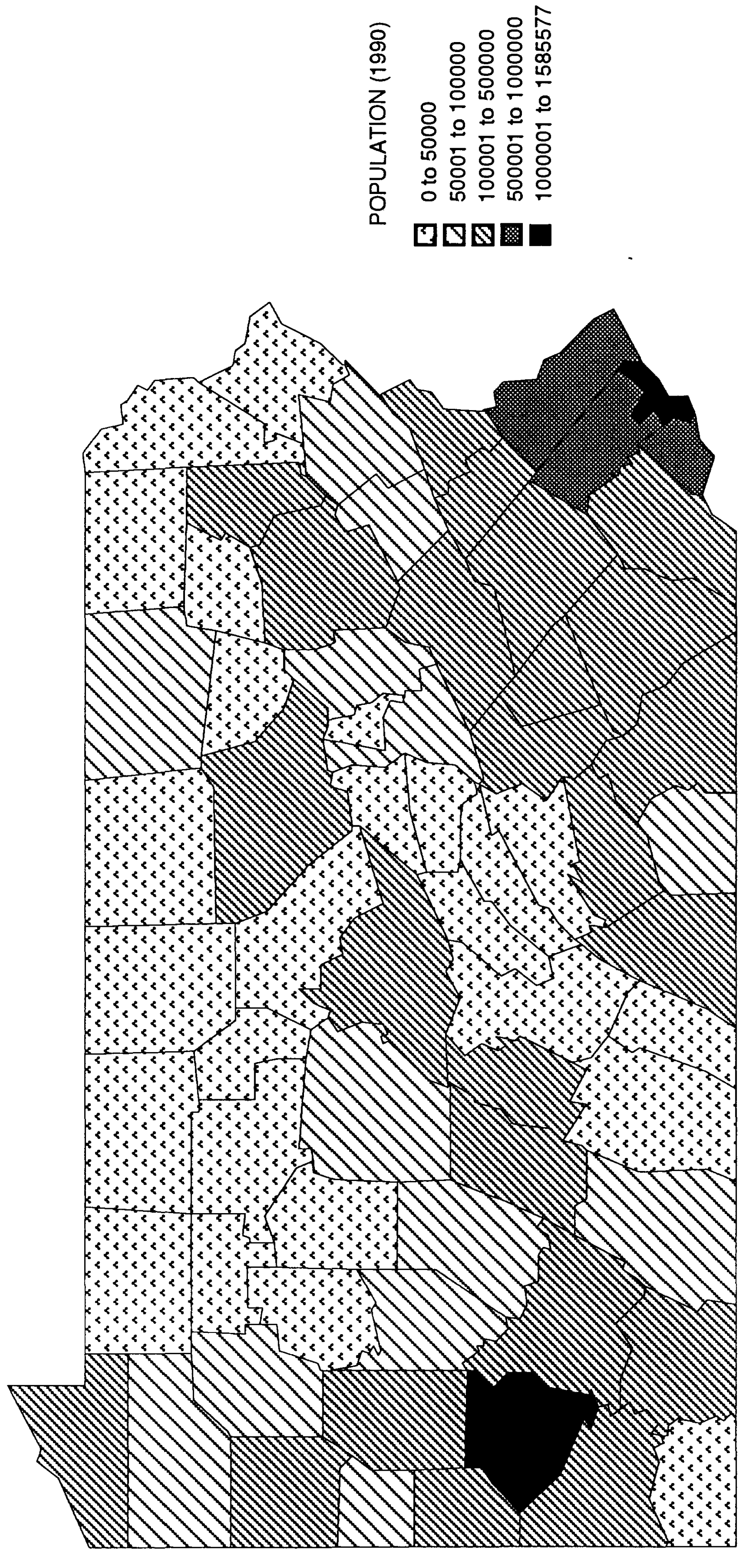


Figure 4. Population of counties in Pennsylvania (1990 U.S. Census data).

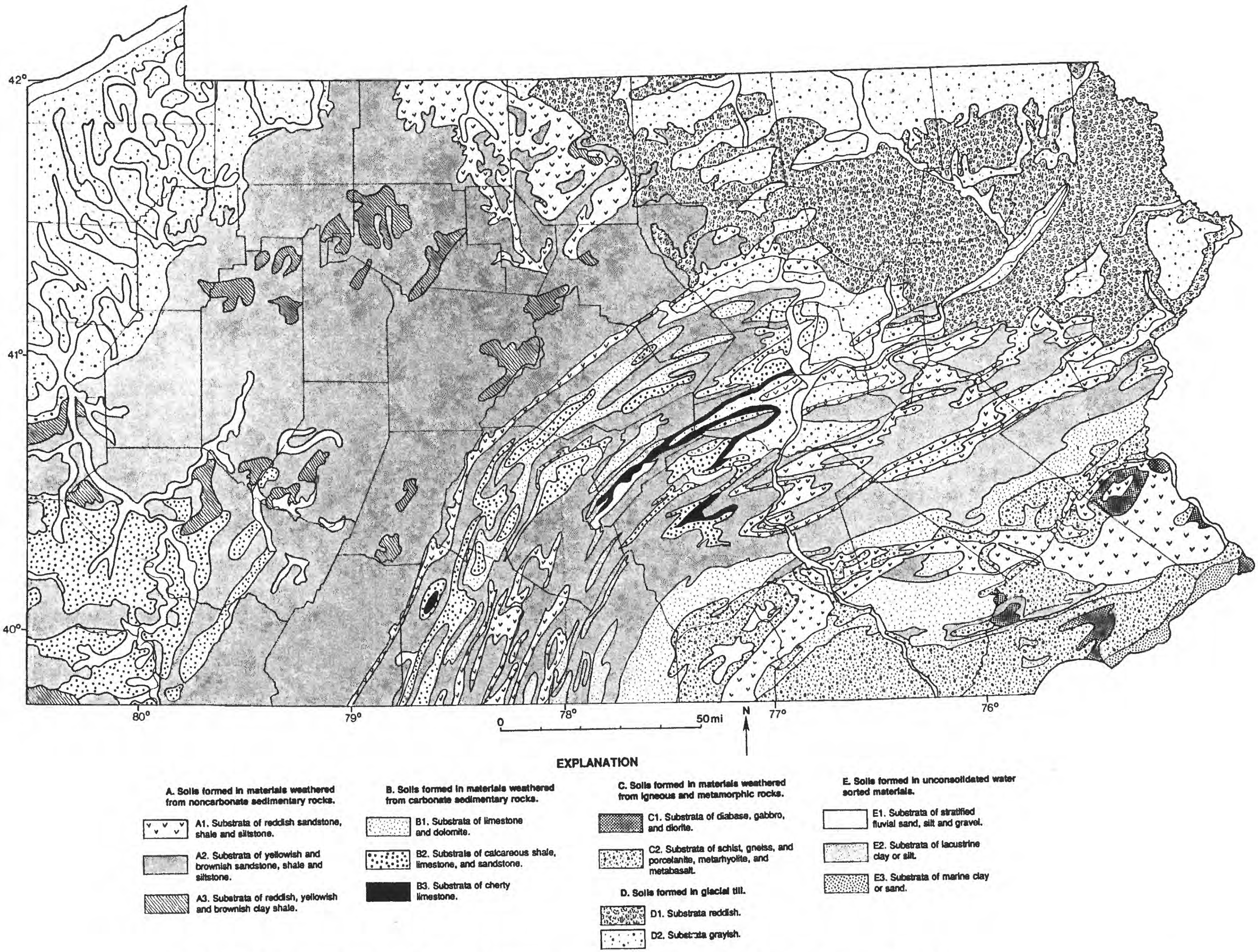


Figure 5. Generalized soil map of Pennsylvania (from Cunningham and others, 1977).

The New England Province

The New England Province in Pennsylvania is underlain by intensely faulted, sheared, and folded Precambrian crystalline rocks of the Reading Prong (Drake, 1984). Most of the province is underlain by granitic gneiss of igneous origin. Irregular areas of hornblende gneiss are evenly distributed throughout the province and small irregular areas of marble and graphite-bearing granitic gneiss occur in the western part of the province (Drake, 1967). A small tongue of the New England Province in east-central Northampton County is characterized by a narrow band of Franklin Marble associated with granitic gneiss, biotite gneiss, and sillimanite gneiss. Small, irregularly distributed layers of the Cambrian Hardyston and Leithsville Formations unconformably overlie or are in fault contact with the Precambrian rocks. The Hardyston consists of quartzite and conglomerate with a thin, zircon- and thorite-rich fossil placer at the base, and the Leithsville consists of deeply weathered dolomite with thin shaly interbeds.

Rocks underlying the New England Province tend to have deeply weathered soils (greater than 1 meter deep) with good drainage. Granitic gneiss forms loam soils with 15-50 percent rock fragments. These soils have moderately rapid permeability. Graphitic gneiss and hornblende gneiss form silty loam to silty clay loam that may be very deep (tens of meters) and have moderate permeability. Sheared fault zones in the granitic and graphitic gneiss may produce soils with rapid permeability. The Hardyston Formation commonly caps hills and is resistant to weathering, producing very thin pebbly and sandy soils with rapid permeability. The Leithsville Formation and Franklin Marble form silty clay loams with moderate permeability.

Piedmont Province

The Piedmont Upland Section is underlain by complexly faulted and folded Precambrian and Lower Paleozoic rocks. Precambrian granitic gneiss forms a prominent rock unit oriented northeast across southeastern Chester County and northern Delaware County. It is bounded on the east, south, and north by major faults. Granitic gneiss underlies the southern tongue of the Piedmont Upland in Lancaster County and graphitic gneiss is a dominant rock type in the northern half of this area, along with quartz monzonite and quartz monzonite gneiss (Crawford and Hoersch, 1984). Granodiorite and granodiorite gneiss occupy most of the southern half of the area and gabbroic gneiss occurs locally. Lower Paleozoic metasedimentary and meta-igneous rocks underlie most of the southern portion of the Piedmont Upland and consist of mica schist, phyllite, and minor hornblende gneiss of the Wissahickon Formation. A narrow belt of Setters Quartzite and Cockeysville Marble outlines the western margin of the Precambrian gneiss in southern Chester County. Scattered narrow belts of metabasalt and a thick belt of gray-green chlorite schist with quartzite also occur within the Wissahickon. The Peters Creek Schist forms a broad belt that extends northeast from the state line in southern Lancaster County and pinches out in eastern Chester County. A narrow belt of black slate and metaconglomerate of the Peach Bottom Slate and Cardiff Conglomerate Formations lies near the northeast edge of the Peters Creek Schist outcrop area. Mafic gneiss forms small elongate pods with serpentinite in southeastern Chester County, northern Delaware County, and in a narrow belt along the Maryland border. Cambrian rocks of the Piedmont Upland include the Chickies Quartzite, greenish-gray phyllite and schist of the Harpers Formation, and quartzite of the Antietam Formation. These units form a narrow outcrop belt in northern Chester and eastern Lancaster Counties and comprise most of the two small Piedmont Upland areas south of the Gettysburg-Newark Lowland in York County.

Rocks underlying the Piedmont Upland tend to have deeply weathered soils (greater than 1 meter deep) with good to moderate drainage. Hornblende gneiss and granitic gneiss form silty to sandy loams containing greater than 15 percent rock fragments. These soils have good drainage and moderate to moderately rapid permeability. Mica schist forms deep silty to clayey loams with good drainage and moderate permeability. Phyllite, slate, and mafic rocks form clayey loams to silty clays with deep soils, poor to moderate drainage, and low to moderate permeability.

The Piedmont Lowland is mostly underlain by Cambrian and Ordovician limestone and dolomite with minor shales. The Cambrian Vintage and Kinzers Formations are dolomite and limestone that form a narrow belt around the Piedmont Upland Cambrian sedimentary rocks, whereas dolomite of the Ledger and Zooks Corner Formations comprise the Piedmont Lowland in north-central Lancaster County. A narrow belt of Buffalo Springs, Snitz Creek, Schaefferstown, and Millbach Formations, which contain more limestone than dolomite, occurs north of this central belt. The Ordovician Conestoga Formation is a limestone with shale partings that occupies most of the Piedmont Lowland in central Lancaster County. The northern Piedmont Lowland is dominated to the south by limestone and dolomite of the Stonehenge, Epler, Ontelaunee, Annville, Meyerstown, and Hershey Formations and in the north by shale, phyllitic shale, and minor sandstones of the Cocalico Formation. Soils of the Piedmont Lowlands are silty clay and silt loams derived mostly from carbonate rocks and shales. These soils tend to be deep, with a clay subsoil, moderate to good drainage, and slow to moderate permeability.

The Gettysburg-Newark Lowland is underlain by late Triassic-early Jurassic sedimentary and igneous rocks of the Newark Supergroup which occur in two basins separated by a narrow constriction (the "Narrow Neck"). The Newark basin is a wide band of sedimentary rock that extends into New Jersey. The basal Triassic Stockton Formation and overlying Lockatong Formation form a broad band of outcrop along the southeastern side of the basin that thins to the southwest. The Stockton consists of fluvial sandstone, siltstone, and conglomerate, and the Lockatong consists of lacustrine black and red shales and siltstones that are interbedded with sandstones to the southwest. The Triassic-Jurassic Brunswick Group (Lyttle and Epstein, 1987) overlies the Lockatong and forms a broad belt underlying approximately half of the basin. The Brunswick Group consists of red and black lacustrine shales and siltstones and fluvial sandstone and conglomerate. The Jurassic Jacksonwald basalt occurs near the top of the Brunswick Group at the western edge of the Newark basin. The Narrow Neck is underlain by a thin band of Stockton Formation which is overlain by conglomeratic sandstone of the Hammer Creek Formation.

The Gettysburg basin is a broad belt of rocks arching southward into Maryland. In the Gettysburg basin, the basal Triassic New Oxford Formation crops out along the southeast margin of the basin and consists of fluvial sandstone, siltstone, and conglomerate. The New Oxford is overlain by the Triassic-Jurassic Gettysburg Formation, which comprises most of the basin fill. The lower third of the Gettysburg Formation consists of fluvial red siltstones and thin sandstones. The upper portion of the Gettysburg Formation consists of lacustrine red and black shales and siltstones with fluvial and deltaic sandstones. The shalier unit of upper Gettysburg Formation is called the Heidlersburg Member. Near the top of the Gettysburg Formation, Jurassic tholeiitic basalts overlain by sedimentary rocks are restricted to two tiny areas adjacent to the border fault. Conglomerates containing clasts composed of the older rocks immediately outside of the basin occur along the northwestern, faulted margins of both basins. The sedimentary rocks of both basins are intruded by large Jurassic diabase dikes and sheets that are folded into broad, dish-like synclines forming characteristic ring-shaped outcrop patterns.

Soils derived from siltstone and shale of the Gettysburg-Newark Lowland tend to be poorly to somewhat poorly drained, have slow permeability, and form deep silty to clayey loams and silty clays with a well-developed clay subsoil. Soils derived from sandstone and conglomerate have shallow to moderately deep silty and sandy loam soils. Drainage varies from moderately good to good and permeability varies from moderate to moderately rapid. Because of the interlayered nature of the sediments in the basin, silt and clay layers are not uncommon within these soils. Silt and clay loams with variable depth, drainage, and permeability are developed on the diabase dikes and sheets of the basin. Generally these soils have good drainage (although some have poor drainage), are moderately deep, and have slow to moderate permeability.

Blue Ridge Province

The Blue Ridge Province is underlain by Precambrian metavolcanic and Cambrian metasedimentary rocks. The Precambrian rocks are metamorphosed and highly deformed rhyolite and basalt with minor greenstone These rocks are overlain by slate, sandstone, and conglomerate of the Loudoun Formation; quartzite and conglomerate of the Weverton Formation; and quartzite and phyllite of the Harpers Formation. The Antietam quartzite forms a narrow band along the western and northern edge of the Blue Ridge Province and caps the ridges that define the boundary with the Ridge and Valley Province. Dolomite of the Cambrian Tomstown Formation forms a narrow outcrop band northwest of the Cumberland-Adams county line.

Metarhyolite, metabasalt, greenstone, and phyllite form stony colluvium with moderate drainage and permeability, and locally form silt and clay loams and silty clays with generally poor drainage and slow permeability. The latter soils are deep and contain significant clay in the subsoil. Quartzite, arkosic sandstone, and conglomerate form shallow to moderately deep soils with good drainage and moderate to moderately rapid permeability.

Ridge and Valley Province

Half of the Great Valley section of the Ridge and Valley Province in Pennsylvania is underlain by Cambrian and Ordovician carbonate rocks and half by Ordovician shales and sandstones. A narrow band of Hardyston Formation quartzite and conglomerate and Leithsville Formation dolomite and dolomitic shale occurs along the contact with the New England Province. These units are overlain by dolomite and minor shaly limestone of the Cambrian Allentown Formation. The Allentown is replaced to the west by several units of limestone and dolomite. Near the Blue Ridge Province, the Cambrian sequence consists of the Tomstown Formation dolomite; the shale, shaly dolomite, and limestone of the Waynesboro and Elbrook Formations; and the limestone and dolomite of the Zullinger and Shady Grove Formations.

In the eastern Great Valley, Ordovician dolomitic carbonate rocks comprise the Richenbach, Epler and Ontelaunee Formations, which are overlain by shaly limestone of the Jacksonburg Formation. The Jacksonburg Formation is replaced to the north by limestone and shaly limestone of the Annville, Meyerstown and Hershey Formations. In the area north of the Narrow Neck, limestone of the Stonehenge Formation forms the base of the Ordovician sequence. Near the Blue Ridge Province, the Stonehenge Formation is overlain by limestone and minor dolomite of the Rockdale Run Formation, Pinesburg Station Formation, St. Paul Group, and Chambersburg Formation.

The Ordovician Martinsburg Formation, consisting mostly of gray to black marine shales with prominent layers of graywacke, makes up the youngest rocks in the Great Valley and forms a broad belt along its northwestern edge. In the central part of the Great Valley, the belt of Martinsburg Formation is replaced by an equivalent belt of phyllitic shale and graywacke sandstone called the Hamburg Klippe. The northern half of the klippe is dominated by sandstones, whereas the southern half contains numerous limestone-rich bands in phyllitic shales.

Soils of the Great Valley formed over sandstone, shale, and siltstone are generally shallow to deep with good drainage, moderate to moderately rapid permeability, and a significant amount of coarse fragments (>15 percent to >50 percent in loam and silty loam). Soils formed on the carbonate rocks of the Great Valley are deep silt to clay loams with clayey subsoils with moderately good to good drainage and slow to moderate permeability.

The Appalachian Mountains section of the Ridge and Valley province is underlain by tightly folded Paleozoic sandstone, shale, and limestone. Cambrian rocks are mostly restricted to the cores of folds in a narrow belt near the western edge of the province in Bedford, Blair, and Centre Counties. Much of the Cambrian sequence consists of dolomite and sandstone of the Gatesburg Formation. Limestone of the underlying Warrior Formation forms narrow lenses in the cores of some folds, and older limestone and shale of the Waynesboro and Pleasant Hill Formations are restricted to two small areas in Blair County. Limestone of the Cambrian Shady Grove Formation occurs in southeastern Fulton County. The Cambrian rocks are overlain by a belt of Ordovician limestone and dolomite of the Stonehenge, Nittany, Axemann, Bellefonte, Loysburg, Snyder, and Benner Formations. These units form the cores of a few folds in southeastern Clinton County. A narrow belt of limestone interbedded with black shale comprises the Nealmont, Salona, and Coburn Formations, which are overlain by gray to black shales, siltstones, and sandstones of the Reedsville Formation. The Reedsville forms a thin band throughout the Ordovician outcrop areas in the Appalachian Mountain section and comprises broader outcrop bands in the southeastern corner of the section, where it overlies Ordovician carbonate rocks. Fluvial sandstone and conglomerate of the Bald Eagle Formation and red fluvial siltstone, sandstone, and shale of the Juniata Formation overlie the Reedsville and Martinsburg Formations, and pinch out east of the Susquehanna River.

The Silurian-age Shawangunk Formation forms a belt of rock that unconformably overlies the Martinsburg Formation east of the Dauphin-Schuykill county line. The Shawangunk consists of fluvial conglomerate and sandstone that grades westward into interbedded sandstone and green shales. To the west, the Shawangunk is laterally equivalent to well-sorted quartz sandstone of the Tuscarora Formation and to ferruginous sandstone, oolite, and greenish-gray shale of the Clinton Group. The Clinton Group is overlain by a narrow belt of interbedded gray shale and limestone of the Silurian Mifflintown Formation. The Silurian Bloomsburg Formation is largely a marine siltstone, sandstone, and shale which overlies the Mifflintown in the west and replaces the Mifflintown to the east. The Bloomsburg Formation, in turn, is overlain by a narrow belt comprising Silurian to Devonian limestone, dolomite, quartz sandstone, and shale. In the east, these rocks comprise the Silurian Poxono Island, Bossardville, and Decker Formations, the Devonian Coeymans and New Scotland Formations, and the Minisink Limestone. In the west, this sequence contains the Silurian Wills Creek and Tonoloway Formations and the Silurian-Devonian Keyser Formation.

Overlying the Silurian-Devonian sequence is narrow belt of Devonian-age, gray marine siltstone, shale, and argillaceous limestone with well-sorted quartz sandstone. In the east, this comprises the Port Ewen Shale, Shriver Chert, Ridgeley and Schoharie Formations, Palmerton Sandstone, and Buttermilk Falls Limestone. In the west, this succession makes up the Old Port and Onondaga Formations. In the eastern part of the province, the Devonian Marcellus Formation, consisting of marine black shale, and the Mahantango and Trimmers Rock Formations, consisting of marine black shale interbedded with gray siltstone and sandstone, form distinct bands of outcrop. The Trimmers Rock Formation becomes coarser to the west and is replaced by similar shales and sandstones of the Harrell, Brallier, Scherr, and Foreknobs Formations. In the northwestern part of the province, the Trimmers Rock is replaced by the Harrell, Brallier, and Lock Haven Formations.

The Devonian Catskill Formation forms a broad belt of outcrop over most of the Appalachian Mountain section and consists mostly of red siltstone, sandstone, and shale with gray interbeds. It is overlain by a narrow band of Mississippian-age fluvial sandstone and conglomerate of the Spechty Kopf and Pocono Formations in the east and the Rockwell and Pocono Formations in the west. The Rockwell Formation also contains carbonaceous shale and is finer grained than the Spechty Kopf Formation. These units are overlain by the red fluvial siltstone, sandstone, and shales of the Mauch Chunk Formation. The Mauch Chunk underlies about 75 percent of the area of Mississippian rocks in the Appalachian Mountains section. It is overlain by the Pennsylvanian Pottsville Group and Llewellyn Formation, which include gray fluvial conglomerate, sandstone, siltstone, and shale with coal beds.

Soils of the Appalachian Mountains section formed over quartzose sandstone, shale, and siltstone are generally shallow to deep, with good drainage, moderate to moderately rapid permeability, and contain coarse fragments (>15 percent to >50 percent in loam and silty loam). Colluvial soils are common. Soils formed on the carbonates and interbedded carbonate and clastic rocks of the Appalachian Mountains are highly variable, but are generally moderately deep to deep, sandy to clayey loams with silty to clayey subsoils, moderately good to good drainage, and slow to moderate permeability.

Appalachian Plateaus Province

The Appalachian Plateaus Province is underlain by sandstone, siltstone, and shale ranging from Devonian to Permian in age. Marine gray sandstone, siltstone, and shale of the Lock Haven Formation make up a large portion of the Devonian section in Tioga and Bradford Counties. It is overlain by red siltstone, sandstone, and red to gray shale of the Devonian Catskill Formation. The Catskill comprises all of the Devonian in this province east and south of the Lock Haven Formation, and most of the Devonian section in Potter, Cameron, and Clinton Counties. West of these counties, the Catskill Formation is underlain and gradually replaced by gray marine siltstone, sandstone, and shale of the Chadakoin and Venango Formations. In the Mountainous High Plateau, the Catskill is overlain by sandstone and minor red shale of the Mississippian Huntley Mountain Formation, and fluvial sandstone and conglomerate of the Mississippian Burgoon Formation. These are overlain by red fluvial siltstone, sandstone, and shale of the Mauch Chunk Formation. A similar rock sequence occurs in the Allegheny Mountain section. To the north and west of the Mountainous High Plateau section, the Mauch Chunk and Burgoon Formation are missing, so that the Huntley Mountain is the only Mississippian unit underlying Tioga, Potter, and Cameron Counties. West of this area, the Mississippian section consists of gray marine and deltaic siltstone, shale, and sandstone of the Riceville Formation, Berea and Corry Sandstone, Cuyahoga Group, and Shenango Formation. The sandstone, conglomerate, shale, and coal of the Pennsylvanian Pottsville Group forms a broad east-west belt across the northern part of the Pennsylvanian section in the Appalachian Plateau and forms parallel bands in the Allegheny Mountain section. Cyclic sequences of gray marine shale, siltstone, sandstone, limestone, and coal comprise the Pennsylvanian-age Allegheny Group, Conemaugh Group, and Monongahela Group, south of the outcrop of Pottsville rocks. The Permian rocks in the southwestern corner of the State consist of cyclic sequences of sandstone, shale, limestone, and coal, and are divided into the Waynesburg, Washington, and Greene Formations.

Most of the Appalachian Plateaus Province has soils derived from sandstone, shale and siltstone, with two exceptions: the Glaciated Pittsburgh Plateau is underlain by soils formed on tills and the Permian age rocks of the Pittsburgh Low Plateau have calcareous soils formed from limestone, shale, and sandstone. Soils derived from sandstone are moderately deep silt loams containing more than 15 percent rock fragments. Permeability is moderate to moderately rapid and drainage is good. Soils derived from shale, limestone, and siltstone are deep, silty to clayey loams with clayey subsoils, slow to moderate permeability, and poor to moderately good drainage.

Central Lowland Province

The Central Lowland Province in Pennsylvania is underlain by gray marine shale and siltstone of the Devonian Northeast Shale and Girard Shale. The Northeast Shale forms a band parallel to the Lake Erie shore and the Girard Shale forms a parallel band of equivalent width to the southeast of it. Parts of the province are covered by highly variable, sandy to clayey glacial till. Soils are moderately well drained to poorly drained sandy loams and silty clay with moderately rapid to slow permeability.

Atlantic Coastal Plain Province

The Atlantic Coastal Plain Province is underlain by unconsolidated sand, gravel, and clay of Tertiary and Quaternary age. Tertiary and Cretaceous-age deposits also occur in small areas overlying crystalline rocks of the Piedmont Province. The Cretaceous Patapsco Formation consists of variegated clay with sand lenses and occurs in patches overlying the Piedmont Lowland section in Montgomery County. Gravelly sand and silt of the Tertiary Bryn Mawr Formation overlie rocks of the Piedmont Upland in irregular patches. The Tertiary Pensauken and Bridgeton Formations comprise most of the Atlantic Coastal Plain Province. They consist of fluvial arkosic quartz sand with pebble beds and minor clay and silt beds. The Pensauken and Bridgeton Formations unconformably overlie the lower Paleozoic Wissahickon Formation. The belt of Quaternary sediment near the Delaware River includes Holocene to Recent fluvial and swamp deposits as well as gray pebbly sand, crossbedded sand, silt, and clay of the Trenton Gravel.

GLACIAL GEOLOGY

Pleistocene glaciers of the Erie-Ontario lobe advanced from the northwest across northwestern Pennsylvania, and glaciers of the Hudson-Champlain lobe advanced from the northeast, covering the northeastern quarter of the State (Fullerton, 1986). Glacial deposits in Pennsylvania range in age from about 550,000 to about 12,500 years B.P. (fig. 6; Pennsylvania Topographic and Geological Survey, 1981).

Glacial deposits in Pennsylvania can be classified into three main categories: till, glaciofluvial deposits, and glacial lake deposits. Till is an unsorted deposit of gravel, sand, silt, and clay, with occasional cobbles and boulders. Thickness of the till ranges from a thin, discontinuous veneer of less than one meter to locally more than 15 meters on end moraines, but it is generally in the range of 1-10 m thick (Richmond and Fullerton, 1991, 1992). The composition of the till typically reflects the underlying bedrock, although clasts of bedrock from many kilometers away are common. In northern Pennsylvania, the till clasts are predominantly sandstone, siltstone, and shale, with minor limestone and crystalline rock from New York and Canada. The older tills (pre-late Wisconsinan) are generally silty and clayey whereas late Wisconsinan tills are generally silty to sandy (Pennsylvania Topographic and Geological Survey,

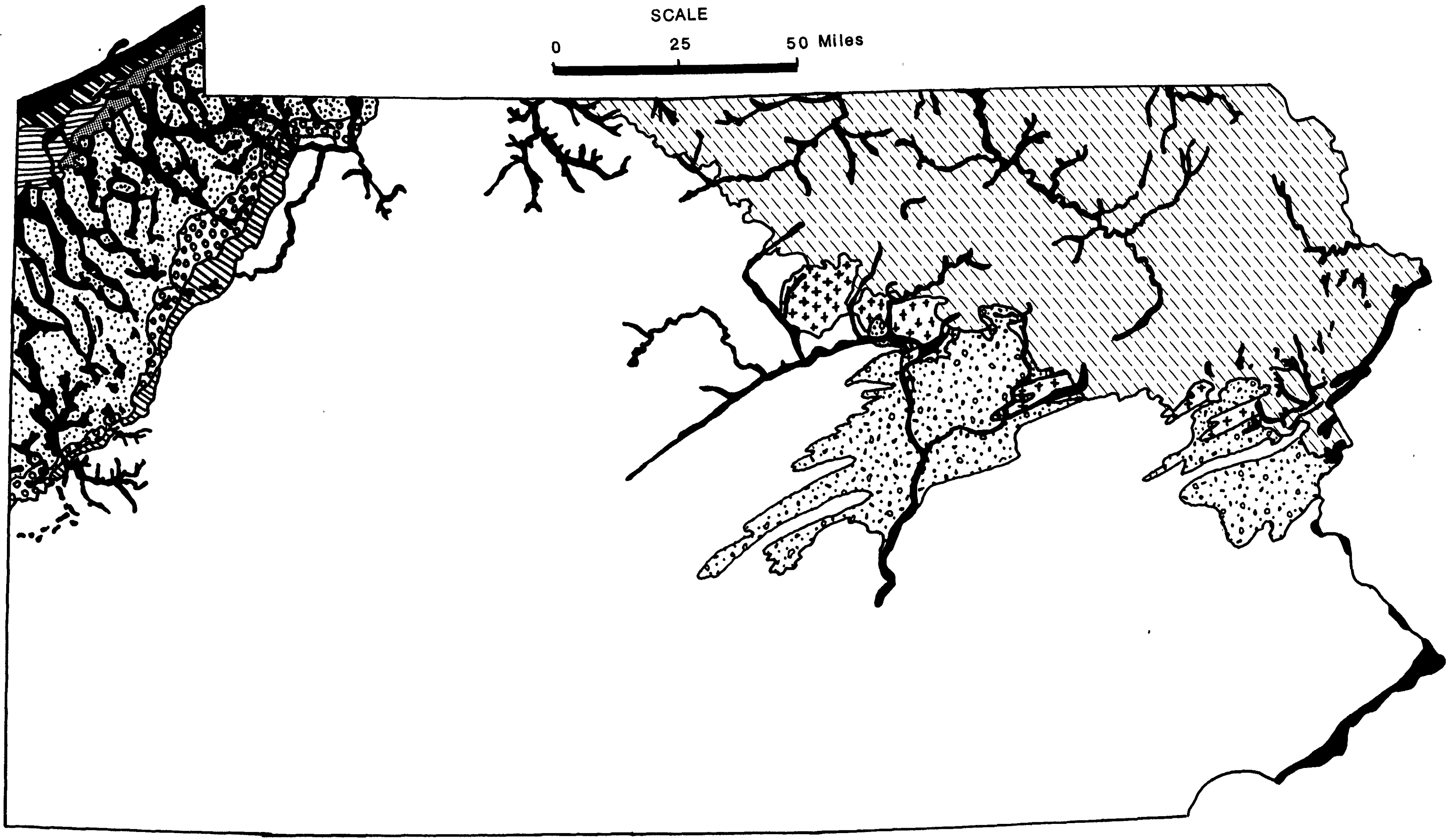


Figure 6. Generalized glacial geologic map of Pennsylvania (from Pennsylvania Topographic and Geologic Survey, 1981).

GLACIAL DEPOSITS OF PENNSYLVANIA
EXPLANATION

(from Pennsylvania Topographic and Geologic Survey, 1981)

AGE	SYMBOL	NAME	DESCRIPTION
RECENT TO ILLINOIAN		STRATIFIED DRIFT	Sand and gravel in eskers, kames, kame terraces, and outwash, principally in valleys; silt and clay in lake deposits in formerly ice-dammed valleys; lake clays and beach sands and gravels along Lake Erie; thin (Recent) to thick (Illinoian) soils.
LATE WISCONSINAN		ASHTABULA TILL HIRAM TILL LAVERY TILL KENT TILL	Thick, gray, clayey to silty to sandy till covering over 75 percent of the ground; topography is mainly gently undulating, but there is also some knob-and-kettle topography; thin soil.
		OLEAN TILL	Moderately thick, gray to grayish-red, sandy till covering 25 to 50 percent of the ground; very thin till covers an additional 25 percent of the ground; topography reflects the underlying bedrock; thin soil.
EARLY WISCONSINAN		TITUSVILLE TILL WARRENSVILLE TILL	Thin, gray (Titusville) to grayish-red (Warrensville), clayey to sandy till covering 10 to 25 percent of the ground; topography reflects the underlying bedrock; moderately thick, well-developed soil.
ILLINOIAN		MAPLEDALE TILL MUNCY TILL	Thin, gray, clayey to silty till in patches covering up to 10 percent of the ground; topography reflects the underlying bedrock; thick, well-developed soil often having a yellowish-red color.

1981). A large proportion of the soils developed on these older tills have seasonally high water tables, slow permeability, and poor drainage. Sandy and stony till soils have good drainage with rapid permeability. Glacial landforms typically associated with till include drumlins, kettles, and moraines. Moraines are ridges of till that form at the margin of a stationary or retreating glacier. Kettles are depressions in the till surface that form when blocks of glacial ice, buried beneath a layer of till, melt away, causing the till to collapse into the depression. The hummocky landscape that forms is called "knob-and-kettle topography". Drumlins are streamlined, conical hills of till that are oriented parallel to the direction of glacial movement.

Glaciofluvial deposits are stratified sands and gravels deposited by glacial meltwater streams. Glaciofluvial features include outwash plains, kames, kame terraces, and eskers. Common to all types of glaciofluvial deposits are their coarse, sandy and gravelly texture, and their stratified (bedded) nature. Coarse sand and gravel deposited by glacial meltwater streams is called outwash and occurs in many glaciated valleys. Kames were formed where meltwater streams on top of the glacier surface deposited sediment in depressions on the glacier's top surface. When the glacier melted, these deposits slumped to the ground surface, forming irregular, stratified hills. Kame terraces were formed by glacial meltwater streams that flowed between the edge of the glacier and a valley wall. Again, when the glacier melted, the stratified deposits slumped to the valley floor, forming irregular, elongate deposits along the sides of valleys. Eskers are long, narrow, sinuous ridges composed of sand and gravel deposited by rivers that flowed in tunnels underneath a stagnant ice sheet or glacier. The soils developed on glacial outwash have moderate to good drainage and moderate to rapid permeability.

Glaciolacustrine (glacial lake) deposits consist of stratified silt and clay deposited on the bottoms of lakes dammed by moraines or ice. Lake-bottom silt and clay deposits occur along the shore of Lake Erie and in some valleys in northwestern Pennsylvania. Coarse-grained sediments associated with glacial lakes include deposits of lacustrine deltas, beaches, or wave-cut outwash terraces. Beach deposits, formed when Lake Erie was at a higher level following glaciation, are found in Erie County. Soils developed on lake-bottom silt and clay typically have poor drainage and slow permeability, whereas soils developed on lacustrine deltas and beaches have moderate to good drainage and moderate to rapid permeability. Glaciolacustrine deposits are mapped with glaciofluvial features on figure 6.

URANIUM OCCURRENCES AND AERORADIOACTIVITY

An aeroradiometric map of Pennsylvania (fig. 7) was compiled from spectral gamma-ray data acquired during the U.S. Department of Energy's National Uranium Resource Evaluation (NURE) program (Duval and others, 1989). For the purposes of this report, low equivalent uranium (eU) is defined as less than 1.5 parts per million (ppm), moderate eU is defined as 1.5-2.5 ppm, and high eU is defined as greater than 2.5 ppm. In figure 7, the Piedmont and New England Provinces have a few areas of low radioactivity but, for the most part, eU ranges from moderate to high. The Blue Ridge has distinctly low aeroradiometric signature, with some moderate eU along the eastern edge of the province. The Great Valley Section has moderate to high eU overall. The Appalachian Mountain Section is predominantly low, with lesser areas of moderate eU and a prominent area of high eU centered over Montour County and adjacent Columbia and Northumberland Counties. The Glaciated Pocono Plateau Section and eastern half of the Glaciated Low Plateau Section have low to moderate eU. The western half of the Glaciated Low Plateau Section has moderate to high eU. The High Plateau Section and much of the

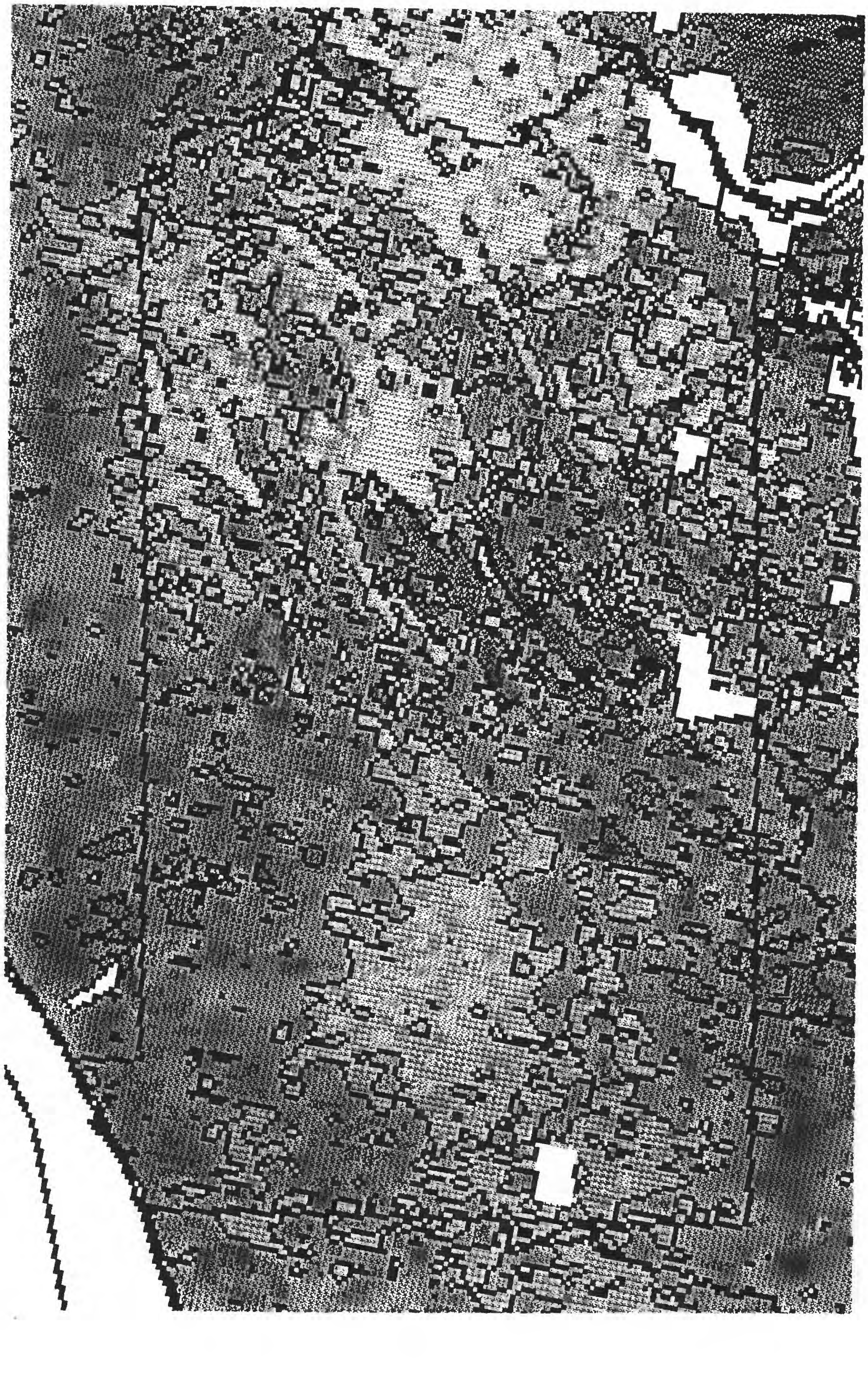


Figure 7. Aerial radiometric map of Pennsylvania (after Duval and others, 1989). Contour lines at 1.5 and 2.5 ppm equivalent uranium (eU). Pixels shaded at 0.5 ppm eU increments; darker pixels have lower eU values; white indicates no data.

Mountainous High Plateau has low and some moderate eU. The Glaciated Pittsburgh Plateau has moderate eU and several areas of high eU. Moderate and high eU covers much of the Pittsburgh Low Plateau Section. R. Smith and J. Barnes (PA Geological Survey, unpub. data) field-checked many of the NURE radiometric anomalies and found a correlation between some of the anomalies and fresh bedrock at or near the surface (as opposed to actual uranium anomalies).

Uranium occurrences in Pennsylvania are widespread. The following description of the known uranium occurrences are provided in order of rock age. Equivalent uranium concentration (fig. 7) is further noted where it appears to correlate with specific areas and is documented in the NURE reports.

Within the Reading Prong, northeast of Pikesville, McCauley (1961) described 0.2 percent U_3O_8 in a pegmatite associated with a magnetite ore body. Montgomery (1957) described uranium minerals within Precambrian serpentine rock associated with the Franklin Marble near Easton. The NURE Portfolios for the Newark and Scranton Quadrangles (LKB Resources, 1978a, c) document a number of moderate to high eU values in granitic gneiss of the Reading Prong and the Piedmont Upland section. Equivalent uranium is especially high in the Reading Prong. A carborne radiometric survey of the Reading Prong (Pennsylvania Topographic and Geological Survey, 1985) recorded numerous elevated gamma-ray readings, most of which correlate with granitic gneiss. The Pennsylvania Geological Survey (1978) observed high radioactivity associated with many faults and shear zones in the Reading Prong. They reported 67 ppm U_3O_8 in a sample from one of the shear zones.

The aeroradioactivity map (fig. 7) shows a group of high anomalies apparently associated with serpentinite and marble units in the Piedmont Upland of eastern Northampton and central Chester Counties and high eU associated with phyllite in the Wissahickon Formation in central York County. The Wissahickon Formation in the Piedmont Upland section also appears to have numerous moderate eU areas (fig. 7). The Catoctin Formation in the Blue Ridge appears to have low eU associated with it. At the Pennsylvania Topographic and Geologic Survey, J. Barnes calculated the median uranium content of 80 samples of Catoctin metabasalt and metadiabase (delayed neutron activation analyses) and found it to be less than 0.5 ppm.

Dennison (1982) reported uranium minerals in the Hardyston Formation. Van Assendelft and Sachs (1982) reported elevated uranium in soils (up to 5 ppm U) and elevated radon in homes overlying dolomites of the Cambrian Leithsville Formation in Lehigh County. The NURE folios for the Newark and Harrisburg Quadrangles (LKB Resources, 1978b, c) indicate that numerous moderate to high eU concentrations are associated with Cambrian carbonate rocks of the Piedmont Lowland and the Great Valley. The shaly dolomites of the Snitz Creek, Elbrook, Leithsville, Ledger, and Allentown Formations all have several areas of high eU values. LKB Resources (1978b, c) also report several high values in the Chickies Quartzite in Lancaster County. Several moderate eU values are reported in the Hardyston Formation in the New England and northern Piedmont provinces. The aeroradioactivity map (fig. 7) shows a concentration of high to moderate eU associated with the Cambrian carbonate rocks in the Piedmont Lowland and Great Valley sections, and associated with the small Cambrian carbonate rock areas near the Allegheny Front in the western Appalachian Mountain section. Moderate to high eU readings appear to correlate with the Harpers Formation in the Blue Ridge Province in Franklin County.

Van Assendelft and Sachs (1982) reported elevated uranium in soils (up to 6.5 ppm U) and elevated radon in homes overlying the Ordovician Beekmantown Group in Dauphin, Northampton, and Cumberland Counties, and overlying the Ordovician Martinsburg Formation (4.96 ppm U in soil) in Lehigh County. The NURE folios for the Newark, Scranton, and Harrisburg Quadrangles

(LKB Resources, 1978a, b, c) report numerous high to moderate eU anomalies in Ordovician carbonates in the Piedmont Lowland, Great Valley, and Appalachian Mountain sections. The Beekmantown Group, St. Paul Group, Conestoga Formation, and the Epler and Rickenbach Formations all have a number of high eU readings (4-6 ppm eU) in shaly limestone and dolomite. The Coburn Formation has particularly high eU readings (up to 12 ppm) in the Appalachian Mountain section. The black shales of the Martinsburg Formation and similar units in the Hamburg Klippe and the Reedsville Formation all have numerous high eU values (commonly 5-7 ppm eU). The aeroradioactivity map of Pennsylvania (fig. 7) shows high to moderate eU values associated with Ordovician rocks of the Piedmont Lowland, Great Valley, and the Appalachian Mountain sections. The sandstone unit of the Hamburg Klippe in Berks County appears to have low to moderate eU.

The NURE folio for the Harrisburg Quadrangle (LKB Resources, 1978a) reports numerous high to moderate eU concentrations in the Silurian limestone, dolomite, and shaly limestone of the Tonoloway, Keyser, and Wills Creek Formations and numerous high eU values (3-8 ppm) in the Clinton Group within the Appalachian Mountain section. The Clinton Group anomalies may be associated with gray shales and/or hematitic sandstones. The Silurian units are not distinguishable as moderate to high areas on the aeroradioactivity map (fig. 7), but the Shawangunk Formation does stand out as distinctly low in radioactivity.

As many as 50 uranium prospects have been reported in the Devonian Catskill Formation (McCauley, 1961; Schmiermund, 1977; Smith, 1980; Smith and Hoff, 1984). The uranium occurs throughout the formation, but most of the occurrences are concentrated near the Allegheny Front in Sullivan and Lycoming Counties. Prospects also occur in Columbia, Bradford, Wyoming, Wayne, Lackawanna, Northumberland, and Huntingdon Counties. According to van Assendelft and Sachs (1982), lower Catskill occurrences are mostly carbonaceous debris associated with limestone pellets in crossbedding, and some of the upper Catskill occurrences are larger roll-front deposits at the contact of red conglomerates with green siltstone. The latter type contain up to 0.5 percent (5000 ppm) U. Smith and Hoff (1984) note that uranium associated with calcareous lag gravels in the upper Catskill has a median concentration of 34 ppm U_3O_8 (these gravels also contain phosphatic fish fossil fragments), the overlying gray sandstone has a median value of 55 ppm U_3O_8, and associated reduced siltstone and shale beds have a median value of 39 ppm U_3O_8. Van Assendelft and Sachs (1982) report elevated radon in homes overlying the Devonian Lock Haven Formation at the Catskill contact in Lycoming County. The NURE folios for the Newark, Scranton, and Harrisburg Quadrangles (LKB Resources, 1978a, b, c) reported moderate to high eU that is commonly associated with Lower Devonian carbonate rocks and black shales of the Hamilton Group, Susquehanna Group, and the lower Catskill Formation. Equivalent uranium as high as 11 ppm occurs in fluvial sandstones of the Catskill Formation. The aeroradioactivity map (fig. 7) shows Devonian rocks of the Appalachian Mountain section as having mostly high to moderate eU and outlines the Allegheny Front boundary in the Catskill Formation and the folds in the Catskill Formation in Lycoming, Montour, and Northumberland Counties. The Catskill fluvial facies in Bradford and Tioga Counties is associated with high eU, whereas the deltaic facies of the Lock Haven Formation in Potter, McKean, Warren, and Cameron Counties and the deltaic facies of the lower Catskill formation in Bedford and Somerset Counties all have moderate to low eU. The Devonian Marcellus Formation has uranium concentrations as high as 16 ppm in black carbonaceous shale, whereas the Hamilton Group, in general, has typical concentrations of 2-3 ppm U (Pennsylvania Topographic and Geologic Survey, 1988, unpub.

Bucks County report). The Devonian Northeast Shale in Erie County and the Venango Shale in Crawford County produce locally high eU.

McCauley (1961) described four occurrences of uranium in the Mississippian Mauch Chunk Formation near the contact with the overlying Pottsville Formation. Uranium concentrations of about 0.15-0.25 percent occur in gray sandstone and conglomerate overlying red siltstone and shale. The nature of these occurrences, with additional references, are further described in Sevon and others (1978), who report concentrations up to 1.8 percent U_3O_8 (R.C. Smith, pers. comm., indicates a concentration of 2.58 percent U_3O_8 from a channel sample at Mount Pisgah). Dennison (1982) reports a uranium show in the Mississippian Pocono Group near Wilkes-Barre. Van Assendelft and Sachs (1982) report that uranium occurrences occur in the Mauch Chunk near the underlying Pocono Group and overlying Pottsville Formation. The NURE portfolios for the Scranton and Harrisburg Quadrangles (LKB Resources, 1978a, b) report moderate eU values for the Pocono Group and high eU values (up to 6 ppm eU) for the Mauch Chunk Formation. The aeroradioactivity map of Pennsylvania (fig. 7) appears to show moderate to high eU values for the outcrop belt of the Mauch Chunk and low to moderate eU for the Pocono Group.

Dennison (1982) reports uranium shows in the lower Freeport Coal of the Pennsylvanian-age Allegheny Group in Clearfield and Beaver Counties. The NURE portfolios for the Scranton and Harrisburg Quadrangles (LKB Resources, 1978a, b) indicate that moderate eU anomalies are common in the Llewellyn Formation, probably associated with coals. The aeroradioactivity map of Pennsylvania (fig. 7) shows moderate to high eU values that appear to be associated with the lower Allegheny Group in Butler, Clarion, and Jefferson Counties, with the lower Conemaugh Group in Beaver, Butler, Armstrong, and Indiana Counties, and with the Monongahela Group in Washington and Westmoreland Counties. High values in Crawford County appear to be at least partially associated with the black shales of the Bedford and Rice Shales. The Pottsville Group is associated with conspicuous low eU readings along the entire belt of its outcrop.

Dennison (1982) reports occurrences of apatite and monazite in the Mather sandstone lentils of the Waynesburg Formation. Moderate eU readings appear to correlate with the Waynesburg Formation in Washington and Greene Counties on the aeroradioactivity map of Pennsylvania (fig 7). The Greene Formation in Greene County correlates with a conspicuous low eU area on the map.

Three prospects of McCauley (1961) were in Triassic fluvial sandstone of the upper Stockton Formation, where gray to black silt lenses occurred in arkosic sandstone channels. Uranium occurrences have also been noted in the upper Stockton Formation by Turner-Peterson (1980) and in black shales (Olsen, 1988) and gray sandstones (J.P. Smoot, unpub. data) of the Lower Brunswick Group. The Pennsylvania Topographic and Geologic Survey (1988, unpub. Bucks County report) discusses more than 30 uranium occurrences associated with Stockton sandstones and from black shale of the Lockatong Formation and Brunswick Group. They report concentrations of 5 to 35 ppm U from channel samples of these units. Geyer and others (1976) note uraniferous mineral assemblages associated with iron ores occurring where diabase sheets have metamorphosed Paleozoic limestones or early Mesozoic limestone conglomerates in the vicinity of the Narrow Neck. Black shales of the Heidlersburg Member and fluvial sandstones of the New Oxford Formation have moderate to high eU values on the NURE aeroradioactivity map (fig. 7). The upper New Oxford Formation contains lithologic associations similar to the uranium-bearing units in the Stockton Formation, but no uranium occurrences have been noted. The black shales and gray sandstones of the Lockatong Formation and the Heidlersburg Member are similar to the uranium-rich units of the Lower Brunswick Group, but no uranium occurrences have been noted. Black shales and gray sandstones in the Upper Brunswick Group and upper Gettysburg Formation may also be locally uranium-rich, but no uranium occurrences have been noted. The NURE folios for the Newark and Scranton Quadrangles (LKB Resources, 1978a, b) report moderate to high eU in the Lower Brunswick Group and the Gettysburg shale, particularly in areas adjacent to diabase sheets. The aeroradioactivity map of Pennsylvania (fig. 7) shows moderate to high eU associated with the upper Stockton and New Oxford Formations and with the Lockatong and lowermost Lower Brunswick Group and the Heidlersburg Member of the Gettysburg Formation. Tertiary gravels and sands all appear to be have low eU on the aeroradioactivity map of Pennsylvania (fig. 7).

INDOOR RADON

Indoor radon data from 2,389 homes sampled in the State/EPA Residential Radon Survey conducted in Pennsylvania during the winter of 1988 are shown in figure 8 and given in Table 1. A map of counties is included for reference (fig. 9). Indoor radon was measured by charcoal canister and data are shown on figure 8 only for those counties with 5 or more data values. The maximum value recorded in the survey was 273.5 pCi/L in Dauphin County. The average for the State was 7.5 pCi/L and 39 percent of the homes tested had indoor radon levels exceeding 4 pCi/L. Counties with maximum indoor radon levels greater than 100 pCi/L include Beaver, Cumberland, Dauphin, Elk, Lancaster, Lebanon, Potter, Union, and York Counties (Table 1). The highest percentage of homes with indoor radon levels over 4 pCi/L appear to be associated with rocks of the Great Valley section, the Piedmont Uplands and Lowlands, parts of the Appalachian Mountain section along the Allegheny Front and in the northern counties, the western Glaciated Low Plateau section, and the Pittsburgh Low Plateau section. The majority of counties in Pennsylvania have average radon concentrations greater than 4 pCi/L. Counties with an average less than 4 pCi/L include Wayne, Lackawanna, and Luzerne Counties in the Glaciated Pocono Plateau, the eastern Glaciated Low Plateau, and northernmost Appalachian Mountain section; Philadelphia, Delaware, and Montgomery Counties in the Atlantic Coastal Plain, the Gettysburg-Newark Lowland, and in the easternmost Piedmont Upland; Huntington County in the southern Appalachian Mountain section; Cambria County in the Allegheny Mountains; Washington, Greene, Crawford, and Lawrence Counties in the Glaciated Pittsburgh Plateau and the Pittsburgh Low Plateau sections; and McKean County in the High Plateau section.

Non-random indoor radon data compiled by EPA Region 3 from homeowners and vendors of radon test kits for over 68,000 homes is presented in figure 10. Non-random (volunteer) indoor radon data tend to be biased toward higher values compared to randomly sampled surveys because it is more likely that many of the data points are from homeowners that tested their homes after receiving word of a nearby high value. However, these data do appear to further emphasize the areas of low and high radon in the State and provide some distinction within the higher radon categories. The Great Valley section and Piedmont and New England Provinces appear to have the greatest percentage of homes with indoor radon levels greater than 4 pCi/L.

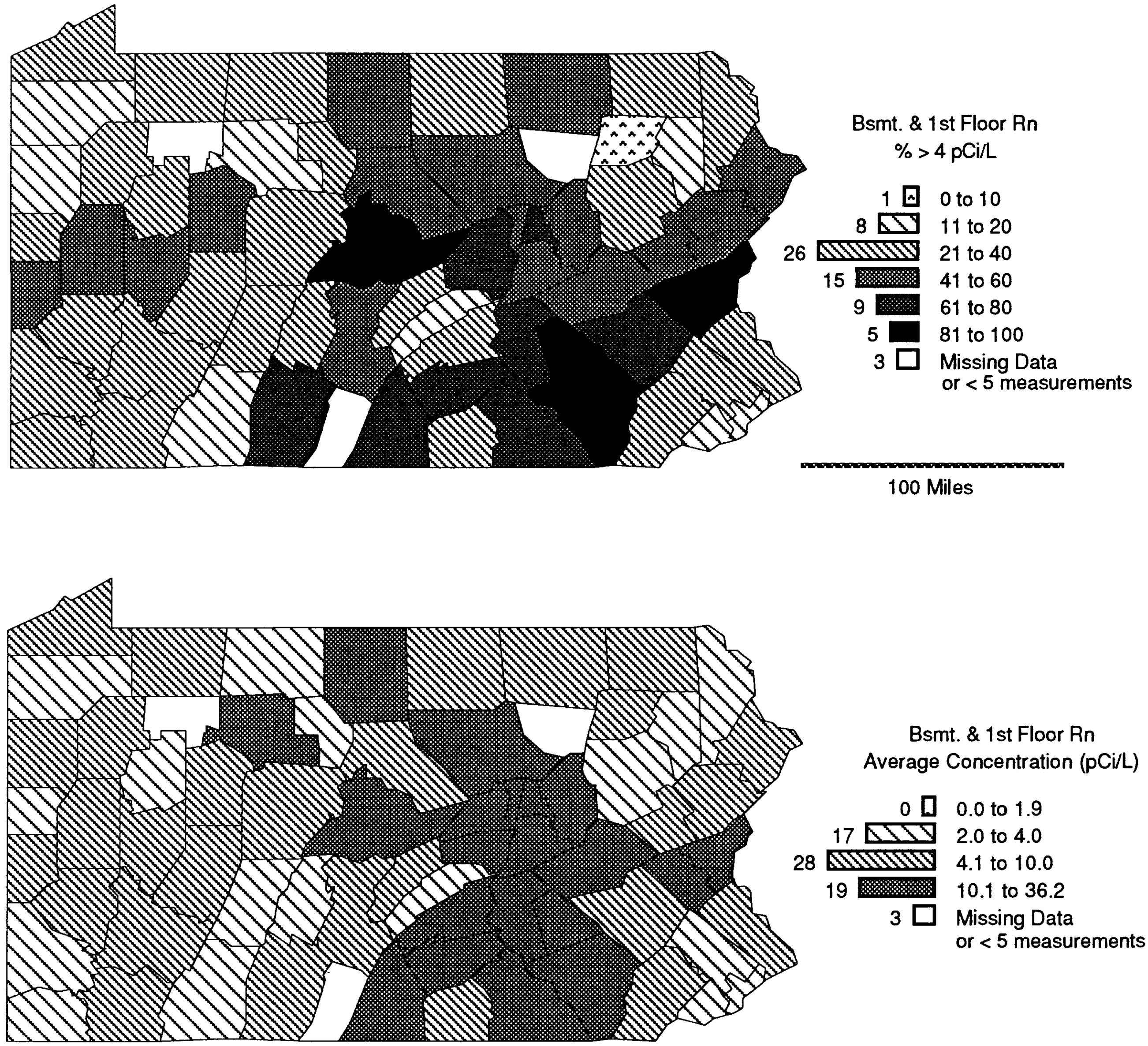


Figure 8. Screening indoor radon data from the EPA/State Residential Radon Survey of Pennsylvania, 1987-88, for counties with 5 or more measurements. Data are from 2-7 day charcoal canister tests. Histograms in map legends show the number of counties in each category. The number of samples in each county (See Table 1) may not be sufficient to statistically characterize the radon levels of the counties, but they do suggest general trends. Unequal category intervals were chosen to provide reference to decision and action levels.

TABLE 1. Screening indoor radon data from the EPA/State Residential Radon Survey of Pennsylvania conducted during 1987-88. Data represent 2-7 day charcoal canister measurements from the lowest level of each home tested.

COUNTY	NO. OF MEAS.	MEAN	GEOM. MEAN	MEDIAN	STD. DEV.	MAXIMUM	%>4 pCi/L	%>20 pCi/L
ADAMS	26	6.8	2.7	2.4	14.9	76.8	35	4
ALLEGHENY	261	4.7	2.4	2.4	9.0	91.9	28	3
ARMSTRONG	15	6.2	3.8	3.6	6.5	24.7	47	7
BEAVER	120	7.9	4.3	3.7	12.5	103.5	46	11
BEDFORD	14	8.5	5.3	5.5	7.9	25.8	64	7
BERKS	40	9.9	5.0	5.8	12.6	68.2	63	13
BLAIR	32	4.0	2.4	2.4	5.0	26.1	28	3
BRADFORD	40	7.8	4.1	4.8	9.9	50.0	58	8
BUCKS	46	4.6	2.9	2.9	5.4	33.2	33	2
BUTLER	97	8.8	4.1	4.0	12.3	74.5	50	16
CAMBRIA	42	3.8	2.4	2.0	4.4	19.2	24	0
CAMERON	5	3.7	2.1	1.4	3.9	9.5	40	0
CARBON	18	8.3	4.5	3.7	10.5	42.5	50	6
CENTRE	22	14.1	8.8	8.2	19.6	89.2	82	9
CHESTER	34	9.9	3.8	3.5	15.3	64.3	38	18
CLARION	13	4.0	2.5	2.9	4.6	17.8	39	0
CLEARFIELD	28	5.3	2.9	2.9	8.5	45.0	29	4
CLINTON	7	9.4	2.1	2.9	17.7	49.0	43	14
COLUMBIA	10	17.5	7.7	8.3	27.6	91.9	60	20
CRAWFORD	21	2.8	1.9	1.6	2.8	11.3	19	0
CUMBERLAND	45	20.6	10.6	11.0	28.8	156.3	78	29
DAUPHIN	49	22.8	7.2	9.4	46.9	273.5	61	22
DELAWARE	39	2.7	1.3	1.4	4.5	26.4	13	3
ELK	17	18.9	2.5	2.1	62.6	260.9	18	12
ERIE	70	4.8	1.8	1.4	7.9	45.9	30	6
FAYETTE	28	4.7	2.4	1.8	6.2	22.0	25	7
FOREST	3	1.8	1.5	1.5	1.1	3.0	0	0
FRANKLIN	20	12.4	7.6	10.8	11.3	45.5	65	15
FULTON	3	28.2	16.2	15.8	32.1	64.6	100	33
GREENE	7	2.7	1.5	2.3	2.2	5.8	29	0
HUNTINGDON	7	4.3	3.3	3.0	3.1	9.8	43	0
INDIANA	17	5.3	2.8	1.9	7.0	26.0	35	6
JEFFERSON	14	6.7	4.6	5.9	5.3	19.9	57	0
JUNIATA	5	3.3	2.2	1.7	3.7	9.7	20	0
LACKAWANNA	81	3.0	1.9	1.6	4.7	40.0	20	1
LANCASTER	69	14.0	9.5	9.3	16.0	105.7	87	16
LAWRENCE	56	3.6	2.4	2.4	3.5	18.0	29	0
LEBANON	21	22.8	12.6	11.5	41.3	196.7	86	24
LEHIGH	23	16.1	9.1	8.5	18.6	78.0	87	26
LUZERNE	118	3.5	2.4	2.3	3.7	22.2	25	1
LYCOMING	28	10.7	4.1	3.3	20.0	77.4	43	11

TABLE 1 (continued). Screening indoor radon data for Pennsylvania.

COUNTY	NO. OF MEAS.	MEAN	GEOM. MEAN	MEDIAN	STD. DEV.	MAXIMUM	%>4 pCi/L	%>20 pCi/L
MCKEAN	15	3.2	1.5	1.9	4.7	19.0	27	0
MERCER	51	4.9	2.2	1.9	13.2	93.4	18	4
MIFFLIN	10	6.3	2.8	1.9	11.1	37.3	30	10
MONROE	55	8.3	4.4	4.4	10.7	63.5	53	11
MONTGOMERY	60	3.2	2.3	2.4	2.6	13.1	28	0
MONTOUR	6	15.6	6.2	4.7	28.4	73.6	67	17
NORTHAMPTON	26	12.5	8.0	7.5	13.1	51.9	89	15
NORTHUMBERLAND	15	11.0	5.2	4.8	19.7	79.7	53	7
PERRY	6	10.7	2.4	2.9	16.2	41.5	33	17
PHILADELPHIA	125	2.3	1.4	1.5	3.8	37.7	11	1
PIKE	8	5.4	2.8	4.6	5.6	16.4	50	0
POTTER	12	35.3	5.3	3.4	76.4	227.2	42	17
SCHUYLKILL	32	13.6	5.0	4.8	18.9	73.4	56	22
SNYDER	6	13.7	6.3	8.0	18.1	49.4	67	17
SOMERSET	23	3.8	2.1	2.6	5.6	27.0	17	4
SULLIVAN	1	6.1	6.1	6.1	***	6.1	100	0
SUSQUEHANNA	20	4.7	2.9	2.6	5.0	17.4	35	0
TIOGA	29	8.4	2.5	1.6	16.1	70.1	35	17
UNION	8	36.2	8.5	7.9	82.6	240.4	75	13
VENANGO	27	6.2	3.0	2.5	9.9	47.5	30	7
WARREN	15	5.0	2.2	1.8	7.6	29.9	33	7
WASHINGTON	45	3.6	2.1	1.8	4.3	20.5	22	2
WAYNE	31	3.0	1.4	1.3	4.6	22.8	23	3
WESTMORELAND	72	4.3	2.7	3.2	4.8	34.3	38	1
WYOMING	12	5.6	2.3	1.8	13.1	47.2	8	8
YORK	68	15.5	7.5	6.6	24.6	155.6	68	21

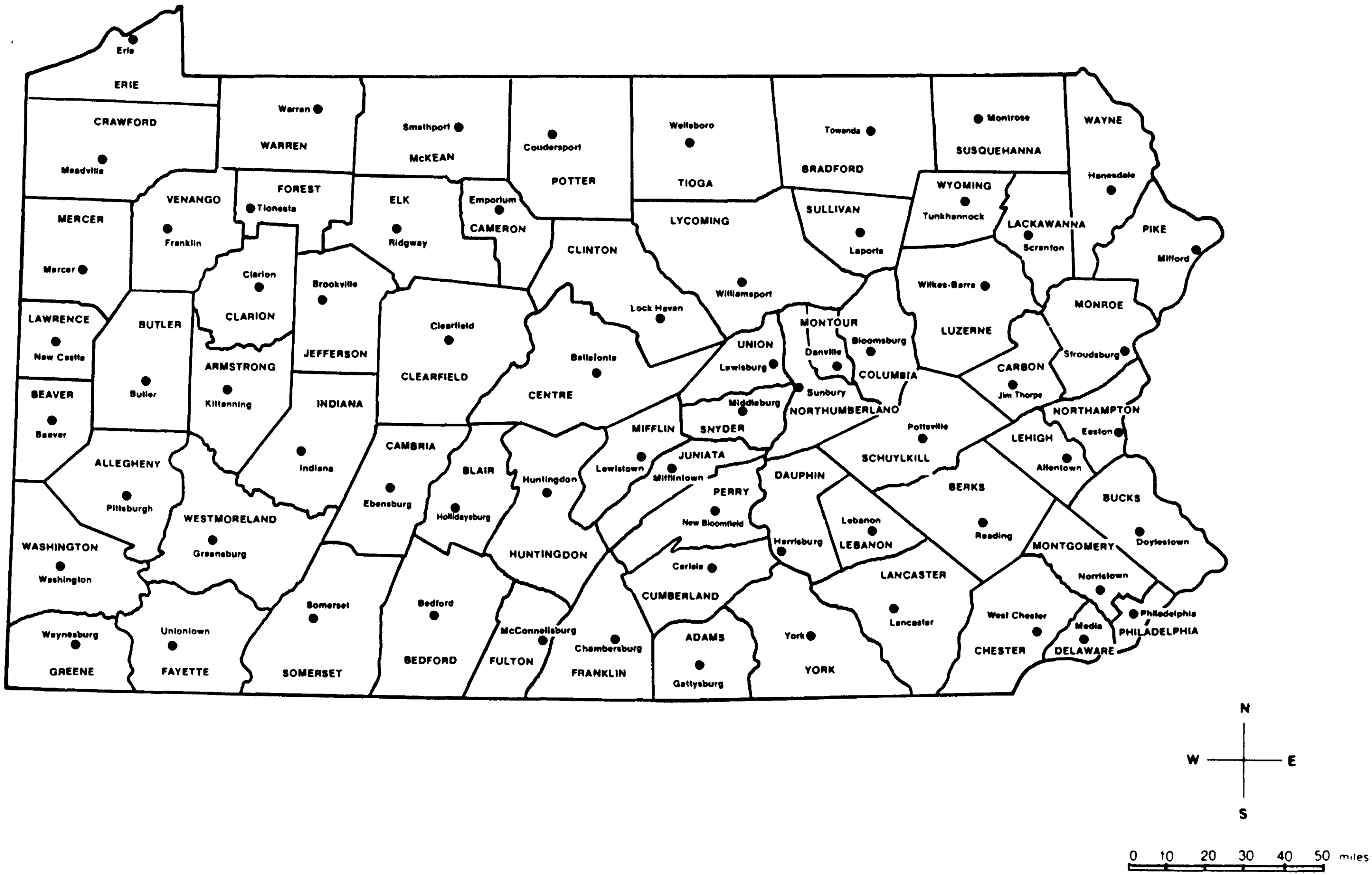


Figure 9. Pennsylvania counties (from Facts on File, 1984).

Figure 10. Map showing percent of homes tested in Pennsylvania with screening indoor radon levels exceeding 4 pCi/L. Data collected by EPA Region 3 from Key Technology, Teledyne, Air-Chek, Inc., and The Radon Project. Total number of readings is 68, 419.

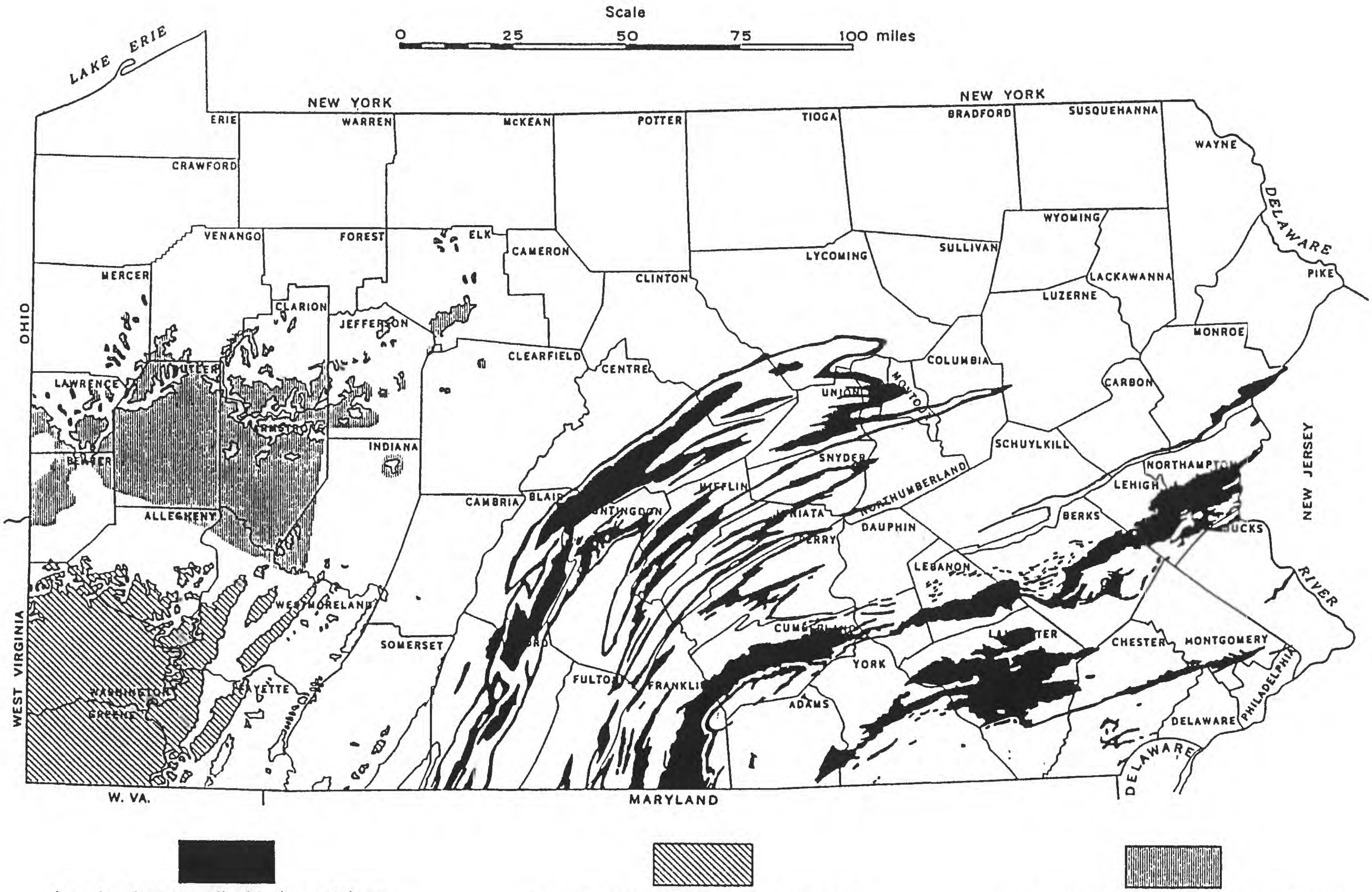
GEOLOGIC RADON POTENTIAL

A number of studies have been done on the correlation of indoor radon with geology in Pennsylvania. The Reading Prong is the most notable example because of the national publicity surrounding a particularly severe case of radon (Smith and others, 1987). These authors and others (Gundersen and others, 1988; Agard and Gundersen, 1991; Gundersen, 1991) found that shear zones within the Reading Prong rocks enhanced the radon potential of the rocks and created local occurrences of very high uranium and indoor radon. Several of the rock types in the Reading Prong are highly uraniferous and are the source for high radon levels throughout much of the New England Province. Smith and others (1987) report a median of 81 ppm U for 47 granite-hosted occurrences in the Reading Prong. Very high indoor radon levels have been found throughout the Reading Prong (R.C. Smith, pers. comm.).

Some rocks within the Piedmont have high geologic radon potential and are associated with high indoor radon and high radioactivity. Rock types in the Piedmont with some naturally elevated uranium concentrations include granitic gneiss, biotite schists, and gray phyllites. Phyllites and schists in other parts of the Piedmont, such as the Wissahickon Formation and Peters Creek Schist equivalents in Maryland and Virginia, shear zones in these rocks, and the faults surrounding mafic bodies within these rocks are known sources of radon and have high indoor radon associated with them (Gundersen and others, 1988; Otton and others, 1988).

Carbonate rocks of the Great Valley and Appalachian Mountain section have been the focus of several studies (van Assendelft and Sachs, 1982; Gross and Sachs, 1982; Greeman and Rose, 1990; Luetzelschwab and others, 1989), and the carbonate rocks in these areas produce soils with high uranium and radium contents and high soil-gas radon concentrations. In general, indoor radon in these areas is higher than 4 pCi/L and the geologic radon potential of the area is high, especially in the Great Valley where the average indoor radon is distinctly higher than in surrounding areas. The limestone and dolomite distribution in Pennsylvania is shown in figure 11 (Pennsylvania Topographic and Geological Survey, 1990). Limestone and dolomite rock at the surface in the Great Valley, Appalachian Mountains, and Piedmont are probably sources of high indoor radon. Carbonate rocks themselves are usually low in radionuclide elements, but the soils developed from carbonate rocks are often elevated in uranium and radium. Carbonate soils are derived from the dissolution of the $CaCO_3$ that makes up the majority of the rock. When the $CaCO_3$ has been dissolved away, the soils are enriched in the remaining impurities, predominantly base metals, including radionuclides. Studies in the carbonates of the Great Valley in West Virginia suggest that the deepest, most mature soils have the highest radium concentrations (Schultz and Wiggs, 1989; Schultz and others, 1992). Rinds containing high concentrations of uranium and uranium minerals can be formed on the surfaces of rocks involved in $CaCO_3$ dissolution and karstification. Karst and cave morphology is also thought to promote the flow and accumulation of radon.

The clastic rocks of Pennsylvania, particularly some of the black to gray shales and fluvial sandstones of the Newark basin and many of the Ordovician through Pennsylvanian-age black to gray shales and fluvial sandstones, have been extensively cited in the literature (as referenced in the uranium occurrences and aeroradioactivity section above) for their uranium content as well as their general uranium potential. Data from Luetzelschwab and others (1989) indicate that gray shales can be effective emanators of radon. Van Assendelft and Sachs (1982) list an extensive table of indoor radon and associated geologic units in Pennsylvania. It appears from the uranium and radioactivity data and comparison with the indoor radon data that the black shales of the Ordovician



Area where limestone and/or dolomite are at the surface. Layers are usually strongly folded and steeply dipping. Includes the economically important high-calcium limestones of the Kinzers, Annville, Benner, and Keyser Formations and the Cockeysville Marble, as well as the high-magnesium dolomites of the Ledger Formation and Cockeysville Marble.

Area underlain by flat-lying, generally thin, but locally thick, limestone beds which may be discontinuous; frequently interbedded with shale.

Area underlain by the generally flat lying Vanport Limestone, a high-calcium limestone. Generally overlain by less than 100 feet of sedimentary rocks, except in the southern part of the area.

Figure 11. Limestone and dolomite areas of Pennsylvania (from Pennsylvania Topographic and Geologic Survey, 1984).

Martinsburg Formation, the lower Devonian black shales, Pennsylvanian black shales of the Allegheny Group, Conemaugh Group, and Monogahela Group, and the fluvial sandstones of the Devonian Catskill and Mississippian Mauch Chunk Formation may be the source of most moderate to high indoor radon levels in the Appalachian Plateau and parts of the Appalachian Mountains section.

Studies in the Newark Basin of New Jersey (Szabo and Zapecza, 1991; Muessig, 1989) indicate that the black shales of the Lockatong and Passaic Formations and fluvial sandstones of the Stockton Formation are a significant source of radon in indoor air and in water. Where these rock units occur in Pennsylvania, they may be the source of high indoor radon as well. Black shales of the Heidlersburg Member and fluvial sandstones of the New Oxford Formation may also be sources of locally moderate to high indoor radon in the Gettysburg Basin, although uranium occurrences have not been found. Diabase sheets and dikes within the basins have low eU. The Mesozoic basins as a whole, however, are variable in their geologic radon potential. The Narrow Neck area is distinctly low in radioactivity (fig. 7) and Montgomery County, which is underlain almost entirely by Mesozoic basin rocks, has an indoor radon average less than 4 pCi/L. Other counties underlain partly by the Mesozoic basin rocks, however, have average indoor radon greater than 4 pCi/L. The Newark basin is high in radon potential whereas the Gettysburg basin is low to locally moderate. For the purposes of this report the basins have been subdivided along the Lancaster-Berks county line. The Newark basin comprises the Mesozoic rocks east of this county line.

Only a few areas in Pennsylvania appear to have geologically low to moderate radon potential. Somerset and Cambria Counties, in the Allegheny Mountain section, have indoor radon averages less than 4 pCi/L, and it appears that low radioactivity and low soil permeability may be factors in the moderate geologic radon potential of this area. These two counties and most of the Allegheny Mountain section are underlain by Pennsylvanian-age sedimentary rocks. The radioactivity map shows low to moderate radioactivity for the Pennsylvanian-age rocks in the Allegheny Mountain section and much higher radioactivity in the Pittsburgh Low Plateau section. Most of the reported uranium occurrences in these rocks appear to be restricted to the north and west of the Allegheny Mountain section. Approximately half of the soils developed on these sediments have low permeability and seasonally high water tables.

The Greene Formation in Greene County appears to correlate with distinctly low radioactivity in figure 7. The indoor radon for Greene County averages less than 4 pCi/L for the few measurements in the State/EPA survey. The nonrandom indoor radon shown in figure 10 shows that Greene (57 measurements) and adjacent Fayette County (223 measurements) have less than 20 percent of the measurements over 4 pCi/L. Philadelphia and Delaware Counties, in the southeastern corner of the State, have average indoor radon less than 4 pCi/L and have low radioactivity. Part of Delaware County and most of Philadelphia County are underlain by Coastal Plain sediments with low uranium concentrations. Soils developed on these sediments are variable, but a significant portion are clayey and have low permeability.

The Blue Ridge Province is underlain by metasedimentary and metavolcanic rocks. A distinct low area of radioactivity is associated with the province (fig. 7), although phyllite of the Harpers Formation may be uraniferous. The soils generally have variable permeability. The metavolcanic rocks in this province have very low uranium contents. It is difficult, given the constraints of the indoor radon data, to associate the high average indoor radon in counties underlain by parts of this province with specific rock units. When the indoor radon data are examined at the zip code level, it appears that most of the high indoor radon levels are associated with the Valley and Ridge (R.C. Smith, pers comm.). Therefore, the Blue Ridge is provisionally ranked low in geologic radon potential, though this cannot be verified with presently existing data.

Radiometric lows and relatively lower indoor radon levels appear to be associated with the glaciated areas of the State, particularly the eastern portion of the Glaciated Low Plateau and Pocono Plateau in Wayne, Pike, Monroe, and Lackawanna Counties. Glacial deposits are problematic to assess for radon. In some areas of the glaciated portion of the United States, glacial deposits enhance radon potential, especially where the deposits have high permeability and are derived from uraniferous source rocks. In other portions of the glaciated United States, glacial deposits blanket more uraniferous rock or have low permeability and low radon potential. The northeastern corner of the State is covered by the Olean Till, made up of 80-90 percent sandstone and siltstone clasts with minor shale, conglomerate, limestone, and crystalline clasts (Richmond and Fullerton, 1992). A large proportion of the soils developed on this till have seasonally high water tables and poor drainage, but some parts of the till soils are stony and have good drainage and high permeability. Low to moderate indoor radon and radioactivity in this area may be due to the seasonally saturated ground and to the tills being made up predominantly of sandstones and siltstones with low uranium contents. A similar situation exists in the northwestern part of the State, which is covered by a wide variety of tills, predominantly the Kent Till, which is made up of sandstone, siltstone, and shale clasts. Many of the soils in this area also have low permeabilities and seasonally high water tables. Where the tills are thinner, the western portion of the Glaciated Low Plateau has higher indoor radon levels and high radioactivity.

SUMMARY

For the purpose of this assessment, Pennsylvania has been divided into fifteen geologic radon potential areas and each area assigned a Radon Index (RI) and a Confidence Index (CI) score (Table 2). The RI is a relative measure of radon potential based on geology, soil, radioactivity, architecture, and indoor radon data, as outlined in the preceding sections. The CI is a measure of the confidence of the RI assessment based on the quality and quantity of the data used to assess geologic radon potential. See the Introduction chapter to this regional book for more information.

Analysis of the geology, radioactivity, and indoor radon data indicate that many of the soils, surficial deposits, and rocks of the State have the potential to generate indoor radon concentrations exceeding 4 pCi/L. Rocks, soils, and surficial deposits of the Atlantic Coastal Plain, Gettysburg Basin, and the Blue Ridge Province have generally low radon potential. Areas of variable or moderate radon potential include rocks, soils, and surficial deposits of the Allegheny Mountain Section, the Glaciated Pittsburgh Plateau Section, the Central Lowland Province, the High Plateau Section, the eastern portion of the Glaciated Low Plateau Section, the Glaciated Pocono Plateau Section and the Permian rocks and residual soils of the Pittsburgh Low Plateau.

This is a generalized assessment of the State's geologic radon potential and there is no substitute for having a home tested. The conclusions about radon potential presented in this report cannot be applied to individual homes or building sites. Indoor radon levels, both high and low, can be quite localized, and within any radon potential area there will likely be areas with higher or lower radon potential than assigned to the area as a whole. Any local decisions about radon should not be made without consulting all available local data. For additional information on radon and how to test, contact your State radon program or EPA regional office. More detailed information on state or local geology may be obtained from the state geological survey. Addresses and phone numbers for these agencies are listed in chapter 1 of this booklet.

TABLE 2. RI and CI scores for geologic radon potential areas of Pennsylvania.

FACTOR	New England Province (Reading Prong) RI	CI	Piedmont Upland/Lowland RI	CI	Newark Basins RI	CI	Great Valley Section RI	CI
INDOOR RADON	3	3	3	3	2	1	3	3
RADIOACTIVITY	3	3	3	3	2	3	2	3
GEOLOGY	3	3	2	3	3	3	3	3
SOIL PERM.	3	3	3	3	2	3	2	3
ARCHITECTURE	3	-	3	-	3	-	3	-
GFE POINTS	0	-	0	-	0	-	+2	-
TOTAL	15	12	14	12	12	10	15	12
RANKING	High	High	High	High	High	High	High	High

FACTOR	Appalachian Mountain Section RI	CI	Allegheny Mountain Section RI	CI	Pennsylvanian rocks of the Pittsburgh Low Plateau RI	CI	Permian rocks of the Pittsburgh Low Plateau RI	CI
INDOOR RADON	3	3	2	3	3	3	2	3
RADIOACTIVITY	2	3	2	3	3	3	2	3
GEOLOGY	2	3	2	3	3	3	2	3
SOIL PERM.	2	3	2	3	2	3	2	3
ARCHITECTURE	3	-	3	-	3	-	3	-
GFE POINTS	0	-	0	-	0	-	0	-
TOTAL	12	12	11	12	14	12	11	12
RANKING	High	High	Mod	High	High	High	Mod	High

FACTOR	Glaciated Pittsburgh Plateau/ Central Lowland RI	CI	High Plateau Section RI	CI	Glaciated Low Plateau Western Portion RI	CI	Glaciated Low Plateau East & Pocono Plateau RI	CI
INDOOR RADON	2	2	2	3	3	3	2	3
RADIOACTIVITY	2	3	1	3	3	3	2	3
GEOLOGY	2	3	2	3	2	3	2	3
SOIL PERM.	2	3	2	3	2	3	1	3
ARCHITECTURE	3	-	3	-	3	-	3	-
GFE POINTS	0	-	0	-	0	-	0	-
TOTAL	11	11	10	12	13	12	10	12
RANKING	Mod	High	Mod	High	High	High	Mod	High

FACTOR	Mountainous High Plateau RI	CI	Blue Ridge Gettysburg basin RI	CI	Atlantic Coastal Plain RI	CI
INDOOR RADON	3	3	1	1	1	3
RADIOACTIVITY	2	3	1	3	1	2
GEOLOGY	2	3	2	3	1	3
SOIL PERM.	2	3	1	3	2	3
ARCHITECTURE	3	-	3	-	3	-
GFE POINTS	0	-	0	-	0	-
TOTAL	12	12	8	10	8	11
RANKING	High	High	Low	High	Low	High

TABLE 2 (continued).

RADON INDEX SCORING:

Radon potential category	Point range	Probable screening indoor radon average for area
LOW	3-8 points	< 2 pCi/L
MODERATE/VARIABLE	9-11 points	2 - 4 pCi/L
HIGH	> 11 points	> 4 pCi/L

Possible range of points = 3 to 17

CONFIDENCE INDEX SCORING:

LOW CONFIDENCE	4 - 6 points
MODERATE CONFIDENCE	7 - 9 points
HIGH CONFIDENCE	10 - 12 points

Possible range of points = 4 to 12

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PRELIMINARY GEOLOGIC RADON POTENTIAL ASSESSMENT OF VIRGINIA

by
Linda C.S. Gundersen
U.S. Geological Survey

INTRODUCTION

This is a generalized assessment of geologic radon potential of rocks, soils, and surficial deposits of Virginia. The scale of this assessment is such that it is inappropriate for use in identifying the radon potential of small areas such as neighborhoods, individual building sites, or housing tracts. Any localized assessment of radon potential must be supplemented with additional data and information from the locality. Within any area of a given radon potential ranking, there are likely to be areas with higher or lower radon levels than characterized for the area as a whole. Indoor radon levels, both high and low, can be quite localized, and there is no substitute for testing individual homes. Elevated levels of indoor radon have been found in every State, and EPA recommends that all homes be tested. For more information on radon, the reader is urged to consult the local or State radon program or EPA regional office. More detailed information on state or local geology may be obtained from the state geological survey. Addresses and phone numbers for these agencies are listed in chapter 1 of this booklet.

GEOGRAPHIC SETTING

The physiography of Virginia (fig. 1), to a large degree, reflects the underlying bedrock geology (fig. 2). Virginia's elevation ranges from sea level to 5,729 feet. The State has been divided into five major physiographic regions: the Coastal Plain, the Piedmont, the Blue Ridge, the Valley and Ridge, and the Appalachian Plateaus (fig. 1). For the purposes of this radon assessment these provinces have also been subdivided based on geology.

The Coastal Plain is characterized by broad areas of low relief, averaging 100 feet above sea level, and gently sloping downward from the Piedmont to the shoreline. It is underlain by unconsolidated to partly consolidated sediments and has a maximum elevation of 300 feet above sea level near the Fall Line. The Fall Line is the boundary between the Coastal Plain and the Piedmont that is marked by a distinct change in river and stream water velocity, including the occurrence of waterfalls. The Piedmont is characterized by gently rolling hills and is underlain by a complicated sequence of metamorphic and igneous rocks. The land surface of the Piedmont slopes gently to the east with a maximum elevation of 1350 feet in the west and a minimum elevation of 300 feet in the east at the Fall Line. The topography of the Piedmont becomes more hilly as it approaches the Blue Ridge to the west. The Blue Ridge is a long narrow province that extends from north to south across the State and is characterized by the most rugged topography in Virginia. It contains the highest mountain in the State, Mount Rogers, at 5729 feet above sea level. The Blue Ridge is underlain by igneous, metamorphic, and sedimentary rocks. To the west of the Blue Ridge is the Valley and Ridge Province, the boundary of which is marked by a broad valley underlain by carbonate rocks and shales. In the northern portion of the State, part of the Valley and Ridge is referred to as the Great Valley and includes the Shenandoah Valley. The rest of the Valley and Ridge consists of well-defined, parallel valleys and ridges underlain by folded Paleozoic sedimentary rocks. More resistant sandstones and conglomerates form the ridges whereas the valleys are underlain by carbonate rocks and shales. In the southwestern portion of

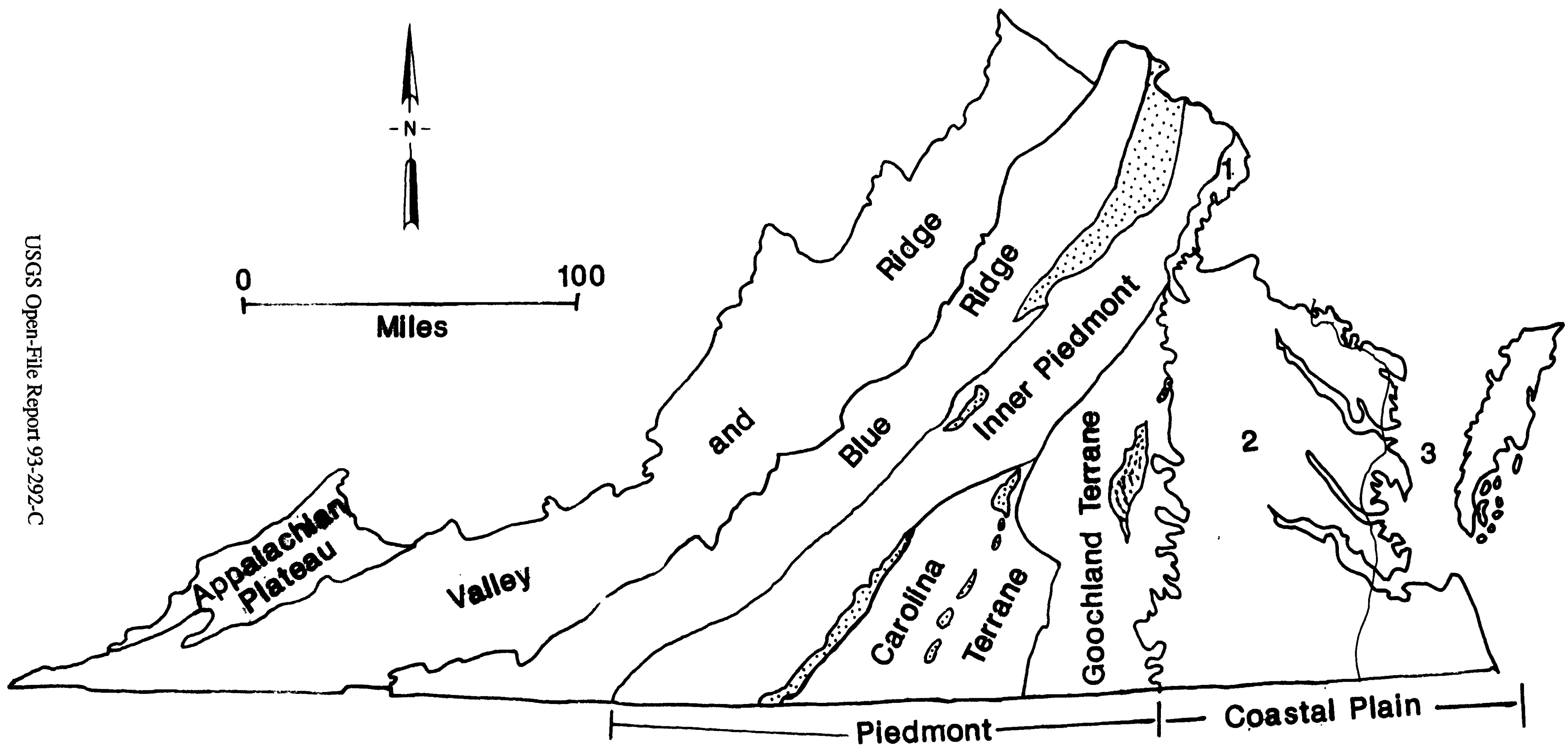

Figure 1. Physiographic/Geologic provinces of Virginia. Stippled areas indicate Mesozoic basins. The Coastal Plain is labeled to show the age of sediments--1, Cretaceous sediments; 2, Tertiary sediments; and 3, Quaternary sediments. (after Dietrich, 1970; Hatcher and others, 1990)

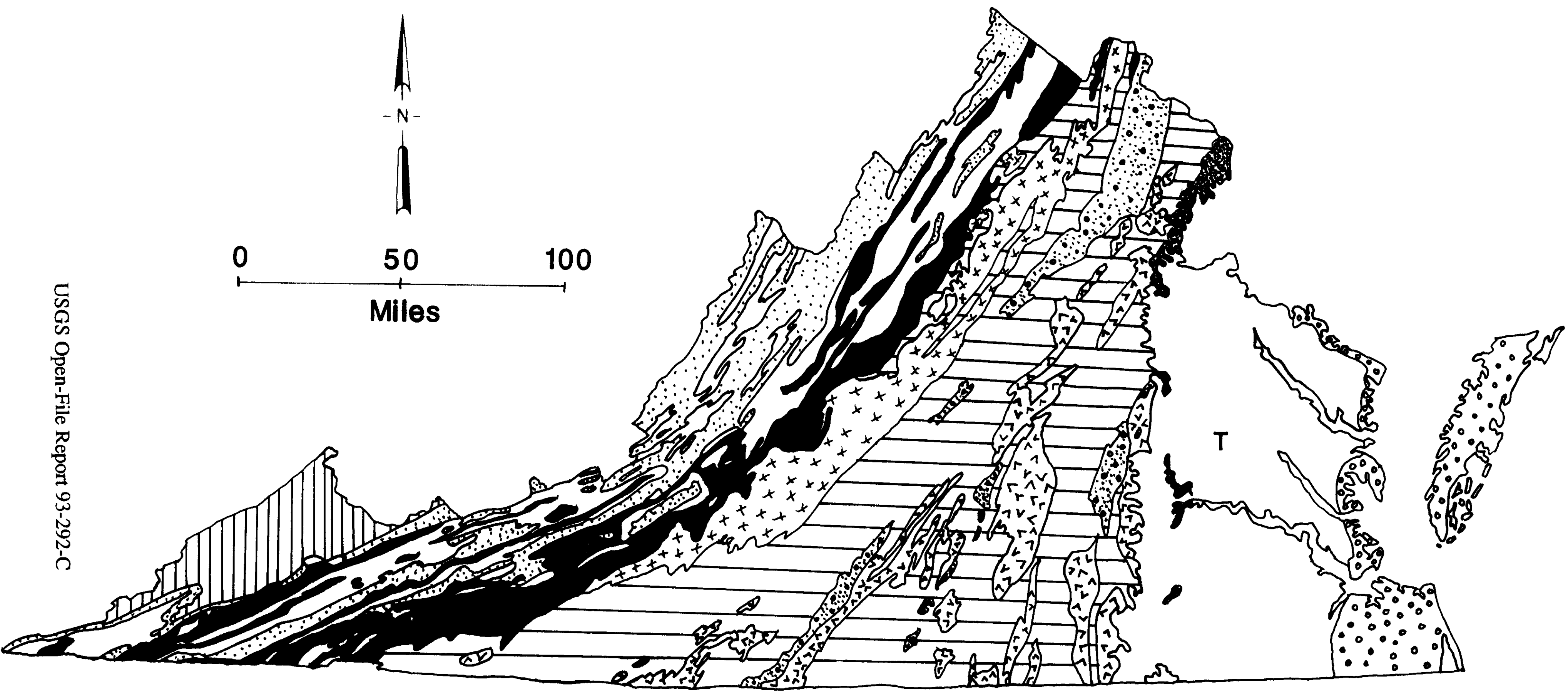

Figure 2. Generalized geologic map of Virginia (from Virginia Division of Mineral Resources, 1987; explanation modified from Virginia Division of Mineral Resources, 1963).

Geologic Units for the General Geologic Map of Virginia

QUATERNARY
Quaternary - Beach sand; mud, sand, and silt of the marshes and tidal flats; fluvial sandy gravel, gravelly sand; silt, and clay; peat and peaty mud of swamps; and eolian dune sand. **Tabb Formation** - Sand, silt, clay, and peat. **Shirley Formation** - Gray and brown sand, gravel, silt, clay, and peat. **Chuckatuck Formation** - Reddish sand, silt, and clay with minor peat. **Charles City Formation** - Gray to reddish brown sand, silt, and clay. **Windsor Formation** - Gray to reddish brown sand, gravel, silt, and clay. **Kent Island Formation** - Gray sand and sandy gravel grading upward into silty and clayey sand. **Wachapreague Formation** - Clayey and silty sand interbedded with clay and silt overlain by gravelly sand. **Nassawadox Formation** - Sand and gravel. **Joynes Neck Sand** - Sandy gravel and gravelly sand grading up into fine sand. **Omar Formation** - Gray to yellowish-orange sand, gravel, silt, clay, and peat.

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TERTIARY
Bacons Castle Formation - Gray quartzose sand, silt and clay.
Chesapeake Group: Chowan River Formation - Gray to green, clayey, silty, shelly sand with boulders and pebbles at the base. **Yorktown Formation** - Gray, shelly sand that is in part glauconitic and phosphatic interbedded with sandy and silty gray clay.. **Eastover Formation** - Gray, muddy, micaceous sand with sandy silt and clay. **St. Marys Formation** - Gray, muddy, fine sand and sandy silt-clay, locally shelly. **Choptank Formation** - Green-gray, shelly, clayey and silty, fine sand with diatomaceous silt. **Calvert Formation** - Gray-green, clayey and silty, shelly, fine sand forming upward-fining sequences into diatomaceous silt.
Pliocene Sand and Gravel - Orange to reddish-brown, locally cross-bedded gravelly sand, sandy gravel, and sand with thin beds of clay and silt. **Miocene Sand and Gravel** - Gray, sand, sandy gravel, silt, and clay with oxidized orange to reddish brown pebbles and cobbles.
Old Church Formation - Shelly, sparsely glauconitic quartz sand.
Lower Oligocene Beds - Gray-green, clayey, silty, micaceous, glauconitic sand.
Chickahominy Formation - Gray-green, glauconitic, micaceous clayey silt and silty clay with basal sand and pebbles.
Pamunkey Group: Piney Point Formation - Gray-green, glauconitic, quartz sand interbedded with carbonate-cemented sand and limestone. **Namjemoy Formation** - Gray-green and black, clayey and silty, glauconitic sand, locally shelly and micaceous, pebbly at top. **Marlboro Clay** - Gray to reddish brown kaolinitic clay with silt and fine sand. **Aquia Formation** - Gray-green, clayey and silty, locally shelly, glauconitic sand, calcareous at base with thin limestone beds. **Brightseat Formation** - Gray to black, clayey and silty, micaceous quartz sand that is locally glauconitic.

CRETACEOUS
Potomac Formation - Cross-bedded, quartzo-feldspathic sand interbedded with gray and mottled red sandy clay and silt. Contains lesser amounts of clay-clast conglomerate and carbonaceous clay and silt.

TRIASSIC-JURASSIC
Igneous rocks - Sills and dikes, diabase and gabbro
Newark Supergroup: Culpeper basin: **Waterfall Formation** - Red to gray arkosic sandstone, conglomerate, and siltstone with black shale interbeds. **Sander Basalt** - Tholeiitic basalt interbedded with red sandstone and siltstone. **Turkey Run Formation** - Red to gray arkosic sandstone, conglomerate, and siltstone with black shale interbeds. **Hickory Grove Basalt** - Tholeiitic basalt interbedded with red sandstone and siltstone. **Midland Formation** - Red to gray arkosic sandstone, conglomerate, and siltstone with black shale interbeds. **Mount Zion Church Basalt** - Tholeiitic basalt interbedded with red sandstone and siltstone. **Catharpin Creek Formation** - Red to gray arkosic sandstone, conglomerate, and siltstone with black shale interbeds. **Balls Bluff Siltstone** - Red to gray arkosic siltstone, sandstone, and conglomerate with black shale interbeds . **Tibbstown Formation** - Red to gray arkosic siltstone, sandstone, and conglomerate with black shale interbeds. **Manassas Sandstone** - Red to gray arkosic sandstone and conglomerate.
Barboursville basin **Balls Bluff Siltstone** - Red arkosic siltstone, sandstone, and conglomerate. **Tibbstown Formation** - Red arkosic siltstone, sandstone, and conglomerate. **Manassas Sandstone** - Red to gray arkosic sandstone and conglomerate.
Taylorsville basin **Doswell Formation** - Red to gray arkosic sandstone, conglomerate, and siltstone with black shale interbeds and some coal beds.
Richmond basin **Otterdale Sandstone** - Arkosic sandstone and conglomerate. **Venita beds** - Black to green shale, siltstone, and sandstone. **Productive Coal Measures** - Gray siltstone, shale, and sandstone with coal beds. **Lower Barren beds** - Gray and black siltstone and shale with sandstone and conglomerate.
Danville basin **Cedar Forest Formation** - Red to gray arkosic sandstone, conglomerate, and siltstone with black shale interbeds. **Leakesville Formation** - Red to gray arkosic siltstone, sandstone, and conglomerate with black shale interbeds. **Dry Fork Formation** - Arkosic sandstone and conglomerate with red to gray siltstone and shale.
Other basins **Triassic undifferentiated** - Red arkosic sandstone, conglomerate, and siltstone with local gray to black shale interbeds and coals.

PENNSYLVANIAN
Harlan Sandstone - Sandstone and shale with coal beds.
Wise Formation - Sandstone and shale with many coal beds.
Gladeville Sandstone - Sandstone, quartzose, gray, coarse-grained.
Norton Formation - Sandstone and shale with coal beds.
Lee Formation - Sandstone and shale with coal beds, conglomeratic at base.

MISSISSIPPIAN
Pennington Group: Bluestone Formation - Shale and sandstone, some red shale in upper part. **Princeton Sandstone** - Sandstone, conglomeratic. **Hinton Formation** - Shale and siltstone, with sandstone, limestone, and dolomite.
Cove Creek Limestone - Limestone, argillaceous.
Fido Sandstone - Sandstone, argillaceous, calcareous in part.
Newman Limestone - Limestone, oolitic or cherty.
Bluefield Formation - Shale, calcareous, with some limestone, siltstone and sandstone.
Greenbrier Limestone - Limestone, oolitic,or cherty.
Maccrady Formation - Red shale and mudstone; red and green sandstone. Includes **Little Valley Limestone** at top locally.
Price Formation - Shale, fossiliferous, and sandstone with coal beds. Includes **Grainger Formation** in southwestern VA.
Pocono Formation - Sandstone and conglomerate with coal locally.
Mississippian-Devonian shales - Shale and silstone, gray and greenish gray. Includes **Chattanooga shale** - black shale
DEVONIAN
Hampshire Formation - Shale and sandstone, red.
Chemung Formation - Shale and sandstone, mostly gray and greenish gray, fossiliferous.
Brallier Formation - Shale, greenish gray, siliceous; and sandstone, greenish, fine-grained.
Mahantango Formation, Marcellus Shale, Milboro Shale, Onondaga Formation, Needmore Shale, Huntersville Chert - Black to gray shale and siltstone with some limestone interbeds.
Ridgeley (Oriskany) Sandstone - Quartz sandstone.
Rocky Gap Sandstone - Quartz sandstone.
Licking Creek Limestone, Helderberg Formation, New Scotland Limestone, Coeymans Limestone - Limestone with some quartz sandstone interbeds.

SILURIAN
Keyser Formation - Limestone, fossiliferous.
Cayuga Group: Hancock Dolomite - Dolomite and limestone. **Tonoloway Formation, Wills Creek Formation** - Argillaceous limestone and dolomite. **Bloomsburg Formation** - Red siltstone, mudstone, and sandstone. **McKenzie Formation** - Green siltstone, shale, and sandstone
Keefer Sandstone - sandstone with beds of fossiliferous, hematitic sandstone.
Rose Hill Formation - Shale
Tuscarora Formation - Quartzite.
ORDOVICIAN
Sequatchie Formation - Limestone, argillaceous, and shale calcareous, mottled red and blue.
Juniata Formation and **Oswego Sandstone** - Fluvial sandstone.
Reedsville Shale - Shale, calcareous, olive-green.
Martinsburg Formation - Black shale with graywacke sandstone interbeds.
Dot Limestone, Poteet Limestone, Rob Camp Limestone, Martin Creek Limestone, Hurricane Bridge Limestone, Woodway Limestone, Ben Hur Limestone, Hardy Creek Lmestone, Moccasin Formation, Eggleston Formation, and **Trenton Limestone** - Limestone, argillaceous limestone, calcareous shale, and shale.
Witten Limestone, Bowen Limestone, Wardell Limestone, Gratton Limestone, Benbolt Limestone, Effna Limestone, Rye Cove Formation, Rockdell Limestone, Lincolnshire Formation, Lurich Formation, Five Oaks Limestone, Elway Limestone, Blackford Formation - Limestone, argillaceous limestone, calcareous shale, and shale.
Collierstown Limestone, Oranda Formation, Edinburg Formation, McGlone Formation, Big Valley Formation, Lincolnshire Formation, Lurich Formation, New Market Limestone - Limestone, argillaceous limestone, calcareous shale, and shale.
Knox Group: Mascot Formation and **Kingsport Formations** - Dolomite and limestone. **Copper Ridge Dolomite** - Dolomite with sandstone interbeds.
Beekmantown Formation - Limestone and dolomite. Includes **Nittany** and **Belefonte Formations** and **Stonehenge Limestone** in northwestern Virginia.
Chepultepec Formation - Limestone and dolomite.
Arvonia Formation - Slate, phyllite and schist with garnet , conglomerate and quartzite.
Quantico Slate - Slate, in part graphitic, including rhyolite flows.
Evington Group: Candler Formation, Joshua Schist, Arch Marble, Pelier Schist, Mount Athos Formation, and **Slippery Creek Greenstone** - Muscovite, chlorite, paragonite, quartz phyllite and schist interbedded with graywacke, volcanic greenstone, and marble.

CAMBRIAN

Conasauga Group: Nolichucky Formation, Maynardville Formation - Shale, olive, with thick beds of limestone. **Pumpkin Valley Shale, Rutledge Limestone, Rogersville Shale,** and **Maryville Limestone** - Limestone and gray to black shale. **Honaker Dolomite** - Dolomite, locally argillaceous.

Conococheague Formation - Limestone and dolomite, contains beds of sandstone.

Elbrook Formation - Dolomite, shaly, argillaceous, some limestone.

Rome Formation - Shale and sandstone, variegated, with dolomite.

Shady Formation - Dolomite,with some limestone. In northern Loudoun County includes the **Frederick Limestone**.

Chilhowee Group: Erwin Formation - Sandstone and quartzite. **Hampton Formation** - Sandstone, shale, and quartzite. **Unicoi Formation** - Conglomerate, shale and quartzite with basalt flows. **Weverton Formation** - conglomerate, shale and quartzite.

Catoctin Formation - Basic lava flows, schist, gneiss, arkose, conglomerate and phyllite.

Mount Rogers Volcanic Group - Rhyolite porphyry, arkose and tuff.

Swift Run Formation - Sandstone, graywacke, andesite tuff, and greenstone.

Mechums River Formation - Phyllite, quartzite, graywacke, and conglomerate.

PRECAMBRIAN

Lynchburg Formation - Phyllite, quartzite, graywacke and conglomerate. Includes **Alum Phyllite, Willis Phyllite, Rockfish Conglomerate** at base in Nelson and Albemarle counties, and **Johnson Mill Formation** and **Charlottesville Formation** in Albemarle County.

Virginia Blue Ridge Complex: Lovingston Formation - Biotite granite, biotite gneiss and biotite, quartz monzonite. **Marshall Formation** - Biotite, quartz, feldspar granite, gneiss and quartz monzonite. **Moneta Gneiss** - Biotite hornblende gneiss. **Old Rag Formation** - Quartz, feldspar granite. **Pedlar Formation** - Granite, granodiorite, hypersthene granodiorite, syenite, quartz diorite, anorthosite, and unakite. **Robertston River Formation** - Hornblende granite and hornblende syenite. **Roseland Anorthosite** - Granular plagioclase rock. **Striped Rock Granite** - Biotite granite and syenite.

GRANITE AND GNEISS OF UNCERTAIN AGE

Leatherwood Granite - Biotite, muscovite granite, locally porphyritic.

Melrose Granite - Biotite, muscovite granite and augen gneiss.

Petersburg Granite - Microcline, biotite granite and chloritic granodiorite.

Redoak Granite - Biotite and muscovite granite, granite gneiss with feldspar phenocrysts, and chloritic granodiorite.

Shelton Granite Gneiss - Granite gneiss, augen gneiss, and mylonite.

Columbia Granite: Biotite and muscovite granite, granodiorite, and quartz monzonite.

Carsonville Granite. Saddle Gneiss; Cattron Diorite; Beverdam Creek Augen Gneiss; Comers Granite Gneiss; Grayson Granodiorite Gneiss; and **Shoal Gneiss** - Biotite and granitic gneiss and granite.

METAMORPHIC ROCKS AND IGNEOUS INTRUSIVES OF UNCERTAIN AGE

Amphibolite and Amphibole rich foliates includes **Sabot amphibolite** of Goochland terrane.

Granite gneiss - Biotite and muscovite granite gneiss, granodiorite gneiss.

Granite and hornblende gneiss - Interlayered mica, quartz, feldspar gneiss and hornblende, feldspar, mica gneiss.

Greenstone volcanics - Basic lava flows, tuff and slate commonly altered to chlorite bearing rocks.

Hornblende gabbro and gneiss - talc, amphibole chlorite schist, chloritic hornblende gneiss; and some amphibolite, chloritic and hornblende diorite; and kyanite schist and quartzite.

Intrusive rocks - Granophyre, peridotite, and related rocks of possible Triassic age.

Metamorphosed sedimentary and volcanic rocks with minor igneous intrusives - Phyllite, schist, gneiss, slate, greenstone, serpentinite, and quartzite, includes the **State Farm Gneiss and Maidens Gneiss** of the Goochland terrane, **the Chopawamsick Formation, Peters Creek Formation, Bassett Formation, Fork Mountain Formation, and Evington Group** of the Inner Piedmont.

Quartz diorite - Diorite with some blue quartz.

Limestone and marble - Includes equivalents of **Cockeysville Marble** in Loudoun and Fauquier counties, the **Everona Limestone** in central Virginia, and limestone and marble in Pittsylvania County.

Virgilina Group - altered andesitic flows and tuffs; slate, quartz sericite schist, muscovite, quartz, paragonite phyllite, and chloritic arkose.

the State is a small portion of the Appalachian Plateaus Province. It is highly dissected and underlain by relatively flat-lying sedimentary rocks.

The population of Virginia in 1990 was 6,187,358, including 66 percent urban population (fig. 3). The average population density is 147 per square mile. The climate is moderate and annual precipitation averages 32-48 inches (fig. 4). Agricultural products include tobacco, soybeans, peanuts, wheat, corn, grain, fruit, and produce.

GEOLOGIC SETTING

The geology of Virginia is complex, and the names of rock formations and the way rocks are grouped have changed with time. This description of the geology tries to convey the major rock types of an area, especially as they pertain to the radon problem. Descriptions in this report are derived from the following references: Virginia Division of Mineral Resources (1963), Brown (1970), Conley (1978), Patchen and others (1985), Krason and others (1988), Mixon and others (1989), Hatcher and others (1989), and Smoot (1991). A general geologic map is given in figure 2. It is suggested, however, that the reader refer to the more detailed state geologic map (Virginia Division of Mineral Resources, 1963) as well as the numerous detailed geologic maps available from the Virginia Division of Mineral Resources (1988).

Coastal Plain

Sediments of the Coastal Plain range in age from Cretaceous to Quaternary, decreasing in age from the Fall Line to the shoreline. The Cretaceous deposits are represented by the Potomac Formation, which forms a thin band of outcrop from Washington D.C. south to Fredericksburg. The Potomac Formation consists of fine- to coarse-grained quartzo-feldspathic sand of fluvial-deltaic origin that is commonly crossbedded and interbedded with massive green sandy clay and silt. Lesser amounts of clay-clast conglomerate and carbonaceous clay and silt also form interbeds.

Tertiary deposits of Oligocene, Eocene, and Paleocene age, known as the Pamunky Group and Old Church Formation, crop out along some of the major river drainages. These deposits are characterized by fine- to coarse-grained glauconitic sand, clay, and silt, and sandy limestone. Some units have abundant fossil shells and fish. Miocene-age sand and gravel crops out along the fall line from Washington D.C. south to the state line. It consists of fine to coarse sand, sandy gravel, silt, and clay, and is commonly oxidized. To the west of these deposits are similar Pliocene-age deposits that cap the westernmost parts of the major drainage divides. They are composed of oxidized gravelly sand, sandy gravel, fine- to coarse-grained crossbedded sands, and thin beds of clay and silt.

The Tertiary-age (upper Pliocene-lower Miocene) Chesapeake Group covers much of the north-central part of the Coastal Plain and crops out along the major drainages. It is characterized by shelly, sometimes diatomaceous, locally phosphatic, quartz sand, silt, and clay, and is divided up into a number of formations. These formations are the Calvert, Choptank, St. Mary's, Eastover, Yorktown, and the Chowan River Formations. The Bacons Castle Formation overlies the Chesapeake Group and is upper Pliocene in age. The Bacons Castle is composed of sand, gravel, silt, and clay and covers much of the southwestern part of the Virginia Coastal Plain. It is characterized by massive pebble and cobble gravel grading into crossbedded pebbly sand and sandy, clayey silt. In the northern part of the Virginia Coastal Plain, it crops out in the drainage divides and consists of thin-bedded clayey silt and fine silty sand.

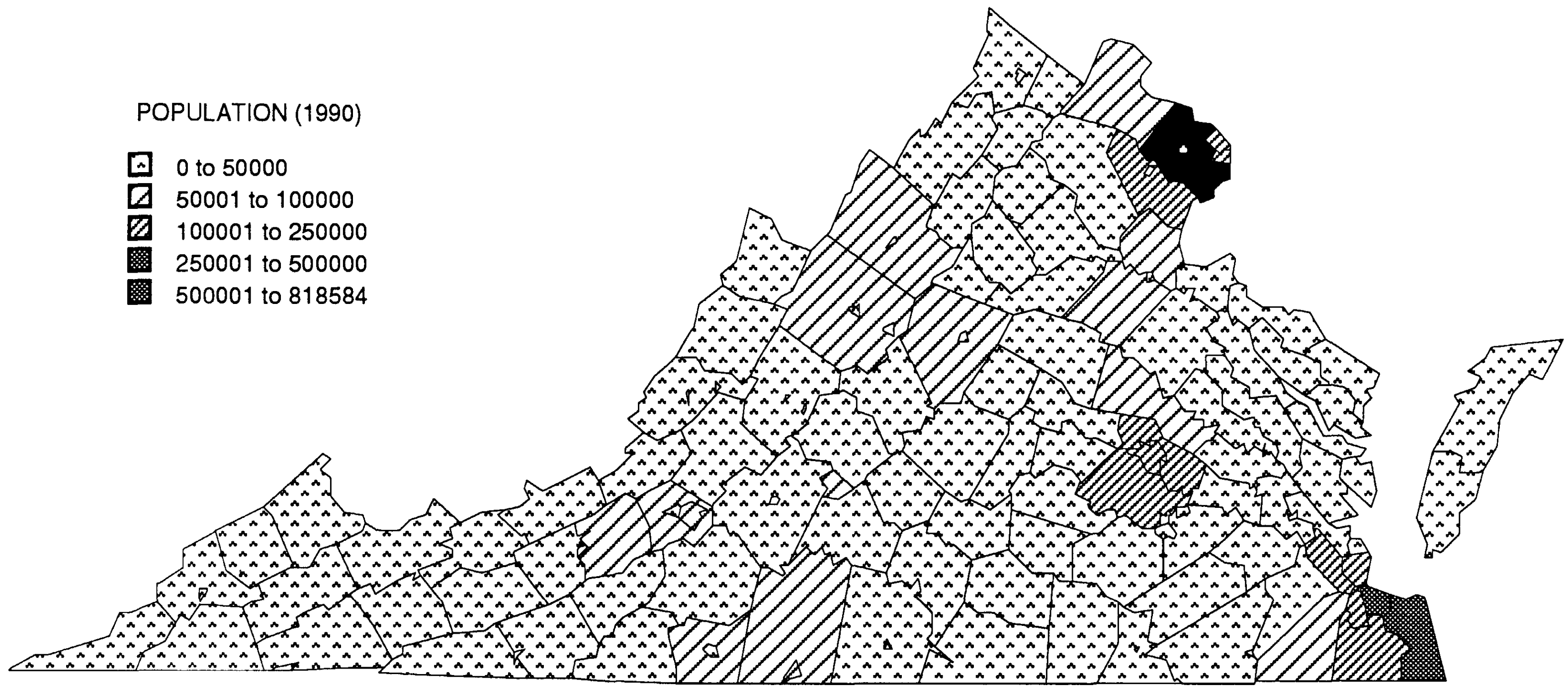


Figure 3. Population of counties in Virginia (1990 U.S. Census data).

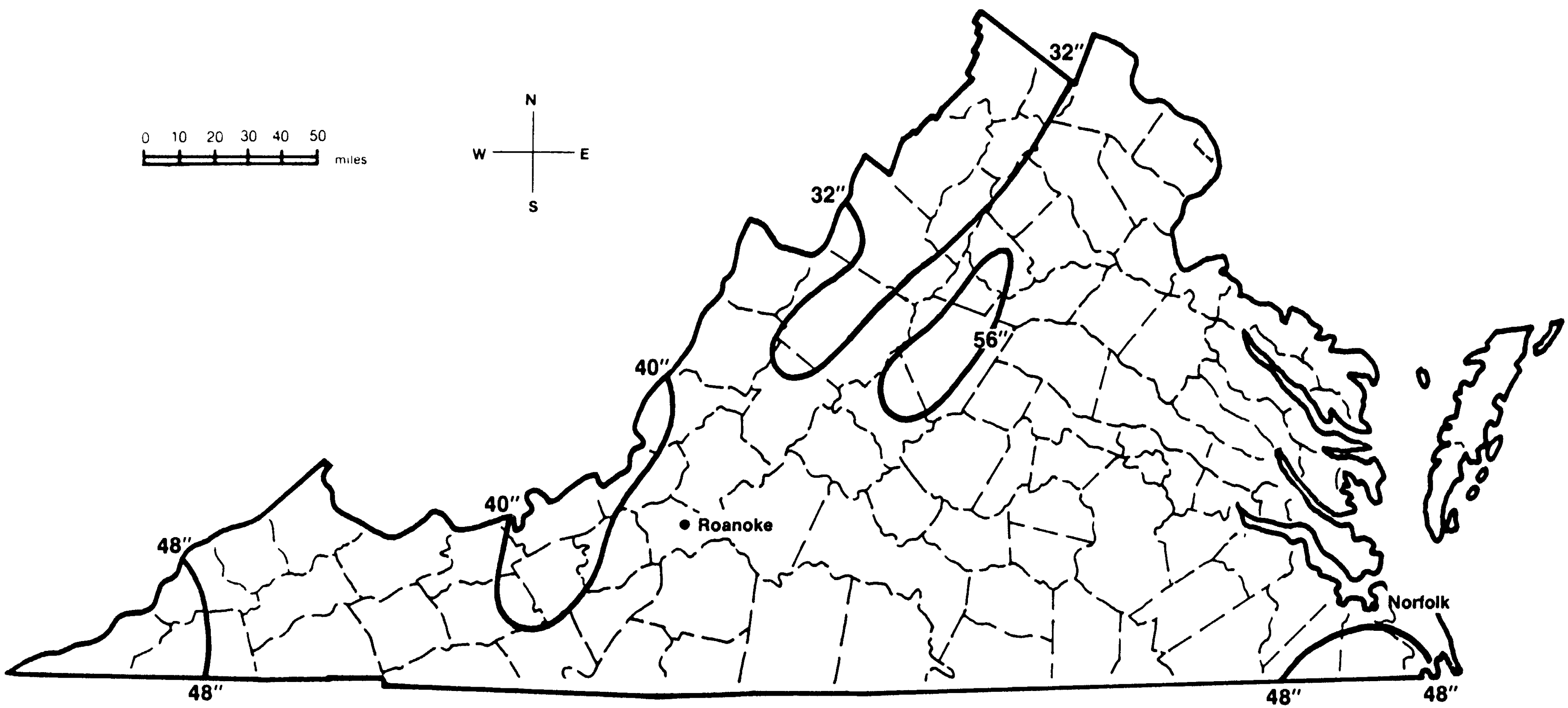


Figure 4. Average annual precipitation in Virginia (from Facts on File, 1984).

At the top of the Tertiary section are the Moorings unit and Windsor Formation. The Moorings unit forms discontinuous bodies west of the Surry scarp and is most extensive in the north-central Coastal Plain. The Windsor Formation is upper Pliocene to lower Pleistocene in age and crops out extensively, predominantly east of the Surrey scarp to the Quaternary/Tertiary boundary near the shoreline. The Windsor Formation is comprised of crossbedded sand and gravel grading upward to massive clayey silt and clay.

The Quaternary deposits of the Coastal Plain are subdivided into many formations and generally represent nearshore sediments of beach, dune, river, estuary, terrace, swamp, lagoon, and marsh origin. They are dominated by quartzose sand and gravel and often grade into silt and clay or contain local deposits of silt, clay, and peat. East of Chesapeake Bay in Northhampton and Accomack Counties, the Quaternary section consists of the crossbedded sands, muddy sand, clay, and silt of the Omar Formation; the fine to coarse sand and gravel of the Joynes Neck Sand; the crossbedded sand and gravel deposits of the Nassawadox Formation; the interbedded clayey silty sand, clayey silt, and gravelly sand of the Wachapreague Formation; and the coarse sand and sandy gravel of the Kent Island Formation. West of Chesapeake Bay, the Quaternary sequence is composed of sand, silt, and clay of the Charles City Formation; sand, silt, clay, and peat of the Chuckatuck Formation; the sand, gravel, silt, clay, and peat of the Shirley Formation; and the sand, silt, clay, and peat of the Tabb Formation.

The Piedmont

The Piedmont is a complicated sequence of Precambrian to Paleozoic metasedimentary and metavolcanic rocks intruded by igneous rocks of mafic to granitic composition. It has been subdivided into several areas for the purpose of this report: the Goochland terrane, the Carolina terrane, the Mesozoic basins, and the Inner Piedmont. The geology of the Piedmont along the Fall Line is dominated by numerous granitic intrusive rocks, including the Petersburg and Occoquan Granites, the Mesozoic sedimentary and igneous rocks of the Richmond Basin (which will be described in a following section), granitic gneiss and amphibolite of the Goochland terrane, and minor diorite, metavolcanic rock, and gabbro. The Goochland terrane is bounded on the west by the Spotsylvania and Nutbush Creek Faults. The terrane comprises some of the aforementioned granites as well as the State Farm Gneiss, the Sabot amphibolite, the Maidens Gneiss, and the Montpelier meta-anorthosite. The State Farm Gneiss is biotite-hornblende granitic gneiss that is locally pegmatitic. The Sabot amphibolite overlies the State Farm Gneiss and is predominantly amphibolite with minor biotite and granitic gneiss. The Maidens Gneiss includes biotite gneiss, amphibolite layers, mica schist, calc-silicate layers, and granitic gneiss.

The Carolina terrane (Hatcher and others, 1989) extends from the Farmville basin south between the Nutbush Creek Fault and the Danville Basin. It consists predominantly of metavolcanic rocks that underlie large parts of Mecklenburg and Lunenburg Counties, the Virgilina Group, the Shelton granite gneiss, granite and hornblende gneiss (especially in Halifax County), the Redoak granite, and various granite gneiss, granitic bodies, mica schist, and minor hornblende gneiss and gabbro. The Virgilina Group flanks the metavolcanic rocks to the west in Mecklenburg and Halifax Counties and consists of volcanic rocks, slate, phyllite, schist, and arkose.

The next terrane to the west is referred to as the Inner Piedmont (Hatcher and others, 1989). In the east, the Inner Piedmont is underlain by metavolcanic rocks of the Chopawamsic Formation which crop out in a wide band from northwestern Spotsylvania County south to Buckingham County, where they are associated with the slate, phyllite, and schist of the Arvonia Formation and Quantico Slate. Most of the Inner Piedmont is underlain by metamorphosed sedimentary rocks, predominantly granitic gneiss, phyllite, and mica schist, including the Candler Formation in the southern and central Inner Piedmont and the Peters Creek Formation in northern Virginia. Some large areas of hornblende gneiss and gabbro crop out in the central part of the Inner Piedmont in Appomattox and Buckingham Counties. The western edge of the Piedmont is underlain by the sedimentary rocks of the Culpeper basin in the north, the Evington Group in the central and south, and the Martinsville Igneous Complex, Bassett Formation, and Fork Mountain Formation in the south. These last three rock types comprise the bulk of the Smith River allochthon (Conley, 1978) which is bounded by the Bowens Creek fault and the Ridgeway fault. The Bassett Formation consists of biotite gneiss overlain by amphibolite, and the Fork Mountain Formation is composed of mica schist and biotite gneiss. The Martinsville Igneous Complex is composed of the Leatherwood Granite and the gabbro, norite, and diorite of the Rich Acres Formation. The Evington Group is a broad band of metamorphic rocks that crop out from Campbell County north to southwestern Fluvanna County. The group consists of mica schist and phyllite with graywacke, greenstone, and marble.

Within the Piedmont, Late Triassic to early Jurassic continental sedimentary and igneous rocks of the Newark Supergroup occur in ten basins that roughly form three northeast-trending belts in east-central Virginia. The western belt includes the large Culpeper basin, which extends into Maryland, the tiny Barboursville basin that is immediately south of the Culpeper , the tiny Scottsville basin to the southwest of the Barboursville, and the large Danville basin, which is the northern extension of the Dan River basin in North Carolina. The central belt consists of four small basins, the largest being the northernmost Farmville basin, south of which is the Briery Creek basin, the Roanoke basin, and the southernmost Scottsburg basin. The easternmost belt consists of the small Richmond basin and the Taylorsville basin, which lies immediately north of the Richmond basin. The strata in each basin dip northwest toward the faulted margin.

In the Culpeper basin, the basal Triassic Manassas Sandstone forms an outcrop belt along the southeast margin of the basin that thins southward. The Manassas Sandstone consists of arkosic sandstone, siltstone, and conglomerate. The Manassas Sandstone is overlain by a broad belt of the Triassic Balls Bluff Siltstone. The Balls Bluff consists of fluvial red siltstones with thin arkosic sandstones, overlain by lacustrine red and black shales and siltstones and fluvial sandstones. Sandier parts of the upper Balls Bluff Siltstone in the southern part of the basin have been assigned to the Tibbstown Formation by Lee and Froelich (1989). The Triassic Catharpin Creek Formation in the northwestern part of the basin forms thick lenses of conglomerates and sandstones that intertongue with the Balls Bluff lacustrine rocks to the south. A relatively narrow belt of Jurassic basalts and sedimentary rocks occur in synclinal folds along the western quarter of the basin. These rocks consist of the Mount Zion Church Basalt, the Midland Formation, the Hickory Grove basalt, the Turkey Run Formation, the Sander Basalt, and the Waterfall Formation. The Midland, Turkey Run, and Waterfall Formations consist of lacustrine black and red shales interbedded with fluvial sandstones. Along the faulted northwestern margin of the basin, all of the formations intertongue with alluvial fan conglomerates consisting of the older rocks immediately outside of the basin. The Culpeper basin sedimentary rocks are intensively intruded by large Jurassic diabase dikes and sheets that are folded into broad dish-like synclines. The Barboursville basin sedimentary sequence includes the Manassas Sandstone and the overlying Tibbstown Formation. The Scottsville basin is mostly filled with Triassic conglomerates that reflect in their composition the older rocks on the faulted side of the basin. Rocks in the Danville basin consist of Triassic red and black shales and siltstones and arkosic sandstone and conglomerate. Jurassic diabase intrudes the Triassic sedimentary rocks and the surrounding crystalline rocks.

The central belt of Newark Supergroup basins have no formal stratigraphic names. The Farmville and Briery Creek basins have thin bands of Triassic arkosic sandstone along the eastern margins that are overlain by a thick belt of lacustrine black shales and siltstones with coal seams near the basal contact. The lacustrine rocks intertongue with conglomerates consisting of clasts of the older rocks immediately outside of the basin near the northwestern border faults. The other two basins consist predominantly of Triassic arkosic sandstones and conglomerates. Narrow Jurassic diabase dikes cut the sedimentary rocks in these basins.

The eastern belt of Newark Supergroup basins is similar in character to the central belt. The Richmond basin consists of the basal Triassic Tuckahoe Formation, comprising a thin arkosic fluvial sandstone (Lower Barren Beds Member) overlain by a black lacustrine shale with coal seams (Productive Coal Measures Member). Both are restricted to a narrow belt on the eastern edge of the basin and overlain by thick sequence of black shales (Vinita Beds Member) that intertongue with conglomerates near the western border fault. Outcrops of the Vinita Member are restricted to a narrow band in the northern part of the basin by the overlying Triassic Turkey Branch Formation, which consists of black to gray lacustrine shales and siltstones with abundant sandstones near the base and top. The southern two-thirds of the basin is underlain by the Triassic Otterdale Formation, which consists of sandstone and conglomerate. The exposed portion of the Taylorsville basin consists of Triassic Doswell Formation. The basal Stagg Creek Member forms a narrow outcrop band along the southern and eastern basin margin and consists of sandstones and conglomerates. The Stagg Creek is overlain by the Falling Creek Member, which forms a parallel narrow outcrop band. It consists of fine-grained fluvial and deltaic sandstones and lacustrine black shales and coal seams. The uppermost Newfound Member covers most of the basin and consists of fluvial sandstones and conglomerates. Some coarse conglomerates near the western border fault are composed of clasts of the older rocks immediately outside of the basin. Narrow Jurassic diabase dikes intrude the sedimentary rocks in these basins.

The Blue Ridge

The boundary between the Blue Ridge and Piedmont is represented in many different ways on different maps. The physiographic Blue Ridge Province is only partly coincident with the geologic Blue Ridge province. For the purposes of this report, the Blue Ridge is defined as the rocks mapped as the Precambrian-Cambrian Catoctin, Swift Run, Lovingston, Mount Rogers, Mechums River, and Lynchburg Formations, Virginia Blue Ridge Complex and part of the Chilhowee Group (Espenshade, 1970). The Chilhowee Group sedimentary rocks, which flank the west limb of the Blue Ridge anticlinorium, are described with the Valley and Ridge Province. However, rocks of the Chilhowee Group, especially the quartzite of the Weverton Formation, are intimately associated with metavolcanic rocks, slate, and conglomerate of the Catoctin Formation in the Blue Ridge. The eastern and western portions of the Blue Ridge in northern and central Virginia are characterized by the Catoctin metavolcanic rocks. The Swift Run Formation underlies the Catoctin on the western limb of the Blue Ridge anticlinorium, and the Lynchburg Formation, which underlies the Catoctin, can be traced from Culpeper County to Patrick and Carroll Counties in the south. The Catoctin Formation includes metabasalt, greenstone, and minor phyllite, arkose, conglomerate, and schist. On the western limb of the Blue Ridge anticlinorium it is underlain by sandstone, conglomerate, graywacke, marble, and greenstone of the Swift Run Formation.

The Lynchburg Formation consists of biotite gneiss, graywacke, conglomerate, quartzite, mica schist, and graphitic schist and phyllite. The lowest part of the Lynchburg, biotite-hornblende gneiss of the Moneta Gneiss, crops out in eastern Bedford County. The Virginia Blue

Ridge Complex is made up of granite, charnockite, granulite, and gneissic rocks of variable composition that crop out in a broad belt that thins from Rappahannock County to Floyd County. It includes the Roseland anorthosite, Striped Rock granite, various granitic gneisses, and the Marshall, Lovingston, Old Rag, Pedlar, and Robertson River Formations. The Old Rag Formation is a quartz-feldspar granite that crops out in northern Madison County. The Pedlar Formation is granodiorite, charnockite, granulite, syenite, diorite, and anorthosite that crops out irregularly from southwestern Rappahannock County to Bedford County. The Robertson River Formation and Mechums River Formation crop out in long linear bands within and on the eastern edge of the Lovingston Formation from Rappahannock County south to Nelson County. The Robertson River Formation is hornblende granite and syenite. The Mechums River Formation is phyllite, quartzite, graywacke and conglomerate and the Lovingston Formation is biotite granite, gneiss, and monzonite. Biotite granite, gneiss, and monzonite of the Marshall Formation crop out to the south of the Lovingston Formation in Amherst County. The Roseland anorthosite is a small body of plagioclase rock within the Marshall Formation.

In the southernmost Blue Ridge to the west of the Lynchburg Formation, granite gneiss of the Virginia Blue Ridge Complex and the Mount Rogers Formation underlies much of Grayson County. The granite gneiss includes biotite gneiss, schist and quartzite and has several local names including the Saddle gneiss, Cattron diorite, Beverdam Creek augen gneiss, Comers granite gneiss, Grayson granodiorite gneiss, and Shoal gneiss. The gneiss is intruded by the Striped Rock granite. The Mount Rogers Formation to the west comprises rhyolite, arkose, and tuff.

Valley and Ridge

The Valley and Ridge Province is underlain by a series of narrow, northeast-trending belts of carbonate rocks, sandstone, and shale that are tightly folded and cut by faults. Valleys are underlain by carbonate rocks and shale, whereas ridges are predominantly underlain by sandstones and cherty carbonate strata.

The oldest rocks of the Valley and Ridge are Cambrian quartzites and shales of the Chilhowee Group. These rocks form a prominent belt along the southeastern margin of the province. In the southern Valley and Ridge, the Chilhowee Group consists of the basal Unicoi Formation, a quartzite with conglomerate at the base and some basalt interbeds; the Hampton Formation, which consists of green shales interbedded with quartzite and sandstone; and quartzite of the Erwin Formation. In the northern Valley and Ridge, the Chilhowee Group consists of the Weverton, Harpers, and Antietam Formations. The Chilhowee Group is overlain by a thick sequence of Cambrian dolomite, limestone, and shale that forms several narrow belts in the southern and western part of the province. The oldest Cambrian unit, the Shady Formation, is a dolomite with limestone interbeds, similar to the younger Elbrook Formation. These units are separated by the shaly Rome Formation which contains thin limestone interbeds. The Conococheague Formation, consisting of limestone and dolomite, is Cambrian and Ordovician in age and constitutes the top of the Cambrian sequence in the north. The Elbrook and Conococheague Formations are interbedded with progressively more common shale units south and westward. In northwestern and west-central Virginia, this rock progression includes the Honaker Dolomite, overlain by green shale of the Nolichucky Formation, followed by the Copper Ridge Dolomite. In southwestern Virginia, this progression consists of the Rowe Formation, Pumpkin Valley Shale, Rutledge Limestone, Rogersville Shale, Marysville Limestone, and the Nolichucky and Maynardville Formations, which are overlain by the Copper Ridge Dolomite.

Ordovician rocks underlie about a third of the province to the north and nearly half of it to the south, but only occur in relatively small areas in the west central part of the province. The lower Ordovician rocks are predominantly limestone with dolomite and shale. The oldest Ordovician rocks in the province are the limestone and dolomite of the Chepultepec and Beekmantown Formations which are equivalent to the more dolomitic Mascot and Kingsport Formations and the Knox Group in the southern part of the province. These are overlain by narrow belts of limestone and shale that are subdivided into over 30 separately named units (please see the geologic map explanation, figure 2, for the names of these units). This carbonate interval is overlain by black shale and graywacke sandstone of the Martinsburg Formation in the north and green shale and argillaceous limestone of the Reedsville Formation to the south. The Martinsburg is overlain by red and green fluvial sandstone and shale of the Juniata Formation and Oswego Sandstone to the north and the Reedsville is overlain by calcareous shale and limestone of the Sequatchie Formation to the south.

Silurian rocks comprise only narrow belts in the northern, east-central, and southern parts of the province. They comprise about one-fourth of the rocks underlying the west-central part of the province. The basal Tuscorora Formation is a quartzite overlain by marine shale of the Rose Hill Formation and the Keefer Sandstone, which includes beds of hematitic sandstone. These are overlain by the Cayuga Group, which includes green marine shale and siltstone of the McKenzie Formation, red sandstone and shale of the Bloomsburg Formation, and shaly limestone of the Wills Creek and Tonoloway Formations, and by limestone of the Keyser Formation. The Tuscorora Formation dominates the Silurian rocks exposed in the west-central part of the province.

Devonian rocks form a prominent belt along the northwestern and south-central portions of the province and comprise most of the rocks underlying the west-central part of the province. The lowermost Devonian rocks are dominated by limestone with some sandstone, including the Coeymans, New Scotland, and Licking Creek Members of the Helderburg Formation. These are overlain by green to black shales with some quartz sandstone and shaly limestone units near the base and includes the Rocky Gap Sandstone, Ridgeley Sandstone, Huntersville Chert, Needmore Shale, Onondaga Formation, the Millboro and Marcellus Shales, and the Mahantango, Brallier, and Chemung Formations. In the northwestern portion of the province, the uppermost Devonian rocks are red shale and sandstone of the Hampshire Formation.

Mississippian rocks are restricted to a few small areas in the northern part of the province and form prominent belts along the east-central, south-central, and southwestern portions of the province. Mississippian rocks to the north consist of quartzose sandstone and conglomerate with minor mudstone and coal beds of the Pocono Formation. To the south the oldest rocks are gray-green shale and sandstone with minor coal beds of the Price Formation, overlain by red shale and sandstone of the Maccrady Formation. These are overlain by the Greenbrier Limestone and to the south by the Newman Limestone. These formations are overlain by shales, calcareous shale and sandstone, and limestone of the Fido Sandstone, Cove Creek Limestone, and the Bluefield and Hinton Formations. The Hinton Formation is combined with greenish sandstone, conglomeratic sandstone, and green to red shale of the Princeton Sandstone and Bluestone Formation to form the Pennington Group, which crops out along southwestern margin of the province and forms the southernmost area of Mississippian rocks in Washington and Scott Counties.

Appalachian Plateaus

Rocks underlying the Appalachian Plateaus are predominantly Pennsylvanian fluvial sandstone, shale, and coal that form a broad syncline. These include the Lee and Norton Formations, Gladeville Sandstone, Wise Formation, and Harlan Sandstone. A few tiny outcrops of Bluestone Formation green and red shale and sandstone occur along the northwestern margin of the province.

SOILS

A generalized soil map for Virginia is given in figure 5. Soils of the Coastal Plain, Piedmont, and lower mountains of the Blue Ridge are relatively deep and well oxidized, and contain clay subsoils (Ultisols). Soils of the high mountains of the Blue Ridge, Valley and Ridge, and Appalachian Plateau are shallower and less oxidized (Alfisols and Inceptisols). The following discussion is condensed from U.S. Department of Agriculture (1979, 1987) and Devereux and others (1965). It is recommended that the reader consult these references, U.S. Soil Conservation Service county soil surveys, and other publications for more detailed information.

Coastal Plain

Soils of the Cretaceous and Tertiary Coastal Plain are Ultisols comprising deep to very deep, nearly level to sloping soils formed in unconsolidated marine sediments and alluvium derived from Piedmont rocks on river terraces. These soils range from sands and sandy loams to clays and clay loams, and they are generally poorly drained. Near the Piedmont, the Coastal Plain soils have clay hardpans with low permeability (Devereux and others, 1965). Soils in the eastern part of the Cretaceous and Tertiary Coastal Plain generally have moderate permeability. Alluvial soils in stream valleys in the southern part of the Coastal Plain have high permeability, although they are commonly poorly to moderately drained.

The Quaternary Coastal Plain is covered primarily by Ultisols, mature, deeply weathered soils with prominent clay accumulations in the subsoil and often containing a moist or wet substratum (U.S. Department of Agriculture, 1987). They are deep, generally poorly drained soils with moderate permeability formed in unconsolidated sediments. Coarse-textured, well-drained soils with moderate permeability derived from Coastal Plain alluvial and estuarine materials occur along the James and Meherrin Rivers (Devereux and others, 1965). Beach sands along the shoreline have high permeability (U.S. Department of Agriculture, 1979). Several fairly large areas are occupied by marshes, such as the Dismal Swamp. Histosols, poorly drained, commonly wet, organic-rich soils, have formed in these environments.

Piedmont

Soils in the Piedmont are Ultisols, sandy, silty, and clayey loams with thin subsurface clay horizons (U.S. Department of Agriculture, 1987). The soils of the Piedmont generally have a light-colored surface and brownish to red subsoils; however, as one travels from south to north, the soils become somewhat darker in the surface and subsoil and contain increasing amounts of organic matter. Northern Piedmont soils also tend to be shallower and contain more friable subsoils than southern Piedmont soils, although heavy plastic (clay-rich) soils occur in some valleys in the northern Piedmont (Devereux and others, 1965). Most of the Piedmont is covered by shallow to deep, moderately permeable soils formed in residuum from acidic rocks such as granite, gneiss, and schist on gently to moderately sloping surfaces. Soils formed in residuum

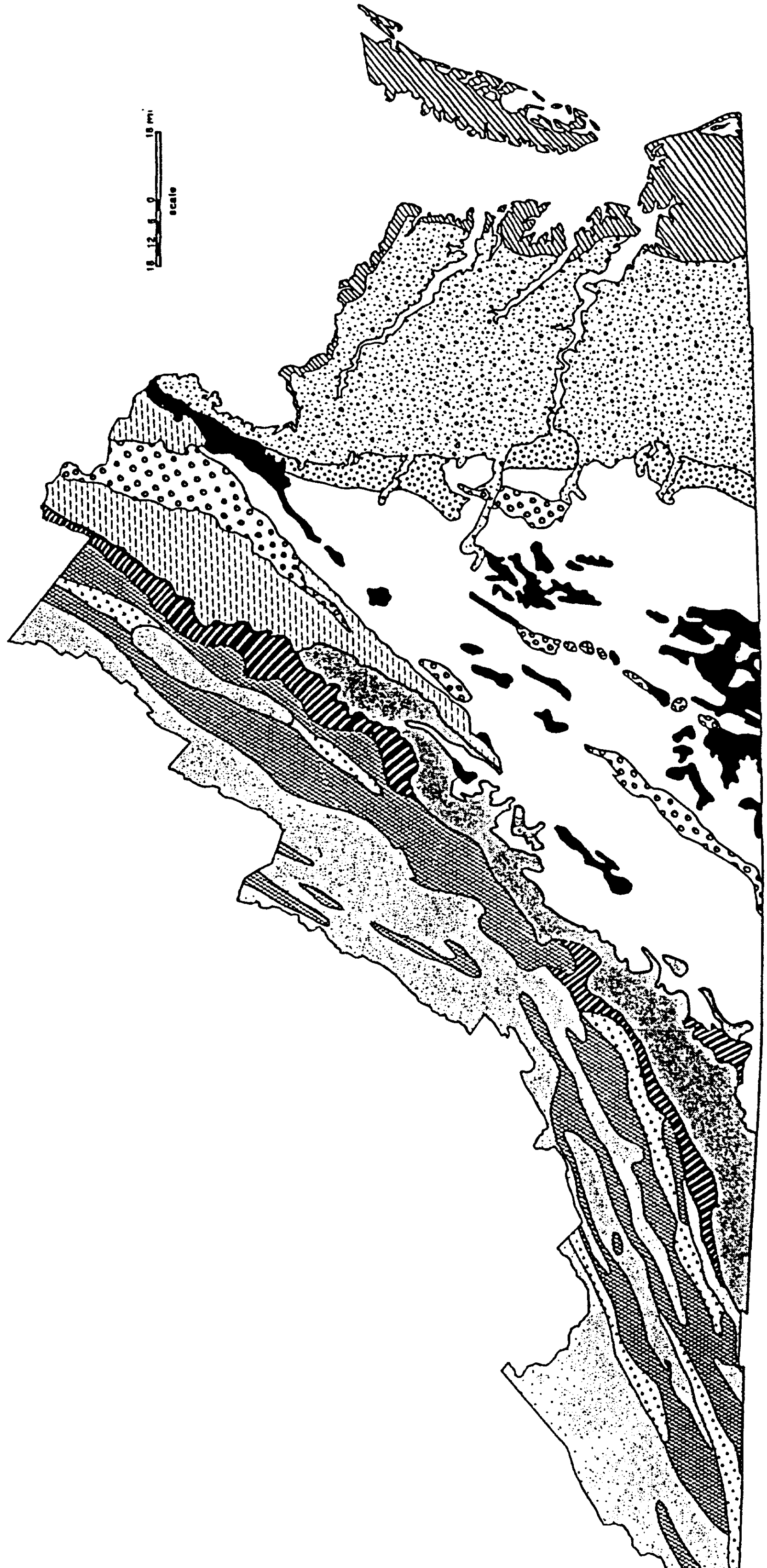


Figure 5. Generalized soils map of Virginia (after U.S. Department of Agriculture, 1979).

GENERALIZED SOILS MAP OF VIRGINIA
EXPLANATION

APPALACHIAN PLATEAU & VALLEY AND RIDGE

Shallow to deep, moderately to highly permeable, steep to very steep soils formed mainly in residuum from acid sandstone, shale, and phyllites; on mountains.

Moderately deep, moderately to highly permeable, gently sloping to steep soils formed in residuum from acid shale; on uplands of dissected valleys.

Shallow to very deep, moderately permeable, gently sloping to steep soils formed in residuum from limestone or interbedded limestone, sandstone, and shale; on uplands in limestone valleys.

BLUE RIDGE MOUNTAINS

Shallow to deep, moderately to highly permeable, moderately steep to very steep soils formed in residuum from sandstone, granite, or greenstone; on mountains.

Moderately deep to deep, moderately permeable, sloping to steep soils formed in residuum from granite, gneiss, and greenstone; on mountains and ridges.

Shallow to deep, moderately to highly permeable, gently sloping to steep soils formed in residuum from acidic or basic rocks; on uplands of the northern Blue Ridge.

PIEDMONT

Shallow to deep, moderately permeable, gently sloping and sloping soils formed in residuum from acidic rocks on uplands of the Piedmont.

Shallow to deep, slowly to moderately permeable, nearly level and gently sloping soils formed in residuum from basic rocks or mixed basic and acidic rocks on uplands of the Piedmont.

Shallow to deep, slowly to moderately permeable, gently sloping soils formed in residuum from sedimentary rocks in Triassic basins of the Piedmont.

Moderately deep to deep, slowly to moderately permeable, gently sloping to sloping soils formed in residuum from igneous and metamorphic rocks or in associated coastal plain sediments; on uplands of the upper Coastal Plain and Piedmont.

CRETACEOUS AND TERTIARY COASTAL PLAIN

Deep to very deep, slowly to moderately permeable, nearly level to sloping soils formed in unconsolidated sediments of the Coastal Plain and river terraces; dominantly above 30 feet elevation. Alluvial soils of valleys in the southern part of this area are highly permeable.

QUATERNARY COASTAL PLAIN

Deep, moderately permeable, nearly level and gently sloping soils formed in unconsolidated sediments of the Coastal Plain or in organic materials; dominantly less than 30 feet elevation.

from basic rocks or mixed basic and acidic rocks on uplands of the Piedmont are shallow to deep, relatively fine-textured soils with low to moderate permeability. In the southern Piedmont, these soils are formed mainly on dark slate, greenstone, and metavolcanic rocks in Mecklenburg and Halifax Counties (Devereux and others, 1965), and on amphibolite, serpentinite, and other ultramafic rocks in the northern Piedmont. The Mesozoic Basins are covered by Alfisols (mineral soils with argillic (clayey) subsurface horizons or fragipans, and which may contain iron-rich or calcic horizons in the subsurface) and Ultisols, comprising shallow to deep, gently sloping, sandy, silty, and clayey loams formed on red sandstone, siltstone, and shale, brown sandstone, some conglomerate, and metasedimentary rocks. Because of their firm, clayey subsurface horizons, these soils have low to moderate permeability. Along the eastern edge of the Piedmont, moderately deep to deep, slowly to moderately permeable soils are formed in saprolite and residuum from igneous and metamorphic rocks or in associated coastal plain sediments on gently to moderately sloping uplands of the upper Coastal Plain and Piedmont.

Blue Ridge

Soils of the Blue Ridge Mountains are mainly Ultisols and Alfisols. Mostly shallow to locally deep, moderately steep to very steep, stony soils formed in residuum from sandstone, granite, or greenstone have formed on the northwestern slopes of mountains in the western Blue Ridge. These soils are well drained to excessively drained and have moderate to high permeability; much of the area is rock outcrop. The southeastern slopes, eastern foot slopes, and smooth mountain tops of the Blue Ridge are covered by moderately deep to deep, moderately permeable, sloping to steep soils formed in saprolite and residuum from granite, gneiss, schist, mica schist, and greenstone. The surface texture of most soils in this map unit are loam, silt loam, or clay loam, and most of the soils are friable throughout the profile. The steep mountain slopes are largely covered by thin, stony soils. On the mountaintops and in intermountain areas of the southern Blue Ridge, the soils are deeper and better developed. Soils developed on weathered mica schist have loose topsoils and clayey, red or brownish micaceous substrata (Devereux and others, 1965) that have relatively low permeability but are easily erodible. Gently to moderately sloping upland areas in the northeastern part of the Blue Ridge are covered by shallow to deep, moderately to highly permeable soils formed in residuum from acidic or basic rocks, primarily metabasalt and granite. Also included in this map unit are moderately permeable silt and clay loams formed on schist and phyllite in the northern Piedmont (fig. 5).

Appalachian Plateaus and Valley and Ridge

The Appalachian Plateaus and Valley and Ridge are covered by Inceptisols and Ultisols. Inceptisols are soils with weakly developed horizons in which materials have been altered or removed and may contain horizons of accumulated silica, iron, or bases, but they generally do not have clayey subsurface horizons. Ultisols are shallow to deep, moderately to highly permeable, steep to very steep soils formed mainly in residuum from acid sandstone, shale and phyllites. Soils of this type occur on mountains. Moderately deep, moderately to highly permeable, gently sloping to steep soils formed in residuum from acid shale cover uplands of dissected valleys. In many areas, rock fragments of various sizes are scattered across the surface and throughout the soil (Devereux and others, 1965). The limestone valleys are covered by shallow to very deep, gently sloping to steep soils formed in residuum from limestone or interbedded limestone, sandstone and shale. Soils on ridges are usually derived from dolomitic limestone that contains significant amounts of chert, and locally, sandstone and shale, which make the rock more resistant to erosion

(Devereux and others, 1965). Soils in the lower-lying limestone valleys are silt loams where the soils are derived from limestone or shale, and sandy loams or loams where the soils are derived from sandstone or mixtures of sandstone and limestone. Many of the shale or shaly limestone-derived soils have plastic clay substrata that impart a low permeability to the soil. The remainder of the soils in this map unit have moderate permeability.

RADIOACTIVITY

An aeroradiometric map of Virginia (fig. 6) was compiled from spectral gamma-ray data acquired during the U.S. Department of Energy's National Uranium Resource Evaluation (NURE) program (Duval and others, 1989). For the purposes of this report, low equivalent uranium (eU) is defined as less than 1.5 parts per million (ppm), moderate eU is defined as 1.5-2.5 ppm, and high eU is defined as greater than 2.5 ppm. In figure 6, low eU appears to be associated with the upper Tertiary and Quaternary sediments of the Coastal Plain; the metavolcanic rocks of the Piedmont and Blue Ridge; the Virginia Blue Ridge Complex from southern Albermarle County to Roanoke County; the Silurian sedimentary rocks of the Valley and Ridge; and parts of the Devonian and Mississippian sedimentary rocks of the Valley and Ridge. Moderate eU is associated with much of the Tertiary sediments of the Coastal Plain; the granitic schist, granite, and gneiss of the Piedmont; granite and gneiss in the northern Blue Ridge; and many of the sedimentary rocks in the Valley and Ridge and Appalachian Plateau. High eU is associated with the Petersburg and Redoak Granites in the eastern and southern Piedmont; the Old Rag and Crozet granites in the northern Blue Ridge; the Striped Rock granite in the southern Blue Ridge; the schists and gneiss of the Goochland terrane; the faulted schist, gneiss, and granite in the southwestern Piedmont, Triassic rocks of the Danville basin; and faulted Paleozoic clastics and carbonates in the southern Valley and Ridge and Appalachian Plateau.

Many of the eU concentrations in the Piedmont, Blue Ridge, and parts of the Coastal Plain (fig. 6) may be attributable to the mineral monazite, which, in the Piedmont and Blue Ridge, is found in high-grade metamorphic rocks and late-stage granitic intrusive rocks. Monazite contains significant amounts of uranium and thorium. Its resistance to weathering and high density result in local concentrations of monazite in soils and as placer deposits in marine, fluvial, and alluvial sediments. Several monazite "belts" in the Piedmont were defined by Mertie (1953); one of these belts extends from the Raleigh Belt of North Carolina into the Goochland terrane of Virginia. During the NURE program, stream sediment samples were analyzed for various elements. An examination of the cerium data from these stream sediment samples can be used to verify whether the source of radioactivity is monazite, as cerium is an element commonly found in monazite. A map of the cerium concentrations exceeding 200 ppm in sediment samples for Virginia (Cook and others, 1982) shows several distinct belts of cerium that correspond to the Grayson gneiss, parts of the Virginia Blue Ridge Complex, the Leatherwood granite, parts of the Evington Group, the Shelton granite gneiss, the schist, granite, and gneiss of the Goochland terrane, and scattered anomalies throughout the Tertiary of the Piedmont and in the Quaternary east of Chesapeake Bay. These belts correspond with several of the areas of high eU seen on the NURE aerial radiometric map (fig. 6). However, uranium in other minerals, or by itself as an oxide, occurs in shear zones, granite intrusives, pegmatites, granite gneiss, black shales, and soils formed from carbonate rocks. These forms of uranium are also the source of much of the high radioactivity found in Virginia. Granitic bodies and pegmatites may contain a number of uranium-bearing minerals, including sphene, zircon, uraninite, allanite, and exotic uranium and thorium minerals, as well as monazite.

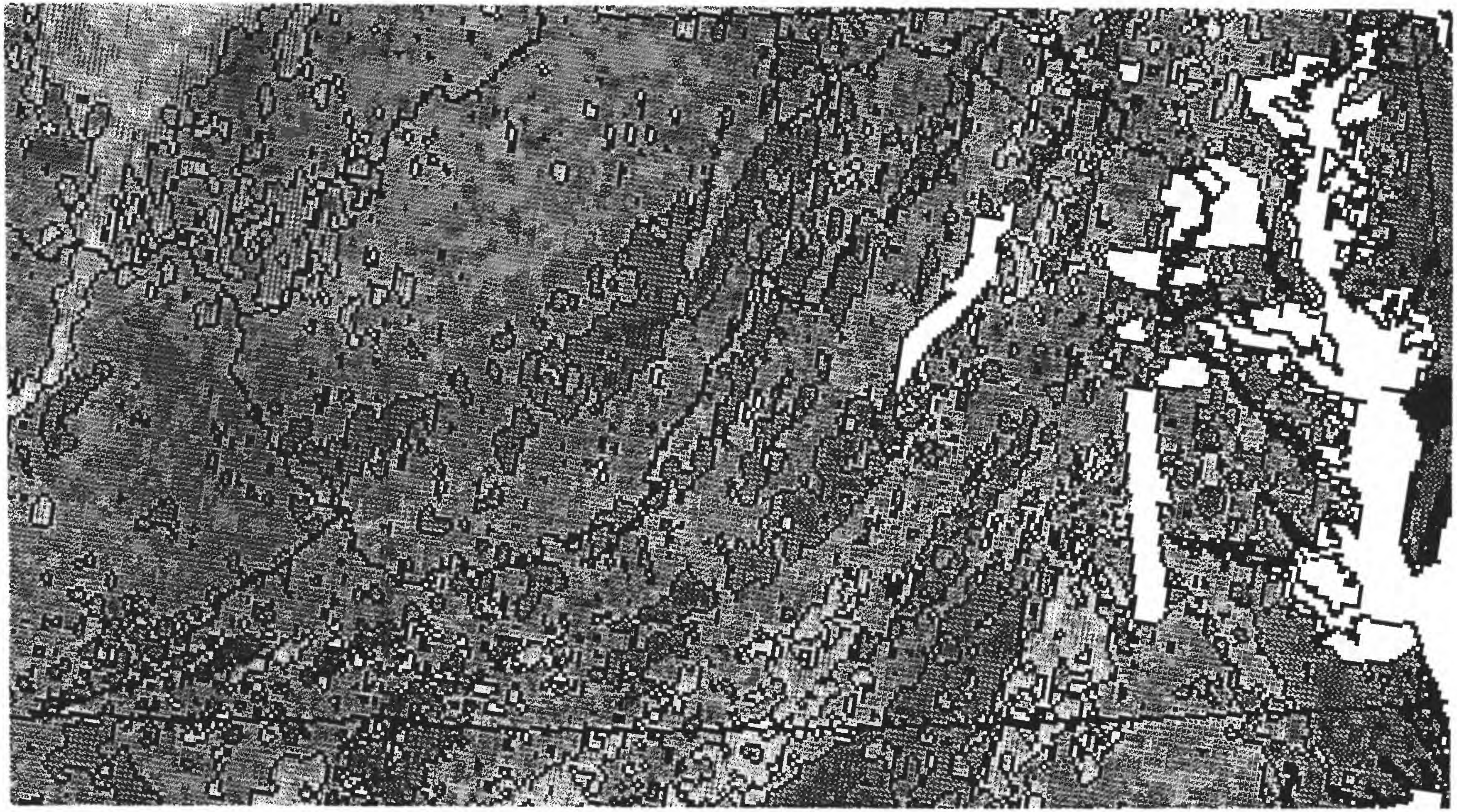


Figure 6. Aerial radiometric map of Virginia (after Duval and others, 1989). Contour lines at 1.5 and 2.5 ppm equivalent uranium (eU). Pixels shaded at 0.5 ppm eU increments; darker pixels have lower eU values; white indicates no data.

Uranium may also be finely disseminated in rocks and soils, such as in black shales, soils formed from carbonate rocks, and graphitic schists and phyllites. Specific, known occurrences of uranium in Virginia are discussed below. The source of uranium in the soils and rocks is important in evaluating their radon potential. Uranium that is "locked up" in mineral species as a trace element will liberate less radon to pore spaces than uranium in uraninite, uranium oxidized with iron on mineral grain surfaces, uranium on fracture and fault surfaces, or finely disseminated uranium in graphitic phyllite or black shales.

There are numerous reports on uranium occurrences of Virginia. Grosz (1983) determined that the Coastal Plain of Virginia was difficult to assess using aerial techniques because of the cultural affects, such as that of agriculture, on surface radioactivity response. However, a regional pattern of radioactivity from the NURE data (fig. 6), which is different from the data obtained by Grosz, suggests that some of the Tertiary sediments have moderate radioactivity. Studies of uranium and radon in the Coastal Plain of New Jersey, Alabama, and Texas by Gundersen and others (1991) suggests that glauconitic, phosphatic, monazite-rich, and carbonaceous sediments are the source of the moderate indoor radon measured in the Coastal Plain of these states. Glauconite contains significant amounts of uranium (Gundersen and Schumann, 1989). Phosphate is an effective scavenger of uranium and phosphatic deposits tend to have high uranium concentrations, in many cases higher than in glauconitic sediments. The occurrence of fossils, especially those high in phosphate such as shark teeth and whale bone, also correlates with moderate to high soil radon concentrations. In a recent study of radon in soils developed from Coastal Plain sediments in Virginia, Berquist and others (1990) found uranium in concentrations as high as 1350 ppm in fossilized bone of the Yorktown Formation; the P_2O_5 concentration was 32 percent (C.R. Berquist, oral comm.). They found that the average soil radon from their samples of Virginia Coastal Plain sediments was generally 1000 pCi/L or less, the Yorktown sands having the highest average radon concentration in soil gas, 959 pCi/L.

Uranium occurrences in the Piedmont and Blue Ridge appear to be associated most often with uraniferous granites, pegmatites, monazite and other radioactive minerals in schist and gneiss, phyllite, and fault zones (especially shear zones). In northern Virginia, Mose and others (1988a, b), Otton and others (1988), and Schumann and Owen (1988) noted that the highest aerial radioactivity, soil-gas radon, and indoor radon levels are associated with phyllite and schist of the Peters Creek Schist in Fairfax County. Neuschel and others (1971) reported elevated radioactivity over a small quartz monzonite pluton northwest of Fredericksburg. Neuschel (1970) also observed elevated radioactivity over granite and granite pegmatites in the area of Spotsylvania.

Several uranium and radon studies have been conducted in the Goochland terrane. Baillieul and Dexter (1982) examined uranium anomalies found during the NURE program in the Hylas fault zone and the Richmond basin west of Richmond. The Hylas zone is a mylonite developed partly in the Petersburg Granite and partly in the Maidens Gneiss and State Farm Gneiss. Baillieul and Dexter (1982) reported chemical uranium concentrations in the mylonite ranging 3-29 ppm U_3O_8 and pegmatite containing 450 ppm U_3O_8. In the Richmond basin, Triassic coaly shale measured 5 ppm U_3O_8 and feldspathic wacke measured 15 ppm U_3O_8. The Petersburg Granite also showed anomalous gamma radioactivity. Radon and uranium studies of the Hylas zone by Gates and others (1990) reported similar results but also showed that the Hylas zone mylonite rocks can produce anomalously high radon in the overlying soils (up to 12,000 pCi/L). Uranium in the Petersburg Granite and surrounding gneiss is distributed in a number of minerals. During deformation these minerals were broken down and the uranium was redistributed into the foliation of the mylonite. This uranium concentration mechanism may be common in most mylonites

(Gundersen, 1991). Gates and others (1990) found that the Sabot amphibolite had low uranium (<1 ppm) and low soil radon (generally < 500 pCi/L). Soils developed on the Maidens and State Farm Gneiss yielded moderate amounts of soil radon (generally in the 700-1000 pCi/L range). Undeformed Petersburg Granite and the Triassic conglomerate (derived from granite and mylonite) yielded moderate to high soil radon (generally 1000-2000 pCi/L). Soils over the pegmatite and mylonite yielded the highest soil radon (generally > 2000 pCi/L). To the south in the Goochland terrane, studies by Krason and others (1988) of anomalous radioactivity in the Powhatan area suggest that the source of the radioactivity is accumulations of monazite in saprolite soils developed on a monazite-rich layer of the Maidens Gneiss. The deposit also appears to be structurally controlled since it corresponds to the crest of the Goochland anticline.

The Swanson uranium deposit in Pittsylvania County is a well known, fault-related uranium deposit (Halladay, 1987). The deposit is located along the Chatham fault on the west side of the Danville basin and is hosted in severely sheared and altered gneiss of the Fork Mountain Formation. Aerial radiometric anomalies are associated with the main ore body and several other anomalies are located to the north along the fault. The ore body is described by Frishman and others (1987) as a stockwork of U-bearing veinlets within the fault zone.

Grauch and Zarinsky (1976) report radioactivity in the Grayson gneiss, in schist near Ridgeway in Henry County and near Woodville in Rappahannock County, in the Lovingston Formation in Albermarle, Bedford, and Culpeper Counties, and in pegmatite in Amelia County. Baillieul and Daddazio (1982) conducted field studies in the Lovingston Formation and found numerous uranium occurrences and areas of very high radioactivity usually associated with shear zones, highly altered schist and gneiss, vein fillings, and mineral accumulations in saprolite. They also evaluated several igneous plutons and found elevated uranium associated with the Old Rag Granite, the Crozet Granite, and where the Ellinsville granodiorite and Green Springs pluton intrude the metamorphic rocks of the Candler and Chopawamsic Formations. They note that no anomalous radioactivity was associated with the Pedlar, Swift Run, and Lynchburg Formations but that the Mechums River Formation did have anomalous radioactivity associated with it.

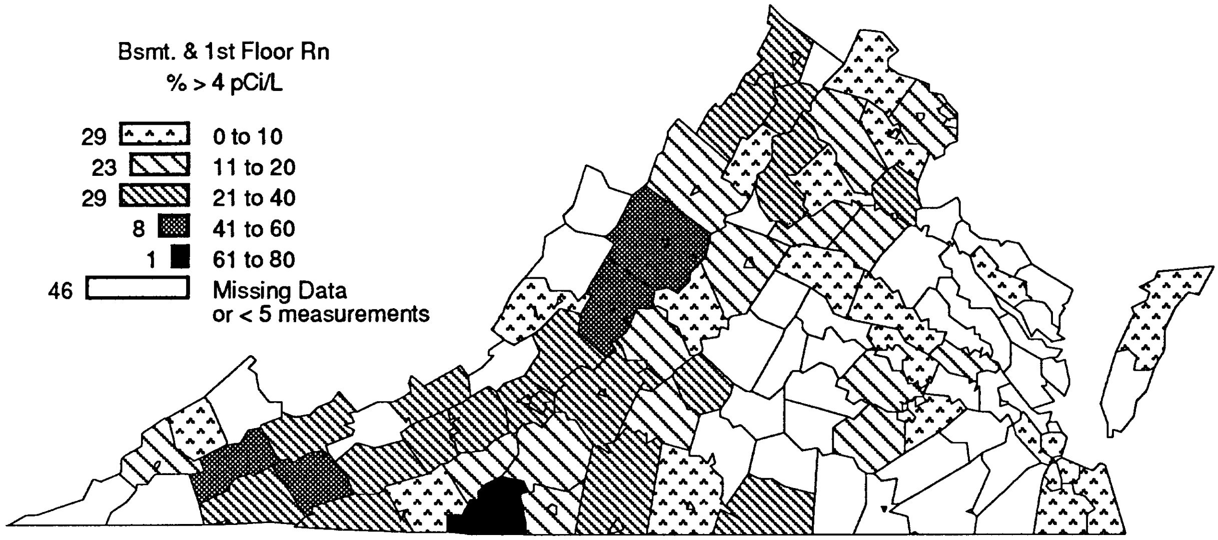
Sandstones and siltstones of the Culpeper basin which have been metamorphosed to hornfels and altered by diabase intrusion are mineralized with uranium and cause documented moderate to high radon levels in Virginia (Otton and others, 1988; Schumann and Owen, 1988). Smoot and Robinson (1988) examined the base metal mineralization and conducted field studies of the radioactivity in the Newark Supergroup and found several units with anomalous radioactivity, especially black shales and reduced fluvial sandstones. Some coarse-grained gray sandstones have significant radioactivity, often associated with green clay clasts and copper. The upper Manassas Sandstone has anomalous radioactivity associated with fluvial crossbeds, with intraclasts, and with lenses of gray carbonaceous silt, particularly in the northern half of the Culpeper basin. The fluvial sandstone immediately below the Cow Branch Member in the Danville basin is similar to the upper Manassas Sandstone and may also contain uranium mineralization. Black shales in the lower part of the lacustrine portion of the Balls Bluff Siltstone are notably uranium-bearing. Border conglomerates in the Danville and Richmond basins, consisting of blocks of mylonite, have high radioactivity. Elevated radioactivity occurs where diabase bodies intrude limestone, limestone conglomerates, or calcareous zones in siltstones and sandstones. Black shales in the Cow Branch Member and immediately overlying lacustrine units are also likely to contain high uranium. Black shales and gray sandstones in the upper Balls Bluff Siltstone, the finer-grained portions of the Catharpin Creek Formation, the Waterfall, Turkey Run, and Midland Formations, the upper portions of the Danville basin lacustrine sequence, and in the Vinita Beds Member of the Tuckahoe Formation may all have locally elevated uranium (J.P. Smoot, oral comm.).

Sedimentary rocks of the Valley and Ridge and Appalachian Plateau have low to moderate eU associated with them on the NURE map (fig. 6). To the north in Pennsylvania, carbonate rocks of the Valley and Ridge and Great Valley have been the focus of several studies (van Assendelft and Sachs, 1982; Gross and Sachs, 1982; Greeman and Rose, 1990; Luetzelschwab and others, 1989) and the carbonate rocks in these areas produce soils with high uranium and radium contents and high radon emanation. Carbonate rocks themselves are usually low in radionuclide elements but the soils developed from carbonate rocks are often elevated in uranium and radium. Carbonate soils are derived from the dissolution of the $CaCO_3$ that makes up the majority of the rock. When the $CaCO_3$ has been dissolved away, the soils are enriched in the remaining impurities, predominantly base metals, including radionuclides. Studies in the carbonate rocks and soils of the Great Valley in West Virginia suggest that the deepest, most mature soils have the highest radium and radon concentrations (Schultz and others, 1992). Rinds containing high concentrations of uranium and uranium-bearing minerals can be formed on the surfaces of rocks affected by $CaCO_3$ dissolution and karstification. Karst and cave morphology is also thought to promote the flow and accumulation of radon. Schultz and others (1992) also measured high radon concentrations in soils and high indoor radon levels in homes on the black shales of the Martinsburg Formation. Analysis of the NURE aerial radiometric data in Virginia (Texas Instruments Incorporated, 1980) indicates that uranium anomalies are associated with Devonian black shales, with the sandstones and shales of the Chemung Formation, shale and sandstone of the Hampshire Formation, sandstone, shale, and coal of the Pocono Formation, limestone and shale of the Greenbrier Group, and with some of the Pennsylvanian sandstones, shales, and coals. However, Baillieul and Daddazio (1982) field checked some of these rock units in northern Virginia and noted a striking contrast in radioactivity between the same rocks in Pennsylvania and Virginia. They concluded that the upper Devonian-Pennsylvanian sandstone units in Virginia have only local areas of elevated radioactivity and do not appear to be as radioactive as their equivalents in Pennsylvania.

INDOOR RADON

Indoor radon data from 1156 homes sampled in the State/EPA Residential Radon Survey conducted in Virginia during the winter of 1991-92 are shown in figure 7 and Table 1. Data are shown in figure 7 only for those counties and cities with 5 or more data values. A map of counties is included for reference (fig. 8). The maximum value recorded in the survey was 81.5 pCi/L in Danville, in Pittsylvania County. The average for the State was 2.7 pCi/L and 17.6 percent of the homes tested had indoor radon readings exceeding 4 pCi/L. Nonrandom commercial data compiled by EPA Region 3 are shown in figure 9 for comparison purposes. Data are shown in figure 9 only for those counties with 15 or more data values.

Both indoor radon data sets show a lack of data for significant parts of the Coastal Plain, southern Piedmont, western Valley and Ridge, and Appalachian Plateaus. Available data are concentrated in the northern and central portions of the State. The most obvious pattern that emerges from these data sets is the abundance of counties that contain houses with high (>4 pCi/L) indoor radon averages in the Valley and Ridge (fig. 7). Correspondingly, the commercial data (fig. 9) show the greatest percentage of readings over 4 pCi/L concentrated in the Valley and Ridge counties. Counties of the Blue Ridge and Piedmont have notably moderate (2-4 pCi/L) county



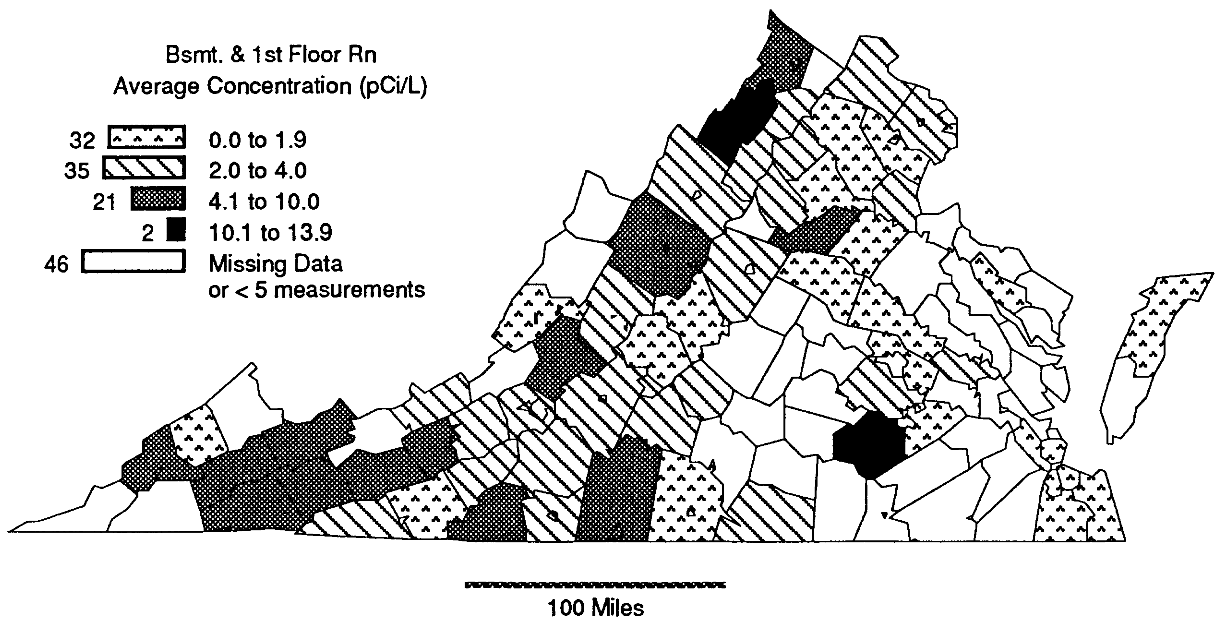


Figure 7. Screening indoor radon data from the EPA/State Residential Radon Survey of Virginia, 1991-92, for counties with 5 or more measurements. Data are from 2-7 day charcoal canister tests. Histograms in map legends show the number of counties in each category. The number of samples in each county (See Table 1) may not be sufficient to statistically characterize the radon levels of the counties, but they do suggest general trends. Unequal category intervals were chosen to provide reference to decision and action levels.

TABLE 1. Screening indoor radon data from the EPA/State Residential Radon Survey of Virginia conducted during 1991-92. Data represent 2-7 day charcoal canister measurements from the lowest level of each home tested.

COUNTY	NO. OF MEAS.	MEAN	GEOM. MEAN	MEDIAN	STD. DEV.	MAXIMUM	%>4 pCi/L	%>20 pCi/L
ACCOMACK	5	0.3	0.2	0.2	0.3	0.8	0	0
ALBEMARLE	12	4.5	1.7	1.8	8.5	30.7	25	8
ALLEGHANY	5	1.6	1.4	1.7	0.7	2.3	0	0
AMELIA	4	1.2	0.6	1.2	1.0	2.5	0	0
AMHERST	14	1.9	1.1	1.0	2.1	7.4	14	0
APPOMATTOX	5	2.3	1.5	0.9	2.4	6.1	20	0
ARLINGTON	14	1.7	1.1	1.3	1.5	4.9	14	0
AUGUSTA	19	3.0	1.8	2.0	3.1	13.4	32	0
BATH	2	4.0	3.3	4.0	3.0	6.1	50	0
BEDFORD	15	1.8	1.0	1.8	1.9	7.8	7	0
BOTETOURT	9	6.6	4.2	3.7	6.7	20.8	44	11
BRUNSWICK	3	1.7	1.6	1.6	0.7	2.4	0	0
BUCHANAN	3	1.3	1.2	1.3	0.7	2.0	0	0
BUCKINGHAM	4	1.0	0.5	0.7	1.0	2.4	0	0
CAMPBELL	17	2.4	1.5	1.8	2.5	9.7	12	0
CAROLINE	3	0.8	0.5	0.8	0.7	1.5	0	0
CARROLL	11	1.5	0.9	0.7	1.3	4.3	9	0
CHARLES CITY	1	1.1	1.1	1.1	0.0	1.1	0	0
CHARLOTTE	4	1.0	0.7	0.7	1.1	2.6	0	0
CHESTERFIELD	59	3.1	1.1	1.1	7.2	49.9	17	3
CLARKE	3	2.8	1.8	2.1	2.7	5.7	33	0
CRAIG	2	2.3	0.7	2.3	3.1	4.5	50	0
CULPEPER	6	1.5	0.9	1.7	1.2	3.4	0	0
CUMBERLAND	2	1.0	1.0	1.0	0.0	1.0	0	0
DICKENSON	6	0.6	0.4	0.6	0.4	1.1	0	0
DINWIDDIE	6	13.9	1.3	0.6	31.7	78.6	17	17
ESSEX	2	1.9	1.6	1.9	1.2	2.7	0	0
FAIRFAX	70	2.1	1.4	1.6	2.0	9.2	10	0
FAUQUIER	9	1.9	1.2	1.2	2.4	7.9	11	0
FLOYD	5	2.9	2.6	2.9	1.3	4.9	20	0
FLUVANNA	2	2.3	2.3	2.3	0.0	2.3	0	0
FRANKLIN	7	2.0	1.1	1.0	2.9	8.5	14	0
FREDERICK	9	6.3	2.1	2.2	12.2	38.5	33	11
GILES	8	3.2	1.1	0.9	4.8	12.0	25	0
GLOUCESTER	3	0.4	0.4	0.4	0.2	0.6	0	0
GOOCHLAND	3	3.1	1.3	0.6	4.4	8.1	33	0
GRAYSON	6	2.3	1.3	1.1	2.8	7.6	17	0
GREENE	1	1.3	1.3	1.3	0.0	1.3	0	0
GREENSVILLE	2	0.5	0.2	0.5	0.6	0.9	0	0
HALIFAX	2	1.5	1.4	1.5	0.5	1.8	0	0
HANOVER	13	0.9	0.7	0.6	0.7	2.0	0	0

TABLE 1 (continued). Screening indoor radon data for Virginia.

COUNTY	NO. OF MEAS.	MEAN	GEOM. MEAN	MEDIAN	STD. DEV.	MAXIMUM	%>4 pCi/L	%>20 pCi/L
HENRICO	30	1.7	0.9	0.8	2.7	14.9	7	0
HENRY	13	2.0	1.5	1.6	1.5	5.7	8	0
ISLE OF WIGHT	1	0.9	0.9	0.9	0.0	0.9	0	0
JAMES CITY	1	1.0	1.0	1.0	0.0	1.0	0	0
KING GEORGE	1	3.5	3.5	3.5	0.0	3.5	0	0
KING WILLIAM	3	0.6	0.4	0.7	0.5	1.0	0	0
LANCASTER	2	1.5	1.2	1.5	1.3	2.4	0	0
LEE	3	4.3	2.5	1.3	5.2	10.3	33	0
LOUDOUN	13	2.0	1.3	2.0	1.4	4.1	8	0
LOUISA	5	0.9	0.8	0.8	0.4	1.4	0	0
LUNENBURG	3	2.1	0.7	1.4	2.6	5.0	33	0
MADISON	6	2.4	1.3	2.1	1.8	4.8	33	0
MATHEWS	1	0.4	0.4	0.4	0.0	0.4	0	0
MECKLENBURG	13	2.5	1.4	2.1	2.5	8.5	23	0
MIDDLESEX	1	1.3	1.3	1.3	0.0	1.3	0	0
MONTGOMERY	11	3.3	1.7	2.1	3.4	10.9	36	0
NELSON	10	1.8	1.4	1.6	1.3	5.1	10	0
NEW KENT	6	2.1	1.7	2.0	1.4	4.5	17	0
NORTHAMPTON	2	0.5	0.4	0.5	0.2	0.6	0	0
NORTHUMBERLAND	2	1.4	1.3	1.4	0.1	1.4	0	0
NOTTOWAY	1	0.8	0.8	0.8	0.0	0.8	0	0
ORANGE	7	4.2	1.7	1.5	6.8	19.4	14	0
PAGE	5	2.2	1.9	1.9	1.0	3.5	0	0
PATRICK	8	7.7	5.7	7.0	6.6	21.8	63	13
PITTSYLVANIA	21	2.8	1.8	2.1	2.7	12.2	24	0
POWHATAN	3	0.4	0.4	0.5	0.2	0.6	0	0
PRINCE EDWARD	4	1.4	0.8	1.1	1.3	3.1	0	0
PRINCE GEORGE	3	0.3	0.2	0.2	0.4	0.8	0	0
PRINCE WILLIAM	16	1.5	1.0	1.5	1.1	4.1	6	0
PULASKI	11	4.8	2.8	3.3	4.8	15.3	36	0
RAPPAHANNOCK	7	3.7	2.4	2.2	3.9	11.9	29	0
ROANOKE	12	2.2	1.1	0.8	2.3	6.1	25	0
ROCKBRIDGE	6	4.0	3.0	4.3	2.5	6.7	50	0
ROCKINGHAM	15	2.7	1.6	1.8	3.0	11.7	13	0
RUSSELL	9	7.0	2.3	3.2	13.4	42.4	44	11
SCOTT	4	5.7	2.7	3.1	7.1	15.8	50	0
SHENANDOAH	15	10.1	3.2	2.7	19.7	77.2	40	13
SMYTH	14	5.8	2.6	2.9	8.5	33.1	43	7
SOUTHAMPTON	2	0.5	0.4	0.5	0.1	0.5	0	0
SPOTSYLVANIA	7	0.9	0.5	0.8	0.8	2.0	0	0
STAFFORD	11	2.3	1.3	1.3	2.5	8.2	27	0
SURRY	1	0.6	0.6	0.6	0.0	0.6	0	0
SUSSEX	2	0.7	0.7	0.7	0.1	0.8	0	0

TABLE 1 (continued). Screening indoor radon data for Virginia.

COUNTY	NO. OF MEAS.	MEAN	GEOM. MEAN	MEDIAN	STD. DEV.	MAXIMUM	%>4 pCi/L	%>20 pCi/L
TAZEWELL	20	5.2	2.9	2.8	6.2	23.1	35	10
WARREN	7	2.6	1.6	1.1	2.6	7.2	29	0
WASHINGTON	20	3.4	2.1	2.1	3.3	12.3	35	0
WESTMORELAND	1	1.5	1.5	1.5	0.0	1.5	0	0
WISE	5	5.8	1.7	1.0	10.9	25.2	20	20
WYTHE	7	4.9	3.4	2.9	5.4	16.5	29	0
YORK	3	0.6	0.3	0.4	0.8	1.5	0	0
C ITY								
ALEXANDRIA CITY	12	1.0	0.5	0.5	1.2	4.0	0	0
BEDFORD CITY	5	1.2	1.0	1.1	0.8	2.6	0	0
BRISTOL	6	7.0	2.5	2.2	11.4	30.0	33	17
BUENA VISTA	5	3.0	2.3	2.7	2.7	7.6	20	0
CHARLOTTESVILLE	15	1.3	0.8	1.0	1.2	4.8	7	0
CHESAPEAKE	23	0.3	0.2	0.2	0.3	1.1	0	0
CLIFTON FORGE	1	0.8	0.8	0.8	0.0	0.8	0	0
COLONIAL HEIGHTS	5	2.4	2.0	2.0	1.9	5.7	20	0
COVINGTON	1	3.1	3.1	3.1	0.0	3.1	0	0
DANVILLE	14	8.7	2.3	2.3	21.1	81.5	36	7
EMPORIA	2	0.5	0.4	0.5	0.4	0.8	0	0
FAIRFAX-CITY	21	2.1	1.3	1.6	2.0	8.5	10	0
FALLS CHURCH	2	1.3	1.2	1.3	0.1	1.3	0	0
FREDERICKSBURG	7	2.8	2.1	2.7	2.0	6.0	29	0
GALAX	3	5.8	4.8	6.8	3.6	8.9	67	0
HAMPTON	7	0.3	0.3	0.3	0.2	0.6	0	0
HARRISONBURG	5	1.8	1.4	1.1	1.3	4.0	0	0
HOPEWELL	5	0.6	0.4	0.4	0.6	1.5	0	0
LEXINGTON	3	4.0	3.9	4.2	1.3	5.2	67	0
LYNCHBURG	20	2.9	2.3	2.6	1.7	6.0	30	0
MANASSAS	7	1.7	1.3	1.1	1.3	3.8	0	0
MARTINSVILLE	7	2.3	1.2	1.6	2.2	6.1	29	0
NEWPORT NEWS	13	0.7	0.5	0.5	0.6	1.6	0	0
NORFOLK	14	0.8	0.4	0.6	1.0	3.7	0	0
PETERSBURG	5	1.1	1.0	1.2	0.6	1.9	0	0
POQUOSON	1	0.4	0.4	0.4	0.0	0.4	0	0
PORTSMOUTH	6	0.4	0.2	0.4	0.5	1.2	0	0
RADFORD	2	3.9	2.1	3.9	4.7	7.2	50	0
RICHMOND-CITY	73	1.4	0.9	0.9	1.4	7.6	7	0
ROANOKE-CITY	45	4.3	3.0	3.0	4.4	27.1	36	2
SALEM	6	5.5	2.8	2.2	8.3	22.2	33	17
SOUTH BOSTON	3	1.1	0.5	0.4	1.4	2.7	0	0
STAUNTON	4	7.3	5.8	7.9	4.7	11.3	75	0
SUFFOLK	3	0.1	0.1	0	0.2	0.4	0	0
VIRGINIA BEACH	39	0.5	0.3	0.2	0.9	4.7	3	0

TABLE 1 (continued). Screening indoor radon data for Virginia.

CITY	NO. OF MEAS.	MEAN	GEOM. MEAN	MEDIAN	STD. DEV.	MAXIMUM	%>4 pCi/L	%>20 pCi/L
WAYNESBORO	6	5.7	4.5	4.2	4.7	14.5	50	0
WILLIAMSBURG	1	1	1	1	0	1	0	0
WINCHESTER	9	3	2.1	2.4	2.7	8.9	33	0

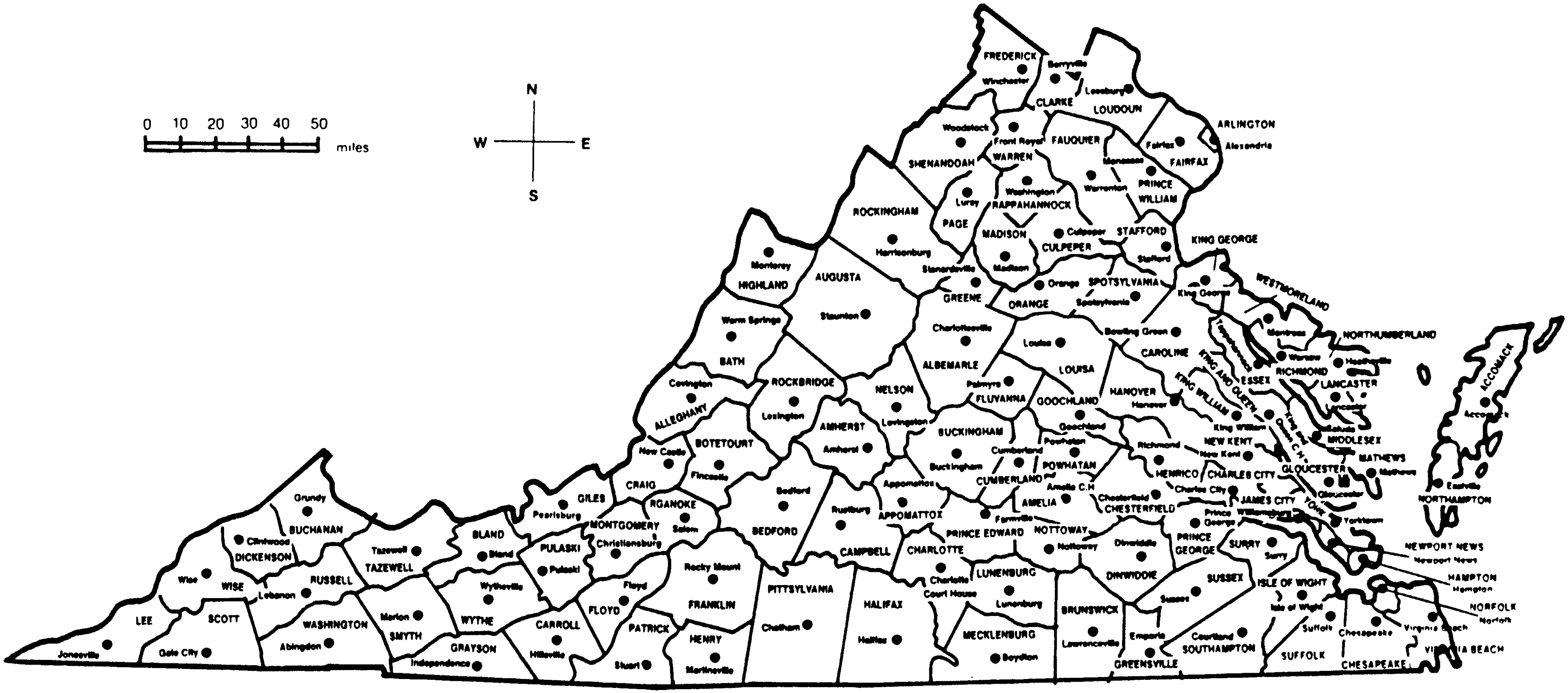


Figure 8. Virginia counties (from Facts on File, 1984).

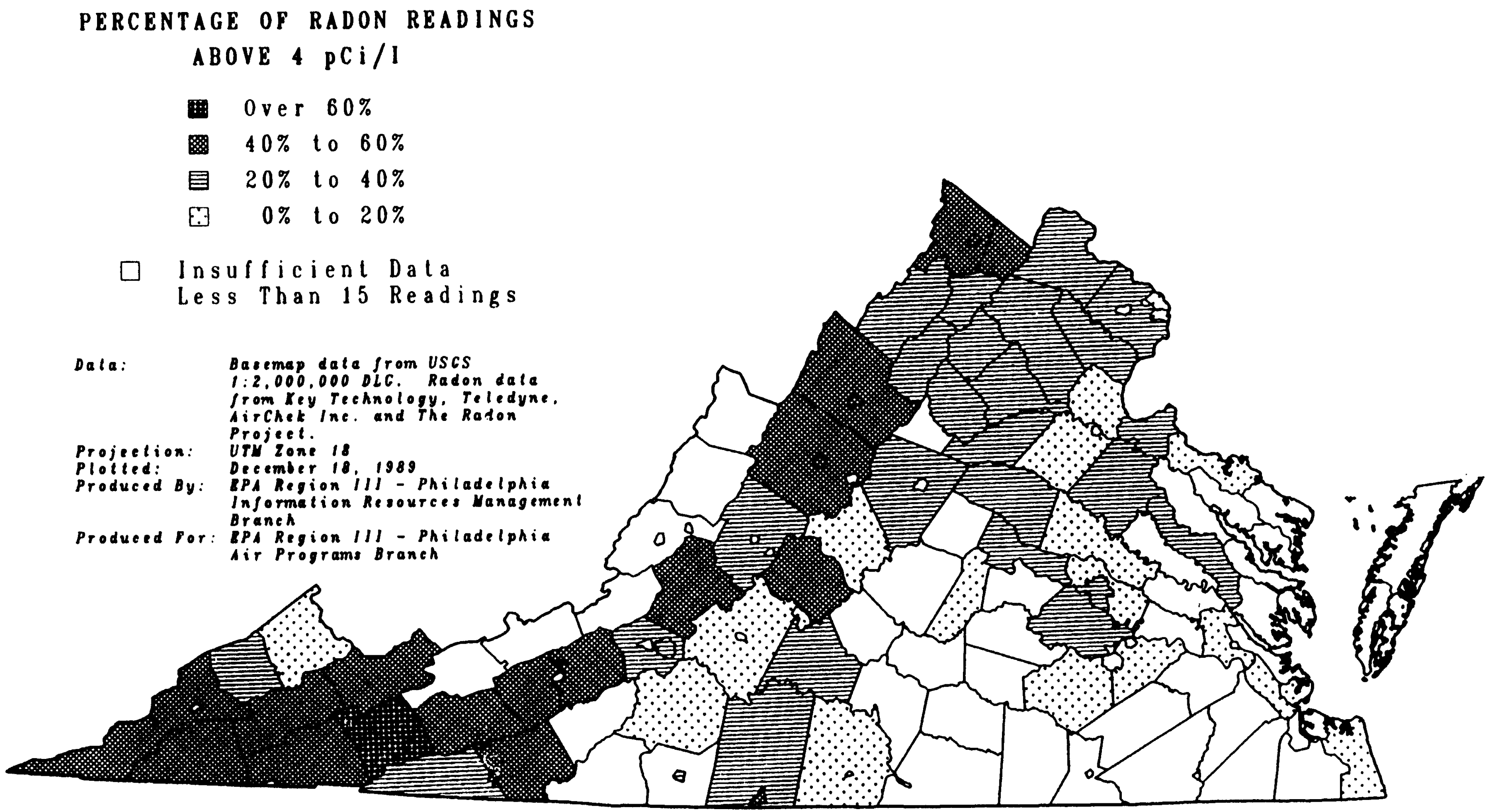


Figure 9. Vendor screening indoor radon data for Virginia compiled by U.S. EPA Region III. Total number of readings = 39,869.

average indoor radon levels (fig. 7). The commercial data also show a distinct drop in the percentage of readings exceeding 4 pCi/L in the Blue Ridge and Piedmont (fig. 9). The Coastal Plain counties have moderate to low (< 2 pCi/L) indoor radon averages.

GEOLOGIC RADON POTENTIAL SUMMARY

For the purpose of this assessment, Virginia has been divided into eight geologic radon potential areas and each area assigned a Radon Index (RI) and a Confidence Index (CI) score (Table 2). These areas correspond to the areas delineated in figure 1. The RI is a relative measure of radon potential based on geologic, soil, radioactivity, architecture, and indoor radon data, as outlined in the preceding sections. The CI is a measure of the confidence of the RI assessment based on the quality and quantity of the data used to assess the geologic radon potential. Please refer to the introduction chapter of this regional book for a detailed discussion of the indexes.

As can be seen in Table 2, the radon potential of rocks and soils in Virginia is variable from low to high. In the following discussion, the factors for each ranking are briefly discussed and local variations within each province or subdivision are indicated. Indoor radon data are clearly lacking for parts of the Coastal Plain, southern Piedmont, and western Valley and Ridge and Appalachian Plateaus. Please note that the confidence index score for the indoor radon factor in these areas is low.

Coastal Plain

The Coastal Plain of Virginia is ranked low in geologic radon potential. Indoor radon levels are generally low; however, moderate to high indoor radon levels can occur locally and may be associated with phosphatic, glauconitic, and heavy mineral-bearing sediments. Equivalent uranium over the Tertiary units of the Coastal Plain is generally moderate. Soils developed on the Cretaceous and Tertiary units are slowly to moderately permeable. Studies of uranium and radon in soils indicate that the Yorktown Formation could be a source for elevated levels of indoor radon (Berquist and others, 1990). The Quaternary sediments generally have low eU associated with them. Heavy mineral deposits of monazite found locally within the Quaternary sediments of the Coastal Plain may have the potential for creating locally moderate to high indoor radon levels.

Piedmont

The Goochland terrane and Inner Piedmont have been ranked high in radon potential. The Carolina terrane has been ranked moderate in geologic radon potential. Rocks of the Goochland terrane and Inner Piedmont have numerous well-documented uranium and radon occurrences associated with granites; pegmatites; granitic gneiss; monazite-bearing metasedimentary schist and gneiss; graphitic and carbonaceous slate, phyllite, and schist; and shear zones. Indoor radon levels are generally moderate but significant very high radon levels occur in several areas. Equivalent uranium (fig. 6) over the Goochland terrane and Inner Piedmont is predominantly high to moderate with areas of high eU more numerous in the south. Permeability of soils developed over granitic igneous and metamorphic rocks of the Piedmont is generally moderate. Within the Goochland terrane and Inner Piedmont, local areas of low to moderate radon potential will probably be found over mafic rocks (such as gabbro and amphibolite), quartzite, and some quartzitic schists. Mafic rocks have generally low uranium concentrations and slow to moderate permeability in the soils they form. The Carolina terrane is variable in radon potential but is generally moderate. Metavolcanic rocks have low eU but the granites and granitic gneisses have moderate to locally high eU. Soils developed over the volcanic rocks are slowly to moderately permeable. Granite and gneiss soils have moderate permeability.

The Mesozoic basins have moderate to locally high geologic radon potential. It is not possible to make any general associations between county indoor radon averages and the individual Mesozoic basins because of the limited extent of many the basins. However, sandstones and siltstones of the Culpeper basin, which have been lightly metamorphosed and altered by diabase intrusion, are mineralized with uranium and cause documented moderate to high radon levels in northern Virginia (Otton and others, 1988). Lacustrine black shales and some of the coarse-grained gray sandstones also have significant uranium mineralization, often associated with green clay clasts and copper. Equivalent uranium (fig. 6) over the Mesozoic basins varies among the basins. The Danville basin has very high eU associated with it, whereas the other basins have generally moderate eU. This radioactivity may be related to extensive uranium mineralization along the Chatham fault on the west side of the Danville basin. Localized high eU also occurs over the western border fault of the Culpeper basin. Soils are generally slowly to moderately permeable over the sedimentary and intrusive rocks of the basins.

Valley and Ridge

The Valley and Ridge has been ranked high in geologic radon potential, with local areas having low to moderate radon potential. The Valley and Ridge is underlain by Cambrian dolomite, limestone, shale, and sandstone; Silurian-Ordovician limestone, dolomite, shale, and sandstone; and Mississippian-Devonian sandstone, shale, limestone, gypsum, and coal. Soils derived from carbonate rocks and black shales, and black shale bedrock may be sources of the moderate to high levels of indoor radon in this province. Equivalent uranium over the Valley and Ridge is generally low to moderate, with isolated high-radioactivity areas. Soil permeability is moderate to high. Studies of soil-gas and indoor radon over the carbonates and shales of the Great Valley in West Virginia and studies in Pennsylvania indicate that the rocks and soils of this province constitute a significant source of radon. Sandstones and red siltstones and shales probably have low to moderate radon potential. Some local uranium accumulations are contained in these rocks.

Appalachian Plateaus

The Appalachian Plateaus Province has been ranked moderate in geologic radon potential. The plateaus are underlain by Pennsylvanian sandstone, shale, and coal. Black shales, especially those associated with coal seams, are generally elevated in uranium and may be sources of moderate to high radon levels. The coals themselves may also be locally elevated in uranium. The sandstones are generally low to moderate in radon potential but have higher soil permeability than the black shales. Equivalent uranium (fig. 6) of the province is low to moderate, and indoor radon is variable from low to high, but indoor radon data are limited in number.

This is a generalized assessment of the State's geologic radon potential and there is no substitute for having a home tested. The conclusions about radon potential presented in this report cannot be applied to individual homes or building sites. Indoor radon levels, both high and low, can be quite localized, and within any radon potential area there will likely be areas with higher or lower radon potential than assigned to the area as a whole. Any local decisions about radon should not be made without consulting all available local data. For additional information on radon and how to test, contact your State radon program or EPA regional office. More detailed information on state or local geology may be obtained from the state geological survey. Addresses and phone numbers for these agencies are listed in chapter 1 of this booklet.

TABLE 2. RI and CI scores for geologic radon potential areas of Virginia. See figure 1 for locations of areas.

FACTOR	Appalachian Plateau RI	Appalachian Plateau CI	Valley and Ridge RI	Valley and Ridge CI	Blue Ridge/ Carolina Terrane RI	Blue Ridge/ Carolina Terrane CI
INDOOR RADON	2	1	3	2	2	2
RADIOACTIVITY	2	3	3	3	2	2
GEOLOGY	2	2	3	3	2	2
SOIL PERM.	2	3	2	3	2	3
ARCHITECTURE	2	-	2	-	2	-
GFE POINTS	0	-	2	-	0	-
TOTAL	10	9	15	11	10	9
	Mod	Mod	High	High	Mod	Mod

FACTOR	Mesozoic Basins RI	Mesozoic Basins CI	Goochland Terrane RI	Goochland Terrane CI	Inner Piedmont RI	Inner Piedmont CI
INDOOR RADON	2	1	2	1	2	2
RADIOACTIVITY	2	2	3	2	3	2
GEOLOGY	2	3	2	3	3	3
SOIL PERM.	2	3	2	3	2	3
ARCHITECTURE	2	-	2	-	2	-
GFE POINTS	1	-	2	-	0	-
TOTAL	11	9	13	9	12	10
	Mod	Mod	High	Mod	High	High

FACTOR	Cretaceous and Tertiary Coastal Plain RI	Cretaceous and Tertiary Coastal Plain CI	Quaternary Coastal Plain RI	Quaternary Coastal Plain CI
INDOOR RADON	1	1	1	1
RADIOACTIVITY	2	2	1	2
GEOLOGY	2	3	1	3
SOIL PERM.	2	3	2	3
ARCHITECTURE	1	-	1	-
GFE POINTS	0	-	0	-
TOTAL	8	9	6	9
	Low	Mod	Low	Mod

RADON INDEX SCORING:

Radon potential category	Point range	Probable screening indoor radon average for area
LOW	3-8 points	< 2 pCi/L
MODERATE/VARIABLE	9-11 points	2 - 4 pCi/L
HIGH	> 11 points	> 4 pCi/L

Possible range of points = 3 to 17

CONFIDENCE INDEX SCORING:

LOW CONFIDENCE	4 - 6 points
MODERATE CONFIDENCE	7 - 9 points
HIGH CONFIDENCE	10 - 12 points

Possible range of points = 4 to 12

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PRELIMINARY GEOLOGIC RADON POTENTIAL ASSESSMENT OF WEST VIRGINIA

by
James K. Otton and Linda C.S. Gundersen
U.S. Geological Survey

INTRODUCTION

This assessment of the radon potential of West Virginia is derived from geologic information from publications of the West Virginia Geological Survey (especially Cardwell and others, 1968), from publications of the U.S. Geological Survey, and from literature on the geologic occurrence of radon. For a brief synopsis of the concepts and methodology used in this report, please refer to the introductory chapter of this volume. Analyses of data gathered during a radon survey in the winter of 1987-1988 by U.S. EPA and the West Virginia Department of Health, and additional indoor radon data compiled from this study and vendor data by EPA Region 3 (Noble and others, 1990) are included in this report. The National Atlas of the United States of America provided much information on the geographic setting. Soil descriptions are developed from a map of West Virginia soils by the Soil Conservation Service (1979).

This is a generalized assessment of geologic radon potential of rocks, soils, and surficial deposits of West Virginia. The scale of this assessment is such that it is inappropriate for use in identifying the radon potential of small areas such as neighborhoods, individual building sites, or housing tracts. Any localized assessment of radon potential must be supplemented with additional data and information from the locality. Within any area of a given radon potential ranking, there are likely to be areas with higher or lower radon levels than characterized for the area as a whole. Indoor radon levels, both high and low, can be quite localized, and there is no substitute for testing individual homes. Elevated levels of indoor radon have been found in every state, and EPA recommends that all homes be tested. For more information on radon, the reader is urged to consult the local or State radon program or EPA regional office. More detailed information on state or local geology may be obtained from the State geological survey. Addresses and phone numbers for these agencies are listed in chapter 1 of this booklet.

GEOGRAPHIC SETTING

Five physiographic regions are delineated in West Virginia: the Central Allegheny Plateau, the Cumberland Plateau and Mountains, the Eastern Allegheny Plateau and Mountains, the Southern Appalachian Ridge and Valley, and the Northern Appalachian Ridge and Valley (fig. 1).

The Central Allegheny Plateau makes up the northwestern third of the State. It consists of a dissected plateau that slopes downward to the Ohio River. Greater than 80 percent of the area is steeply sloping (greater than 25 percent) with relief ranging from 300-1000 feet.

The Cumberland Plateau and Mountains forms the southwestern part of the State. This area is deeply dissected with steep slopes and narrow ridgetops. Greater than 80 percent of the area is steeply sloping. Relief usually exceeds 1000 feet.

The Eastern Allegheny Plateau and Mountains is a high plateau that is locally deeply dissected to form mountainous areas. In the plateau areas gentle slopes (less than 10 percent) occur but most of the area has steep slopes and relief that usually exceeds 1000 feet.

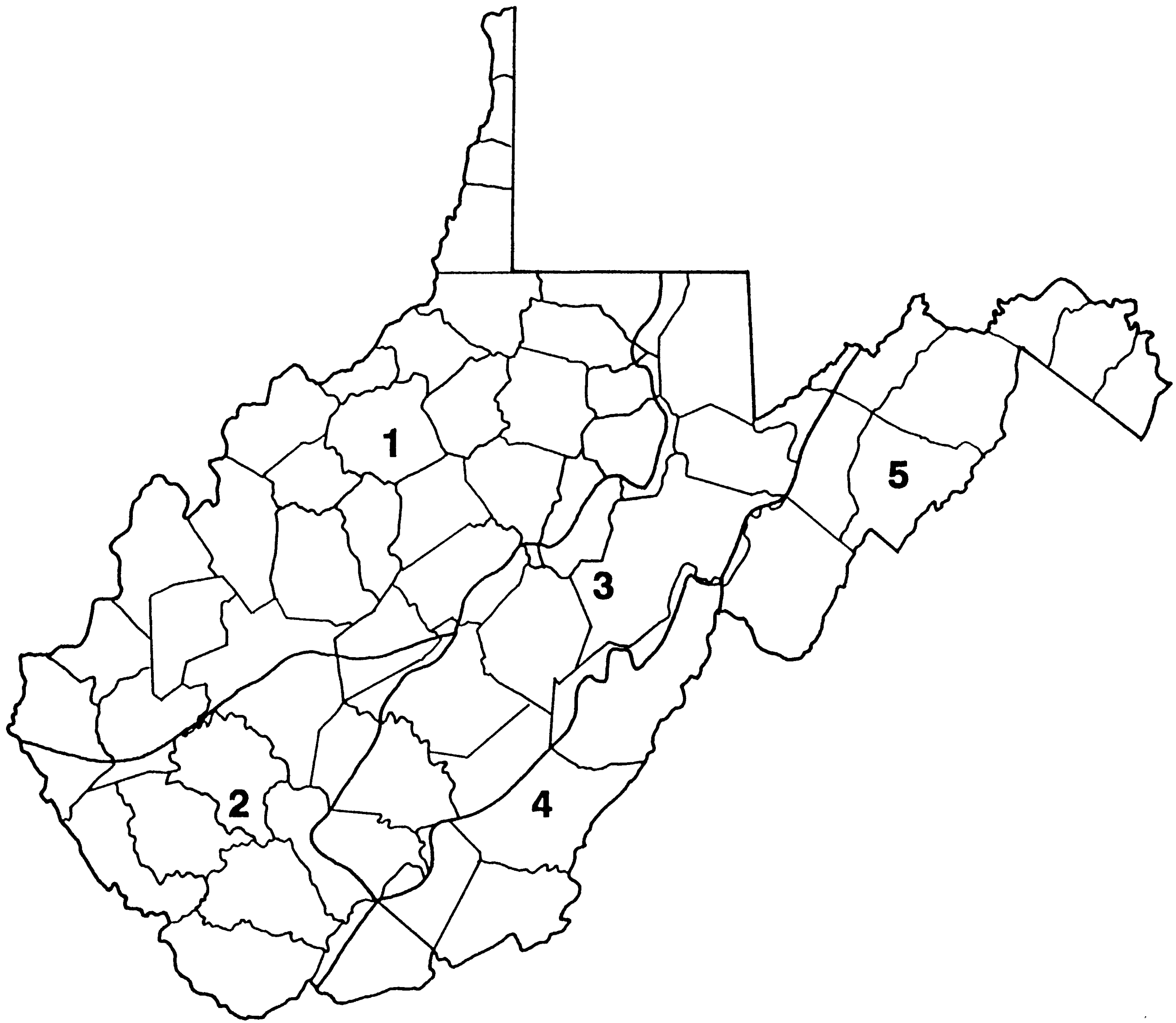


Fig. 1- Physiographic regions of West Virginia. After Soil Conservation Service (1979). 1- Central Allegheny Plateau; 2- Cumberland Plateau and Mountains; 3- Eastern Allegheny Plateau and Mountains; 4- Southern Appalachian Ridge and Valley; and 5- Northern Appalachian Ridge and Valley.

The Southern and Northern Appalachian Ridge and Valley are characterized by northeast-trending ridges and valleys with relief exceeding 1000 feet. Gently sloping areas are generally confined to the valleys.

Precipitation ranges from 35-40 inches in the Appalachian Ridge and Valley areas, 45-60 inches in the Eastern Allegheny Plateau and Mountains Province, and about 45 inches in the remainder of the State (fig. 2).

Population distribution (fig. 3) and land use in West Virginia reflect in part the geology, topography, and climate of the State. In 1990 the population of West Virginia was 1,793,477, including 36 percent urban population. The average population density is approximately 77 per square mile. The climate is humid continental except for marine modification in the eastern panhandle. West Virginia has distinct seasonal changes. The mean annual temperature ranges from 52°F to 56°F.

GEOLOGIC SETTING

The Central Allegheny Plateau is underlain by generally flat-lying shale, siltstone, sandstone, and some limestone of Permian and Pennsylvanian age (fig. 4). The area is deeply dissected. Steep slopes are common and much of the area is covered by colluvium and landslides. Areas of open mine cuts and spoil piles occur in Harrison, Barbour, Monongalia, Marion, Taylor and other counties in the eastern part of this province.

The Cumberland Plateau and Mountains is covered by sandstone, siltstone, shale and coal of Pennsylvanian age. Extensive underground and surface mining of coal has occurred in this province. The area is deeply dissected, steep slopes are common, and much of the area is covered by colluvium and landslides. Areas of open mine cuts and spoil piles occur throughout this province.

The Eastern Allegheny Plateau and Mountains is underlain by shale, siltstone, sandstone, and some limestone of Pennsylvanian, Mississippian, and Devonian age. Underground and surface mining of coal occurs in a few areas. Colluvium derived from shale, siltstone and sandstone predominates throughout this province. Landslide areas occur in the southwestern half of this province. Areas of open mine cuts and spoil piles also occur in the southwestern half of this province. Some areas of karst occur in the limestones that underlie this province (fig. 5).

The Southern Appalachian Ridge and Valley is underlain by shale, siltstone, limestone, and sandstone of Mississippian, Devonian, Silurian, and Ordovician age. These rocks have been folded and locally cut by thrust faults. Colluvium dominates the surficial materials. Karst topography and associated caverns are common in areas underlain by limestone (fig. 5). Land subsidence caused by historical collapse of solution features has occurred in Greenbrier County (See figure 6 for location of counties discussed in this report.).

The Northern Appalachian Ridge and Valley consists of parallel sandstone ridges separated by narrow to locally broad valleys underlain by shale and limestone. Most of these rocks are Devonian in age but Mississippian, Silurian, Ordovician, and Cambrian rocks also occur. The Great Valley, a broad valley underlain mostly by limestone and shale, occupies much of Berkeley and Jefferson Counties. Metamorphosed basalts in the Catoctin Formation occur along the southeastern edge of Jefferson County. Colluvium dominates most surficial materials except in the broad limestone valleys of Berkeley and Jefferson Counties where deep residuum has formed. Karst topography and associated caverns occur in areas underlain by limestone.

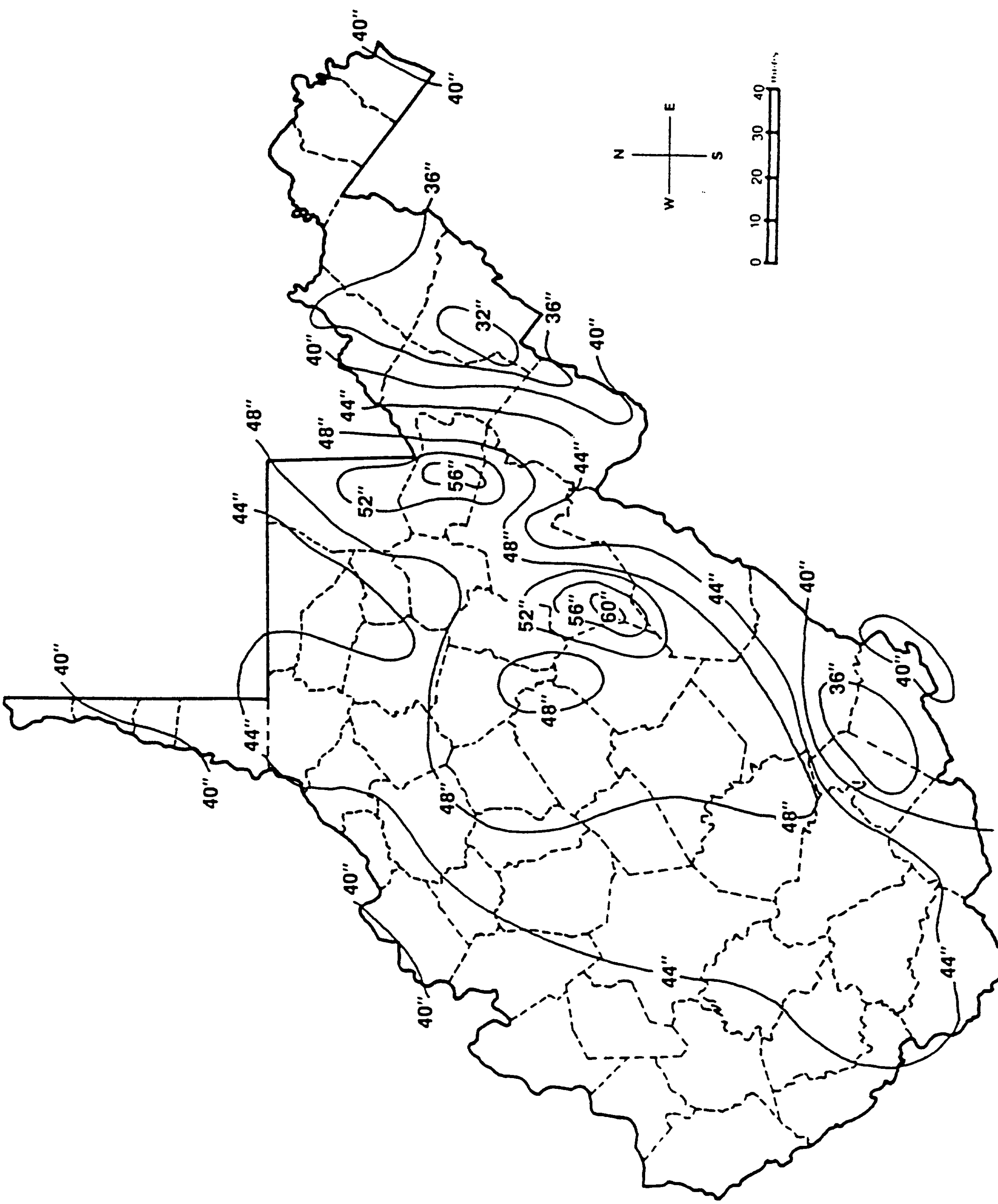


Fig. 2- Map showing average annual precipitation in West Virginia. From Facts on File, Inc., 1984.

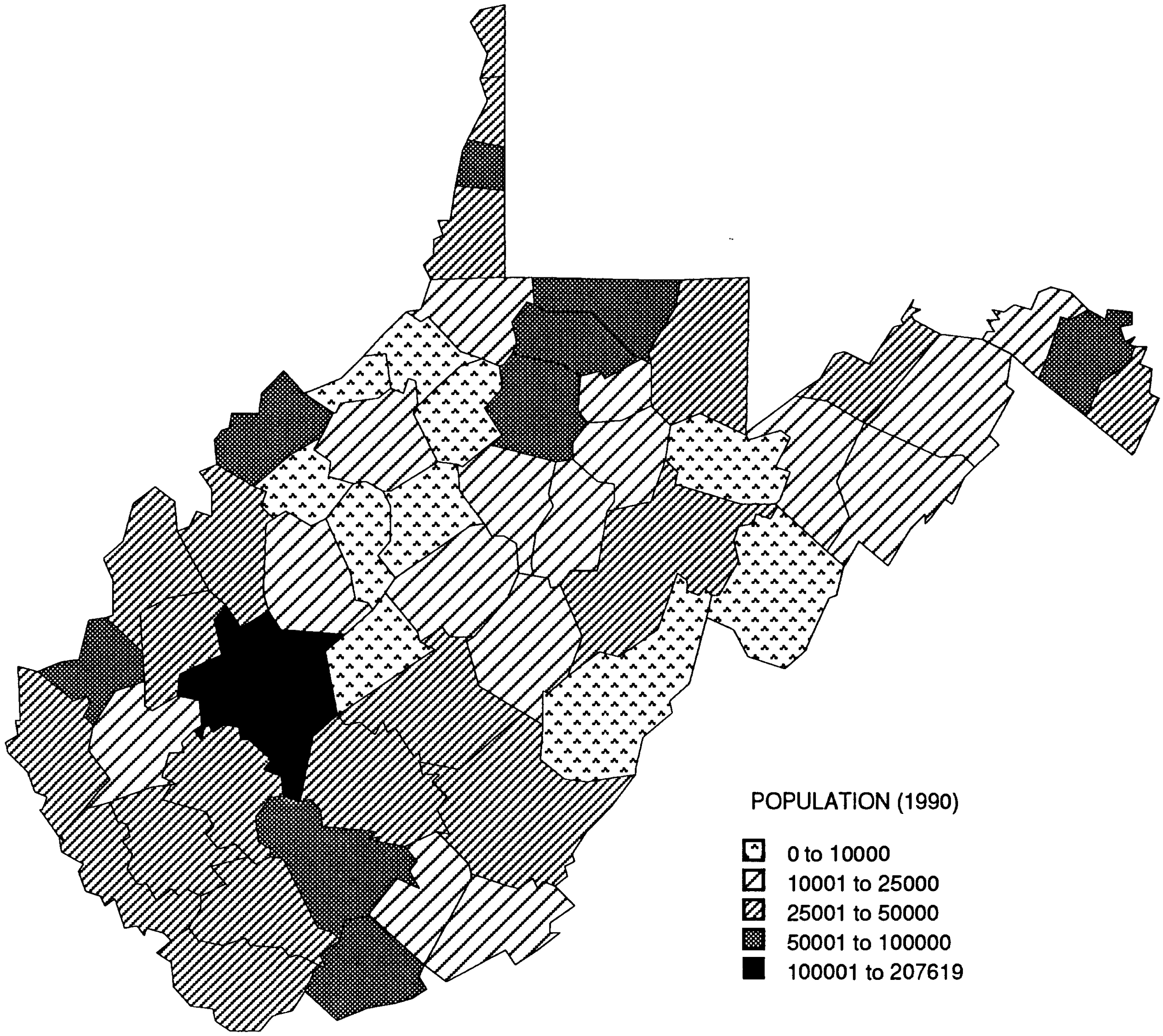


Figure 3. Population of counties in West Virginia (1990 U.S. Census data).

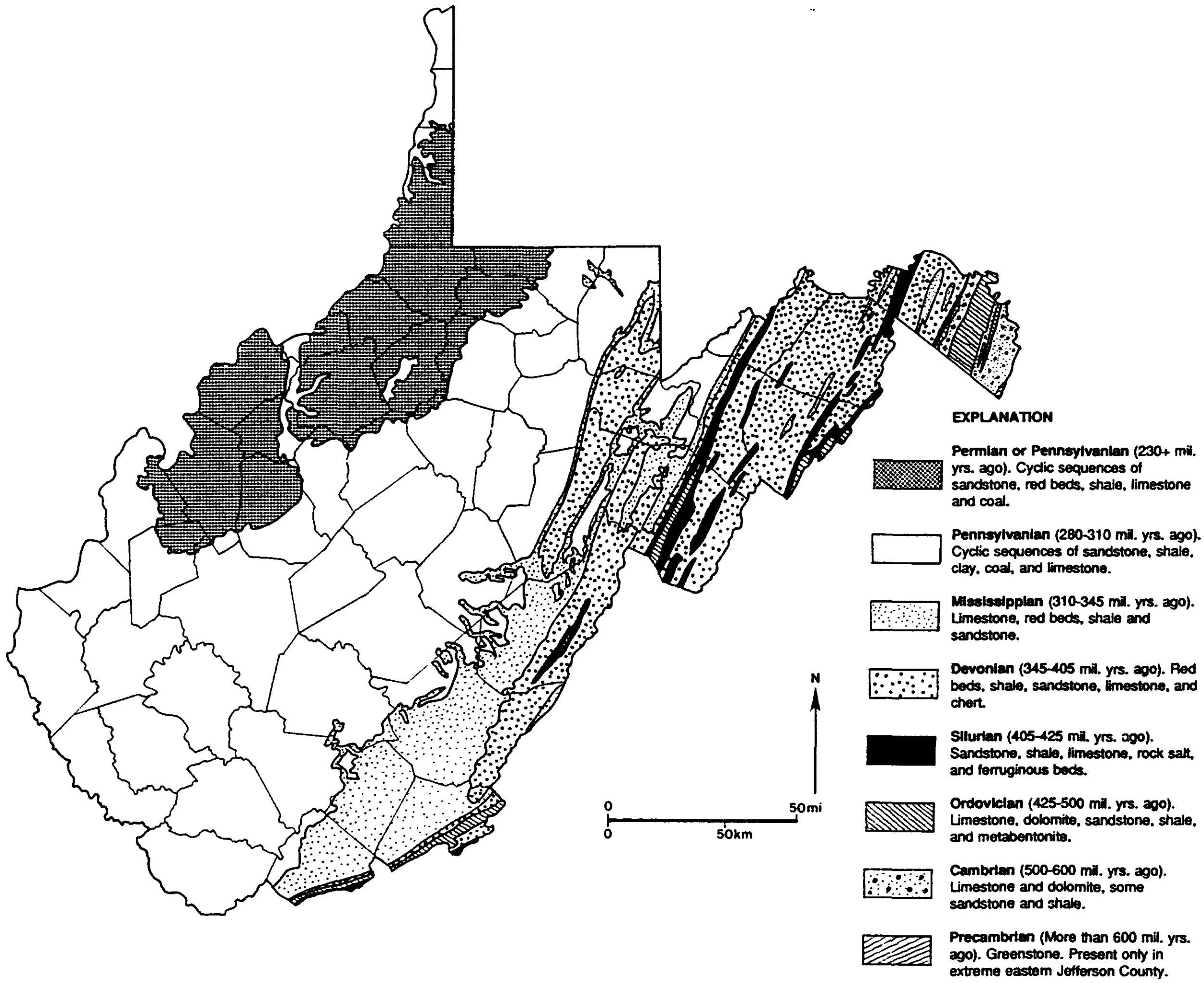


Fig. 4- Generalized bedrock geologic map of West Virginia. From Erwin, 1969.

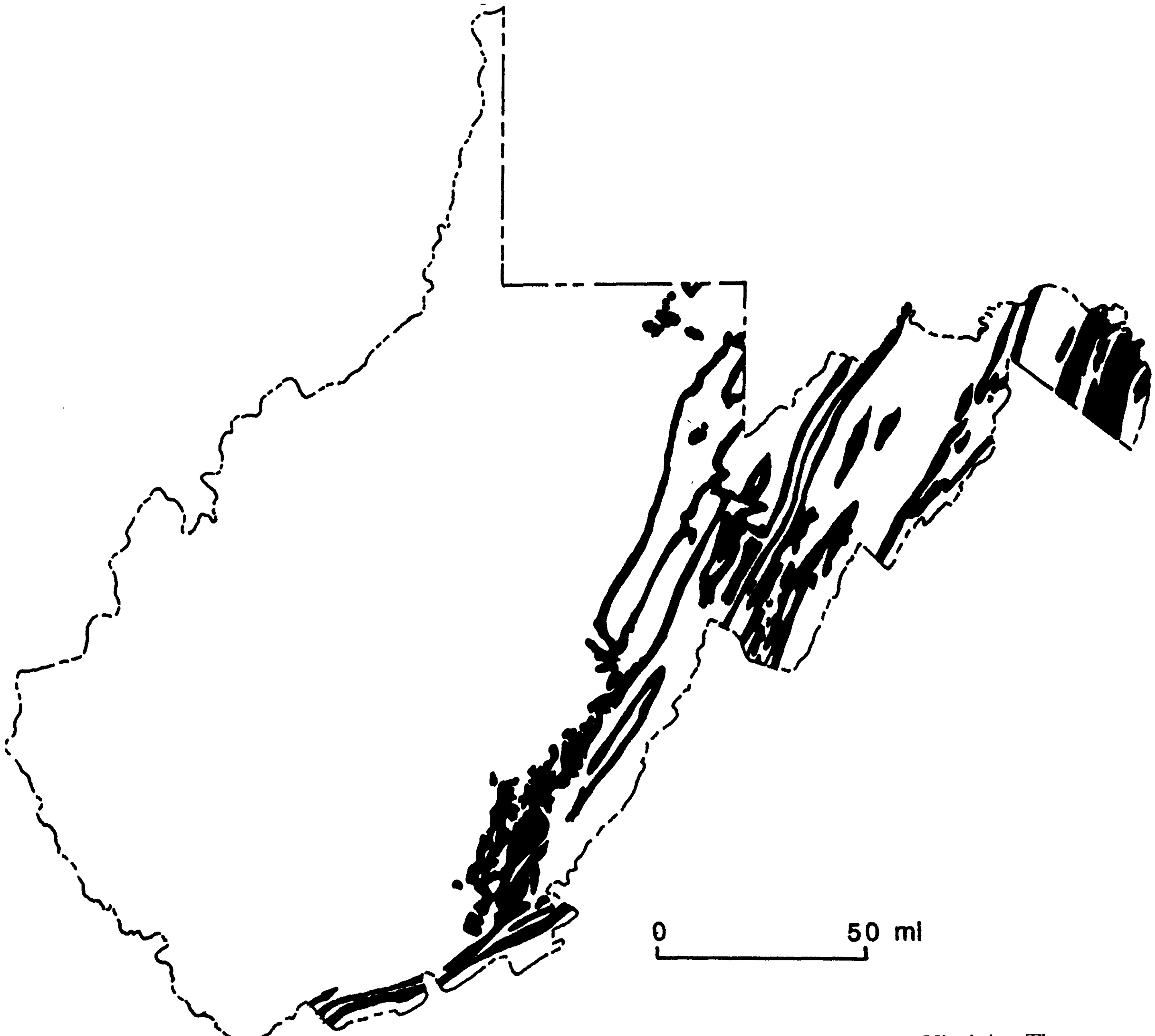


Fig. 5- Map showing the major outcrop areas of Cambrian through Mississippian limestone in West Virginia. These are areas that may contain karst and/or thick residual soils enriched in uranium and radium. The most important area of karst occurs in Greenbrier County (see Fig.6 for location) where historical collapse of solution features has occurred. Modified from West Virginia Geological and Economic Survey (1979).

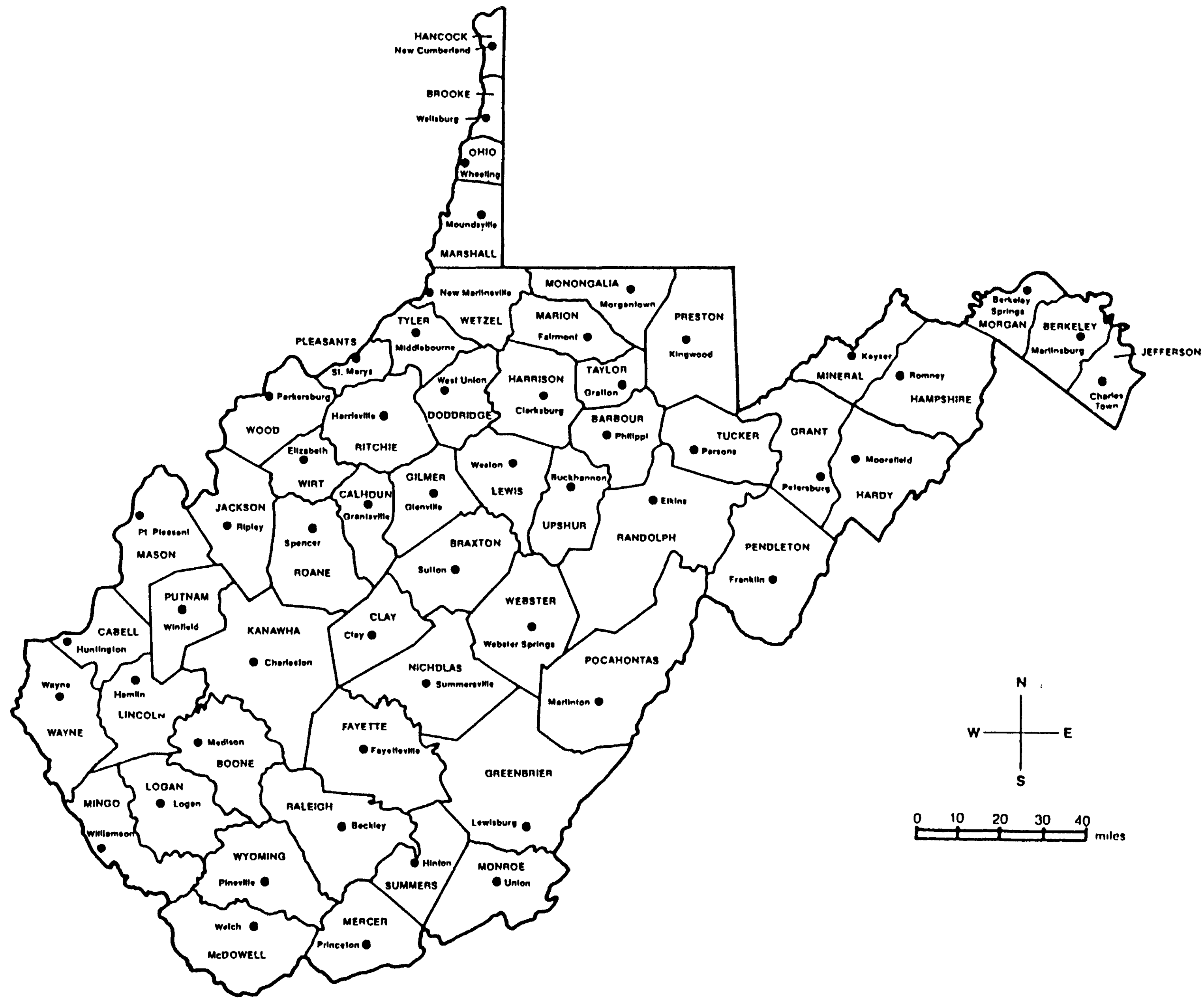


Fig. 6- Map showing counties in West Virginia. From Facts on File, Inc., 1984.

An aeroradioactivity map of the State (Duval and others, 1989) shows that the Central Allegheny Plateau generally ranges from 1.5-3.0 ppm eU with the entire province averaging between 2.0 and 2.5 ppm eU (fig. 7). Much of western Mason County and parts of Hancock, Brooke, and Ohio Counties ranges from 2.5-3.0 ppm eU. The Cumberland Plateau and Mountains and the Eastern Allegheny Plateau and Mountains ranges from 0.5 to 2.5 ppm eU with the two regions averaging between 1.0 and 1.5 ppm eU. Some areas of somewhat elevated eU in these areas may reflect the increased values associated with shale-rich coal mine wastes. The two Appalachian Ridge and Valley provinces range from 0.5 to 3.5 ppm eU and average between 2.0 and 2.5 ppm eU. Elevated eU values (2.5-3.5 ppm) in the Ridge and Valley areas are associated with residual soils developed on Mississippian shale and limestone in Pocohontas, Greenbrier, and Monroe Counties (Greenbrier Group); with Devonian shale and limestone in Mineral, Hampshire, Grant, and Hardy Counties; and with Cambrian, Ordovician and Mississippian limestones in Morgan, Jefferson, and Berkeley Counties.

A few, isolated uranium (U) occurrences and radioactive anomalies were found in West Virginia during uranium exploration in the 1970s (Jacob, 1975). A sample from an outcrop of the Mississippian Mauch Chunk sandstone in Webster Springs, Webster County, West Virginia, yielded 400 ppm U. Radioactivity anomalies (maximum of 45 times background) occur in sandstones of the Mississippian Pocono Formation near Marlinton in Pocohontas County. A sample from one locality contained 160 ppm U and 1100 ppm thorium (Th). These anomalies are probably related to heavy mineral concentrations in the sandstone. Just east of Parkersburg, Wood County, uranium occurs in sandstone of the Permian Dunkard Group. Samples of sandstone containing fossil plant debris yielded 50-90 ppm U (Jacob, 1975).

Ordovician, Silurian, and Devonian dark gray to black shales occur in narrow outcrop belts in all counties expect Jefferson County in the Northern Appalachian Ridge and Valley; in Pocohontas, Greenbrier, and Monroe Counties in the Southern Appalachian Ridge and Valley; and in Randolph County in the Eastern Allegheny Plateau and Mountains (fig. 8). These shales are relatively high in uranium content (> 2.5 ppm U) and locally generate radon in soil gas exceeding 4000 pCi/L (Schultz and others, 1992). Soil-gas radon values exceeding 2000 pCi/L generally result in indoor values exceeding 4 pCi/L. Dark gray to black shales in West Virginia include or occur in the Ordovician Martinsburg Formation, Silurian Rochester Shale (Clinton Group), the Devonian Needmore Shale (Onesquethaw Group), the Devonian Marcellus Formation, the Devonian Harrell Shale, and the Devonian Brallier Formation. The uraniferous Marcellus Shale and underlying limestones in Onandaga County, New York, are a source of significant elevated indoor radon (Hand, 1988) and also generate high radon in West Virginia. Evidence suggests that uranium from the Marcellus has moved downward during weathering into the underlying limestones, thus both the black shale and the subjacent limestones are a source of radon indoors. Uranium from uraniferous shales in West Virginia may also be redistributed by weathering to other units.

SOILS

Most soils throughout West Virginia are poorly developed because weathered sedimentary rock on the moderate to steep slopes across the State tends to continually move downhill under the influence of gravity, forming colluvium. Slightly weathered soils generally tend to have uranium and radium contained within the structure of the rock and mineral fragments, where radon formed from radium decay has less of an opportunity to escape to soil pores. Deep, residual soils occur in

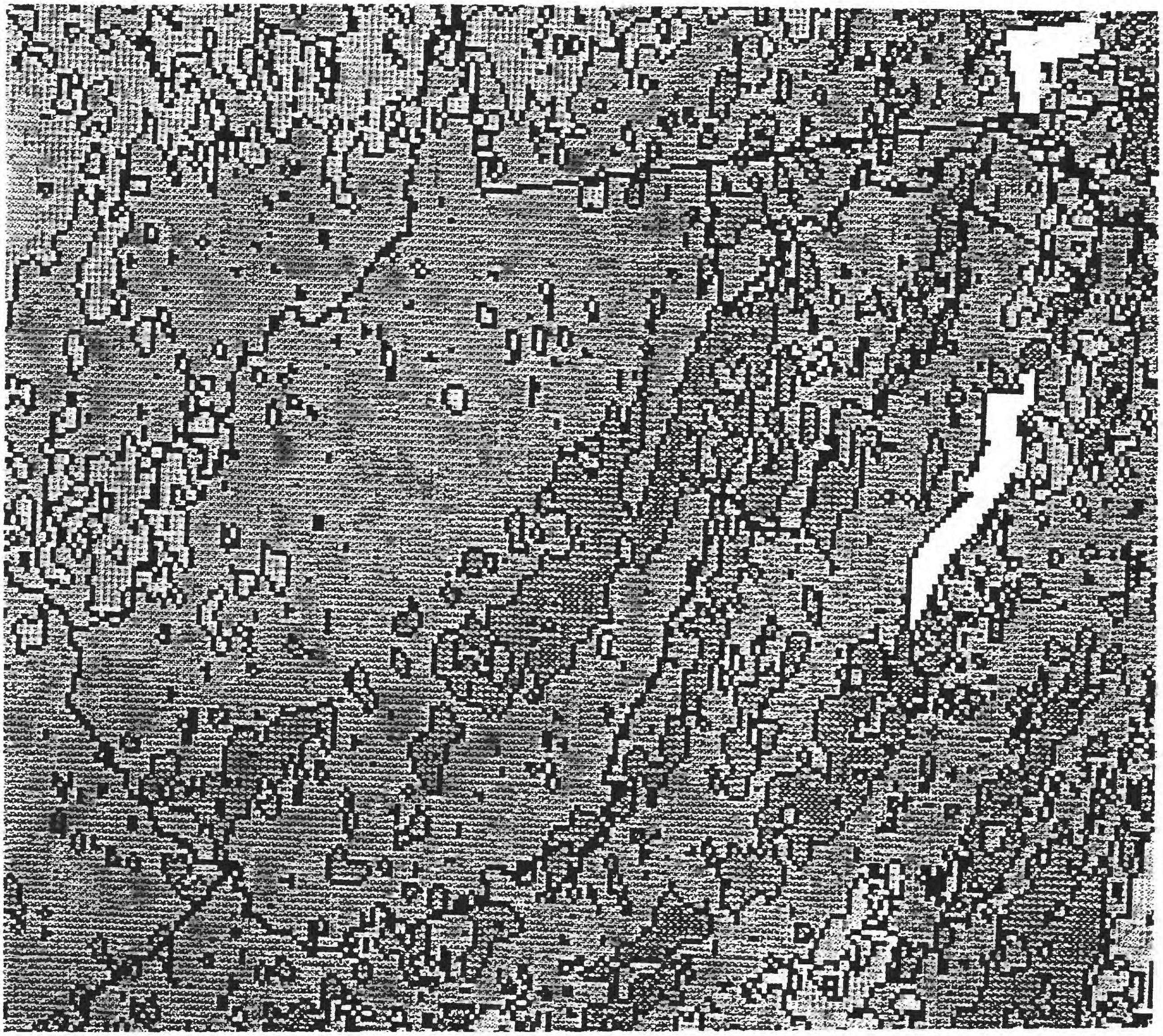


Fig. 7- Aeroradiometric map of West Virginia and nearby areas. Patterns increase in ppm eU by 0.5 ppm increments. Contours are drawn at the 1.5 ppm and 2.5 pm eU boundaries. Maximum values in this map area are 3.0-3.5 ppm eU. Map from Duval and others (1989).

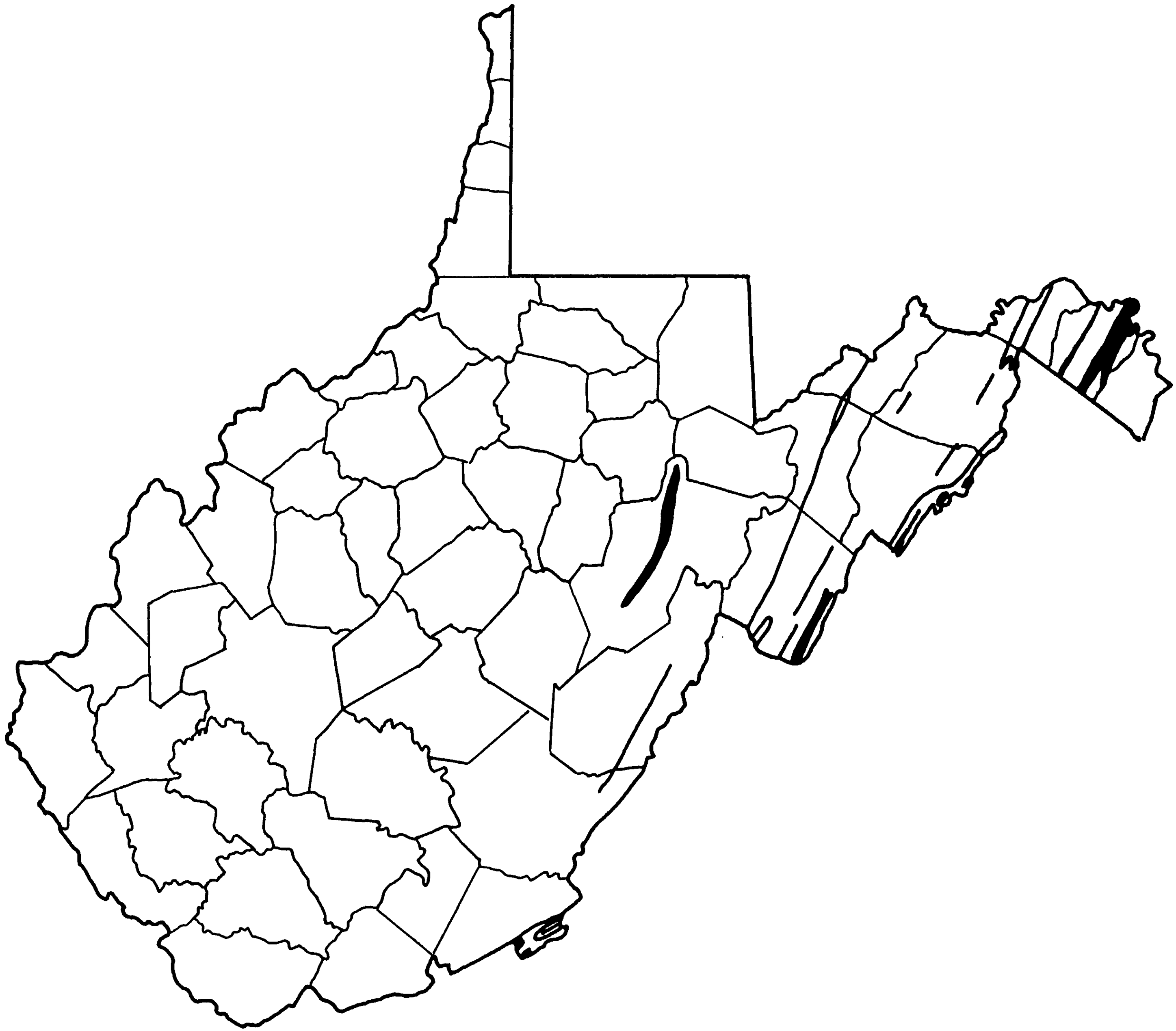


Fig. 8- Map showing the approximate location of outcrop belts of sedimentary rocks containing dark gray to black shales in West Virginia. For more precise location information and generalized descriptions of these uraniferous shale-bearing units see Cardwell and others, 1968.

the broader, gently sloped valleys of Berkeley and Jefferson Counties in the Northern Appalachian Ridge and Valley. Lesser areas of deep, residual soils developed on limestone occur in the Southern Appalachian Ridge and Valley. In deep residual soils, uranium and radium have commonly been released from the mineral grains of the original rock and now are found on the surfaces of soil grains. Radon more readily escapes from these mineral grains to soil pores than in cases in which the radium is mostly contained deeper within mineral fragments.

Except for the highest parts of the Eastern Allegheny Plateau and Mountains, all of West Virginia lies within the mesic udic soil moisture-temperature regime. The high areas in the central Allegheny Mountains lie within the frigid udic soil moisture-temperature regime (note: Frigid soils have 0-8°C mean annual soil temperatures whereas mesic soils have 8-15°C mean annual soil temperatures). Both frigid udic and mesic udic soils are very moist (56-96 percent pore saturation in sandy loams, and 74-99 percent saturation in a silty clay loam) in the winter and are moderately moist (44-56 percent saturation in sandy loams, and 58-74 percent in a silty clay loam) in the summer (Rose and others, 1991). In places where soils are generally moderately moist to very moist, soil moisture will tend to inhibit radon migration by diffusion and flow. However, steeply sloped soils, in which water drains rapidly from the soil profile, are common in West Virginia. In these soils, radon may migrate more readily and the radon potential of these steeply sloped areas is increased.

The Central Allegheny Plateau soils are typically sandy to clayey loams, usually with abundant sandstone fragments and shale chips. Most soils are on moderately steep to very steep slopes. Soils are generally acid, thin, and many soils in the central and southwestern part of the province contain swelling clays (i.e., form shrink-swell soils). The more clayey soils have low permeability and are often wet.

Soils of the Cumberland Plateau and Mountains are typically sandy to clayey loams usually with abundant sandstone fragments and shale chips. All soils are on moderately steep to very steep slopes. Soils are thin and commonly stony. Soils on valley floors are subject to frequent flooding.

Soils of the Eastern Allegheny Plateau and Mountains include sandy to clayey loams usually with abundant sandstone fragments and shale chips. Soils are usually thin, and many are stony. Clayey loams have low permeability and are often wet where slopes are gentle. Soils on valley floors are subject to frequent flooding.

In the Southern Appalachian Ridge and Valley, sandy to clayey loams and rock outcrops occur on ridges. These soils are typically thin and are often stony. The valleys are characterized by silty clay loams with abundant chips of noncalcareous shale and sandstone with smaller areas of silty clay loams containing chips of calcareous shale and limestone. Some deep, red clayey soils developed from limestone also occur. Many soils on gentle slopes are wet and have low permeability.

The Northern Appalachian Ridge and Valley soils are variable. Sandy to clayey loams and rock outcrops occur on ridges. These soils are typically thin and are often stony. Some thin sandy soils have formed on ridge tops. Soils in the valleys are characterized by silty clay loams with abundant chips of noncalcareous shale and sandstone, with smaller areas of silty clay loams containing chips of calcareous shale and limestone. Deep, red clayey soils developed from limestone occur in the valleys of Berkeley and Jefferson Counties. Soils on stream bottoms are subject to frequent flooding.

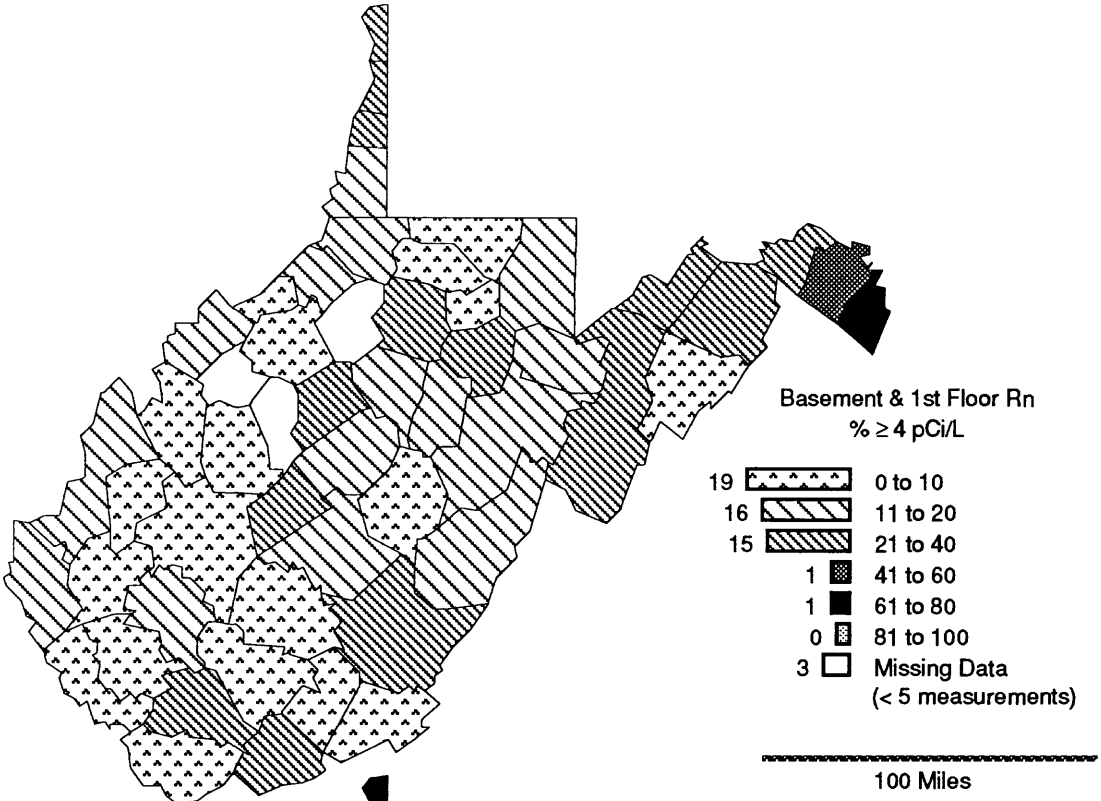
INDOOR RADON DATA

The West Virginia Department of Health and the U.S. EPA conducted a population-based survey of indoor radon levels in 1006 homes in West Virginia during the winter of 1987-88 (Table 1; fig. 9). In figure 9, data are shown only for those counties with 5 or more data values. Geologic interpretations of population-based data must be made with caution because the measured houses are typically only from a relatively few population centers in a given county and the distribution of these houses do not reflect the variation in geology in the county. For example, a county may have a relatively high radon potential on well-drained, uraniferous soils on hillslopes that occur over a widespread area, but if housing is generally located on poorly-drained soils with low uranium contents situated on the valley floor, a population-based survey for that area will contain relatively low indoor radon values.

The maximum value recorded in the State/EPA Residential Radon Survey was 82.1 pCi/L in Greenbrier County (Table 1). Counties with indoor radon averages exceeding 4 pCi/L include Berkeley, Hampshire, Jefferson, Morgan, and Pendleton in the Northern Appalachian Ridge and Valley, Greenbrier in the Southern Appalachian Ridge and Valley, Tucker in the Eastern Allegheny Plateau and Mountains, and Brooke and Hancock in the northernmost part of the Central Allegheny Plateau (Table 1).

A summary of 6799 readings has been compiled by U.S. EPA Region 3 (Noble and others, 1990) by county and zipcode for West Virginia. Although these data are in part from nonrandom sources that are subject to sampling biases, the number of values in the dataset and the coverage of the urban centers and rural areas of the State is extensive. A detailed analysis of this dataset is beyond the scope of this report; however, these data confirm many of the observations in the population-based study. Values exceeding 100 pCi/L occur in Jefferson, Berkeley, Greenbrier, Marion, and Marshall Counties. Counties in which more than 10 percent of the homes tested had indoor radon levels of 20 pCi/L or more include Jefferson, Berkeley, Morgan and Hampshire in the Northern Appalachian Ridge and Valley, Greenbrier in the Southern Appalachian Ridge and Valley, and Barbour, at the eastern edge of the Central Allegheny Plateau.

Table 2 shows data from the State/EPA study and the study by Noble and others (1990) for counties, combined and summarized by geologic province. Note that the percentages of indoor radon values greater than 4 pCi/L reported by Noble and others (1990) are systematically higher than those of the State/EPA survey. Values in indoor radon datasets compiled from volunteer data (data reported by homeowners or radon measuring companies to officials) are typically higher than controlled surveys because once a high value is reported in an area or neighborhood, nearby residences are commonly tested at a higher rate than would be if random testing was employed. These residences are often high for the same geologic, construction, or other reasons that the first reported value was high, so the data set would become biased toward higher indoor radon values. Note that the percentages are much higher for the Southern Appalachian Ridge and Valley in the Noble study than in the State/EPA study. This reflects a higher proportion of homes from Greenbrier County in the Noble study than in the State/EPA study. The geology of Greenbrier County favors significantly elevated indoor radon.



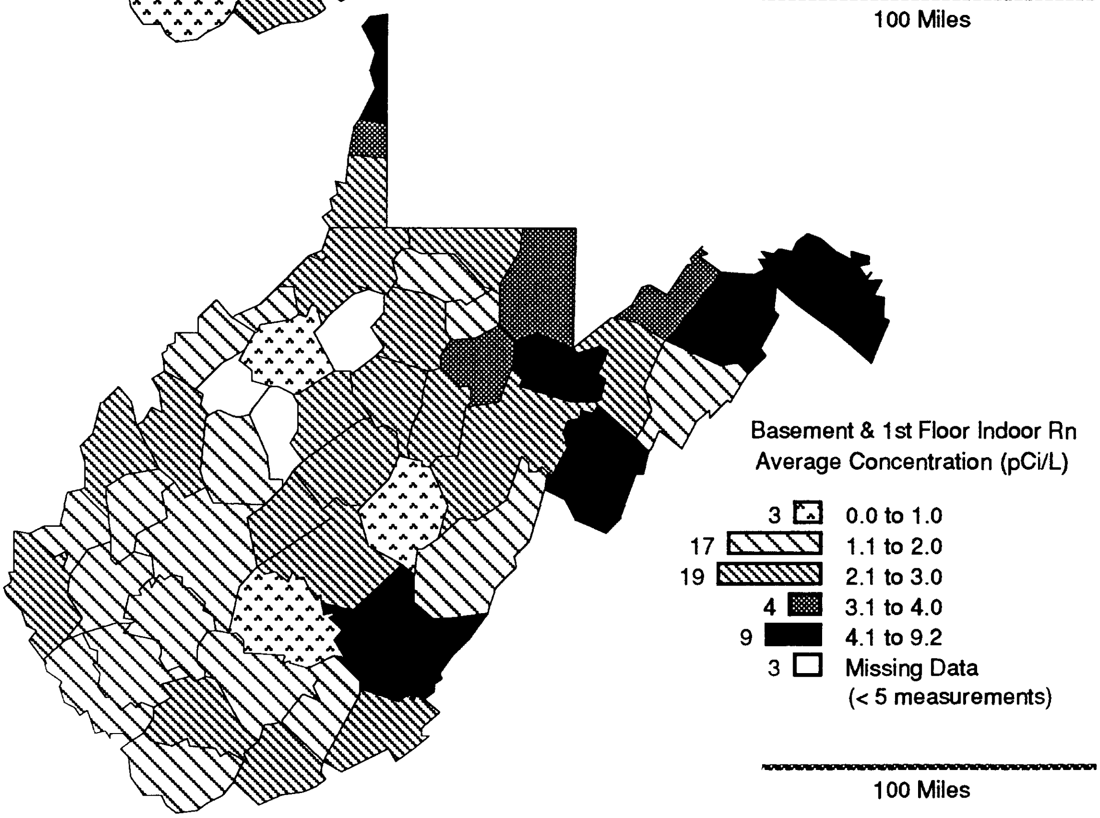


Figure 9. Screening indoor radon data from the EPA/State Residential radon Survey of West Virginia, 1988-89, for counties with 5 or more measurements. Data are from 2-7 day charcoal canister tests. Histograms in map legends show the number of counties in each category. The number of samples in each county (see Table 1) may not be sufficient to statistically characterize the radon levels of the counties, but they do suggest general trends. Unequal category intervals were chosen to provide reference to decision and action levels.

TABLE 1. Screening indoor radon data from the State/EPA Residential Radon Survey of West Virginia conducted during 1989-90. Data represent 2-7 day charcoal canister measurements from the lowest level of each home tested.

COUNTY	NO. OF MEAS.	MEAN	GEOM. MEAN	MEDIAN	STD. DEV.	MAXIMUM	%>4 pCi/L	%>20 pCi/L
BARBOUR	21	3.6	2.3	1.9	4.2	15.3	24	0
BERKELEY	19	7.3	4.0	3.6	9.6	41.8	47	5
BOONE	15	1.8	0.7	0.8	2.9	11.0	13	0
BRAXTON	15	2.3	1.7	1.8	1.9	7.3	13	0
BROOKE	25	5.5	3.5	3.7	6.0	25.0	40	4
CABELL	43	1.6	1.1	1.0	1.6	6.7	12	0
CALHOUN	3	0.9	0.8	0.8	0.6	1.5	0	0
CLAY	7	2.8	1.9	1.3	2.7	8.0	29	0
FAYETTE	24	1.0	0.7	0.7	0.8	3.3	0	0
GILMER	8	2.3	1.2	1.1	2.4	7.0	25	0
GRANT	10	2.9	1.5	1.6	2.9	8.7	30	0
GREENBRIER	18	8.2	2.4	2.2	19.1	82.1	33	11
HAMPSHIRE	12	5.7	3.8	3.7	7.8	29.9	33	8
HANCOCK	34	4.4	2.6	3.0	4.7	20.8	38	3
HARDY	9	1.3	1.0	1.0	0.7	2.4	0	0
HARRISON	37	2.4	1.2	1.4	3.0	14.6	22	0
JACKSON	11	2.1	1.9	2.1	1.1	4.6	9	0
JEFFERSON	13	9.2	5.9	7.2	8.2	27.4	69	8
KANAWHA	108	1.9	1.3	1.3	1.9	13.5	8	0
LEWIS	15	2.2	1.3	1.4	2.2	8.2	13	0
LINCOLN	11	1.5	1.1	0.9	1.4	5.4	9	0
LOGAN	16	1.2	0.9	0.8	0.9	3.5	0	0
MARION	36	1.7	1.3	1.3	1.2	4.8	6	0
MARSHALL	18	3.0	1.9	1.8	3.6	13.9	17	0
MASON	7	2.5	1.6	2.0	2.4	7.3	14	0
MCDOWELL	8	1.1	0.9	1.3	0.5	1.5	0	0
MERCER	20	2.8	1.7	1.5	3.0	12.7	30	0
MINERAL	15	3.5	2.4	2.0	3.2	12.0	33	0
MINGO	10	1.3	1.0	1.1	0.8	3.0	0	0
MONONGALIA	20	2.4	1.2	1.5	4.3	20.4	5	5
MONROE	20	2.1	1.4	1.8	1.9	7.0	10	0
MORGAN	13	4.7	2.7	2.8	6.1	22.9	38	8
NICHOLAS	16	2.3	1.6	1.9	2.0	6.9	19	0
OHIO	47	3.4	2.1	1.9	3.6	14.1	26	0
PENDLETON	8	5.2	2.6	3.4	6.2	19.7	38	0
PLEASANTS	6	1.4	0.9	0.9	1.2	3.4	0	0
POCAHONTAS	18	1.8	1.0	1.3	1.8	7.2	11	0
PRESTON	31	3.1	1.7	1.5	3.9	15.8	16	0
PUTNAM	20	1.5	0.8	0.9	1.8	6.7	10	0
RALEIGH	38	1.5	1.0	1.1	1.5	6.8	8	0
RANDOLPH	25	2.4	1.4	2.1	2.4	9.9	12	0

TABLE 1 (continued). Screening indoor radon data for West Virginia.

COUNTY	NO. OF MEAS.	MEAN	GEOM. MEAN	MEDIAN	STD. DEV.	MAXIMUM	%>4 pCi/L	%>20 pCi/L
RITCHIE	8	0.8	0.7	0.8	0.5	1.4	0	0
ROANE	6	1.6	1.2	1.2	1.2	3.7	0	0
SUMMERS	11	1.2	1.0	1.1	0.8	3.1	0	0
TAYLOR	11	2.0	0.9	1.0	2.8	9.8	9	0
TUCKER	6	4.8	2.7	2.2	6.9	18.7	17	0
TYLER	8	2.4	1.6	2.6	1.4	4.1	13	0
UPSHUR	7	2.4	1.7	2.4	1.6	4.7	14	0
WAYNE	16	2.7	1.6	1.8	2.7	10.8	19	0
WEBSTER	5	1.0	0.8	0.8	0.6	1.6	0	0
WETZEL	12	2.6	1.4	1.7	3.2	12.1	17	0
WIRT	3	1.6	0.8	0.6	2.1	4.0	0	0
WOOD	44	1.9	1.2	1.2	2.6	16.4	14	0
WYOMING	19	2.7	1.4	1.6	3.2	13.7	21	0

TABLE 2. Indoor radon data from the State/EPA Residential Radon Survey and Noble and others (1990), grouped by geologic province.

Province	State/EPA no. of homes	State/EPA arith. mean	State/EPA %>4 pCi/L	Noble et al no. of homes	Noble et al %>4 pCi/L
Central All. Plateau	593	2.40	15.3	3576	20.0
Cumb. Plat./Mtns	113	1.73	8.0	339	10.9
Eastern All. Plateau	114	2.35	11.4	461	16.3
S. Appalachian Ridge and Valley	87	3.35	18.4	449	30.5
N. Appalachian Ridge and Valley	99	5.28	38.4	1883	45.6

GEOLOGIC RADON POTENTIAL

Because steep, well-drained soils are common throughout West Virginia and soil eU values range from about 1.0 to 3.5 ppm, no county in the State can be expected to have buildings completely free from indoor radon values exceeding 4 pCi/L. Some areas of the State may have high average indoor radon levels and high percentages of homes exceeding 4 pCi/L, largely due to the physical and radiochemical properties of the soils underlying these areas.

Carbonate rocks themselves are usually low in radionuclide elements, but the soils developed from carbonate rocks are commonly elevated in uranium and radium. When the carbonate minerals dissolve away, the soils are enriched in the remaining clay and iron oxides which collect impurities, including base metals, uranium, and radium. The accumulation of uranium is strongly enhanced where the carbonate rocks are phosphatic because phosphatic carbonate rocks contain more uranium initially and the phosphate and associated uranium concentrate readily in the residual soils. Karst terrains that develop on carbonate rocks also enhance radon potential because the bedrock contains numerous solution openings that accumulate radon and increase the bedrock permeability. Soils derived from Cambrian-Ordovician carbonate rock units of the Valley and Ridge Province cause known indoor radon problems in eastern Tennessee (Goldsmith and others, 1983), western New Jersey, western Virginia, and central and eastern Pennsylvania (Greeman and others, 1990, Sachs and others, 1982).

High levels of radon in soil gas have been documented in deep, residual soils developed on Cambrian and Ordovician limestones in Berkeley and Jefferson Counties (Schultz and others, 1992). These soils contain as much as 4 times the concentration of radium and 10 times the concentration of uranium as the underlying bedrock. Such soils have developed over rocks of the Elbrook Formation, the Conococheague Formation, and the Beekmantown Group and locally contain soil-gas radon in excess of 4,000 pCi/L. Twenty-two of 98 soil-gas samples taken at homesites in these two counties exceeded 2000 pCi/L. These units also contain chert and cherty fragments in soils may contribute to high soil permeability. Siltstone, fine-grained sandstone, and dark gray shale of the Martinsburg Formation in these two counties contain elevated concentrations of uranium and produce soils that also locally exceed 4000 pCi/L (Schultz and others, 1992). Berkeley and Jefferson Counties have a high percentage of homes exceeding 4 pCi/L in the State/EPA study (47.4 and 69.2 percent respectively) and in the study by Noble and others (1990; 49.2 and 52.4 percent respectively).

Dark shales similar to those found in West Virginia are a source of high indoor radon in Kentucky (Peake and Schumann, 1991). Glacially-derived soils with fragments of the uraniferous Ohio shale are the principal cause of the high percentage of homes with indoor radon levels exceeding 4 pCi/L (72-92 percent) and levels as high as 200 pCi/L indoors in the Columbus, Ohio area (M. Hansen, written commun., 1988). Because of their high swelling clay content, soils developed on many dark shales provide poor foundation conditions for structures and may locally cause cracking of concrete. Structures sited on dark shales or colluvium containing abundant fragments of dark shale are very likely to have elevated indoor radon levels, especially where fractures increase the bedrock permeability and sloping topography tends to promote drainage and keep the soils drier. Such structures may locally have radon levels exceeding 200 pCi/L indoors.

SUMMARY

For the purpose of this assessment, West Virginia has been divided into five geologic radon potential areas and each area assigned a Radon Index (RI) and a Confidence Index (CI) score (Table 3). These radon potential areas correspond to the physiographic regions (fig. 1). The RI is a semi-quantitative measure of radon potential based on geology, soils, radioactivity, architecture, and indoor radon. The CI is a measure of the relative confidence of the RI assessment based on the quality and quantity of the data used to assess geologic radon potential (see the Introduction chapter to this regional booklet for more information).

The Central Allegheny Plateau has moderate geologic radon potential overall, owing to persistently moderate eU values and steep, well drained soils. However, Brooke and Hancock Counties, in the northernmost part of this province, have average indoor radon levels greater than 4 pCi/L. This appears to be related to underlying Conemaugh and Monongahela Group sedimentary rocks which have elevated eU values (> 2.5 ppm) in this area and in adjacent areas of western Pennsylvania.

The Cumberland Plateau and Mountains have low radon potential. The eU values for the province are low except in areas of heavy coal mining, where exposed shale-rich mine waste tends to increase the radon potential. Indoor radon levels average less than 2 pCi/L in most counties.

The Eastern Allegheny Plateau and Mountains have moderate geologic radon potential overall. Locally high indoor radon levels are likely on dark gray shales of Devonian age and colluvium derived from them in Randolph County. The southern part of this province has somewhat lower eU values and indoor radon averages are also somewhat lower.

The Southern Appalachian Ridge and Valley Province has moderate radon potential overall. The eU signature for this province is elevated. Locally high radon potential occurs in areas of deep residual soils developed on limestones of the Mississippian Greenbrier Group, especially in central Greenbrier County where eU values are high. Elevated levels of radon may be expected in soils developed on dark shales in this province or in colluvium derived from them.

The Northern Appalachian Ridge and Valley has high radon potential. The eU signature of the soils is elevated. Soils developed on the Martinsburg Formation and on limestones and dolomites throughout the province contain elevated levels of radon—a very high percentage of homes exceed 4 pCi/L in this province. Karst topography and the locally high permeability in soils associated with it increases the radon potential. Structures sited on uraniferous black shales may have very high indoor radon levels. Steep, well-drained soils developed on phyllites and quartzites of the Harpers Formation in Jefferson County also produce high average indoor radon levels.

Uranium occurrences are rare but not unknown in West Virginia. Where a structure is sited over a uranium occurrence, indoor radon levels may be extreme, possibly exceeding 200 pCi/L.

This is a generalized assessment of the State's geologic radon potential and there is no substitute for having a home tested. The conclusions about radon potential presented in this report cannot be applied to individual homes or building sites. Indoor radon levels, both high and low, can be quite localized, and within any radon potential area there will likely be areas with higher or lower radon potential than assigned to the area as a whole. Any local decisions about radon should not be made without consulting all available local data. For additional information on radon and how to test, contact your State radon program or EPA regional office. More detailed information on state or local geology may be obtained from the State geological survey. Addresses and phone numbers for these agencies are listed in chapter 1 of this booklet.

TABLE 3. Radon Index (RI) and Confidence Index (CI) for geologic radon potential areas of West Virginia. See figure 1 for locations of areas.

	Central Allegheny Plateau		Cumberland Plateau & Mountains		Eastern Allegheny Plateau & Mts	
FACTOR	RI	CI	RI	CI	RI	CI
INDOOR RADON	2	3	1	3	2	3
RADIOACTIVITY	2	3	1	3	2	3
GEOLOGY	2	2	2	2	2	3
SOIL PERM.	2	3	2	3	2	3
ARCHITECTURE	2	-	2	-	2	-
GFE POINTS	0	-	0	-	0	-
TOTAL	10	11	8	11	10	12
RANKING	MOD	HIGH	LOW	HIGH	MOD	HIGH

	Southern Appalachian Ridge & Valley		Northern Appalachian Ridge & Valley	
FACTOR	RI	CI	RI	CI
INDOOR RADON	2	3	3	3
RADIOACTIVITY	2	3	2	3
GEOLOGY	3	3	3	3
SOIL PERM.	2	3	2	3
ARCHITECTURE	2	-	2	-
GFE POINTS	0	-	+2	-
TOTAL	11	12	14	12
RANKING	MOD	HIGH	HIGH	HIGH

RADON INDEX SCORING:

Radon potential category	Point range	Probable screening indoor radon average for area
LOW	3-8 points	< 2 pCi/L
MODERATE/VARIABLE	9-11 points	2 - 4 pCi/L
HIGH	> 11 points	> 4 pCi/L

Possible range of points = 3 to 17

CONFIDENCE INDEX SCORING:

LOW CONFIDENCE	4 - 6 points
MODERATE CONFIDENCE	7 - 9 points
HIGH CONFIDENCE	10 - 12 points

Possible range of points = 4 to 12

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