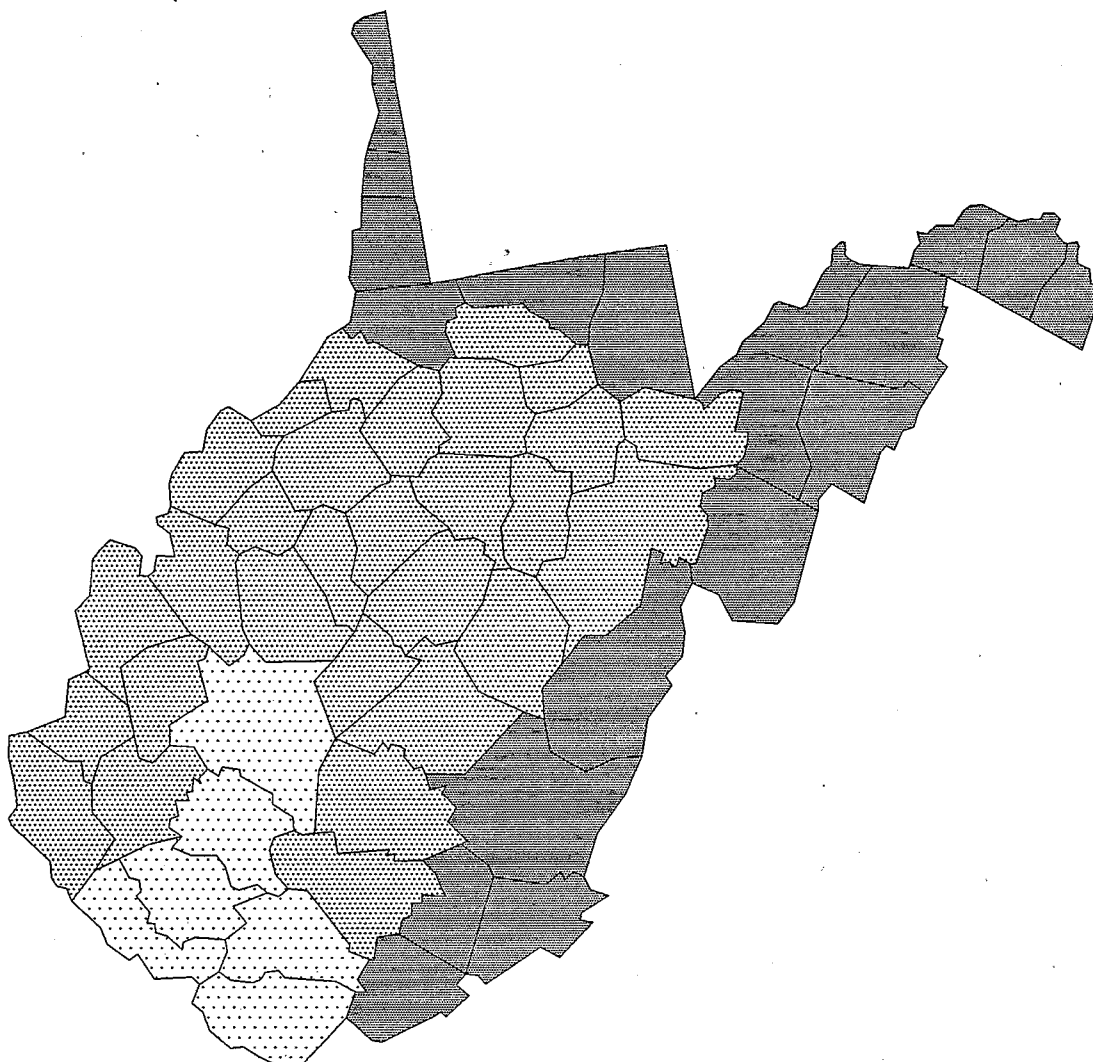

EPA EPA's Map of Radon Zones

WEST VIRGINIA



**EPA'S MAP OF RADON ZONES
WEST VIRGINIA**

**RADON DIVISION
OFFICE OF RADIATION AND INDOOR AIR
U.S. ENVIRONMENTAL PROTECTION AGENCY**

SEPTEMBER, 1993

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OVERVIEW

Sections 307 and 309 of the 1988 Indoor Radon Abatement Act (IRAA) direct EPA to identify areas of the United States that have the potential to produce elevated levels of radon. EPA, the U.S. Geological Survey (USGS), and the Association of American State Geologists (AASG) have worked closely over the past several years to produce a series of maps and documents which address these directives. The EPA Map of Radon Zones is a compilation of that work and fulfills the requirements of sections 307 and 309 of IRAA. The Map of Radon Zones identifies, on a county-by-county basis, areas of the U.S. that have the highest potential for elevated indoor radon levels (greater than 4 pCi/L).

The Map of Radon Zones is designed to assist national, State and local governments and organizations to target their radon program activities and resources. It is also intended to help building code officials determine areas that are the highest priority for adopting radon-resistant building practices. The Map of Radon Zones should not be used to determine if individual homes in any given area need to be tested for radon. **EPA recommends that all homes be tested for radon, regardless of geographic location or the zone designation of the county in which they are located.**

This document provides background information concerning the development of the Map of Radon Zones. It explains the purposes of the map, the approach for developing the map (including the respective roles of EPA and USGS), the data sources used, the conclusions and confidence levels developed for the prediction of radon potential, and the review process that was conducted to finalize this effort.

BACKGROUND

Radon (Rn^{222}) is a colorless, odorless, radioactive gas. It comes from the natural decay of uranium that is found in nearly all soils. It typically moves through the ground to the air above and into homes and other buildings through cracks and openings in the foundation. Any home, school or workplace may have a radon problem, regardless of whether it is new or old, well-sealed or drafty, or with or without a basement. Nearly one out of every 15 homes in the U.S. is estimated to have elevated annual average levels of indoor radon.

Radon first gained national attention in early 1984, when extremely high levels of indoor radon were found in areas of Pennsylvania, New Jersey, and New York, along the Reading Prong-physiographic province. EPA established a Radon Program in 1985 to assist States and homeowners in reducing their risk of lung cancer from indoor radon.

Since 1985, EPA and USGS have been working together to continually increase our understanding of radon sources and the migration dynamics that cause elevated indoor radon levels. Early efforts resulted in the 1987 map entitled "Areas with Potentially High Radon Levels." This map was based on limited geologic information only because few indoor radon measurements were available at the time. The development of EPA's Map of Radon Zones and its technical foundation, USGS' National Geologic Radon Province Map, has been based on additional information from six years of the State/EPA Residential Radon Surveys, independent State residential surveys, and continued expansion of geologic and geophysical information, particularly the data from the National Uranium Resource Evaluation project.

Purpose of the Map of Radon Zones

EPA's Map of Radon Zones (Figure 1) assigns each of the 3141 counties in the United States to one of three zones:

- o Zone 1 counties have a predicted average indoor screening level > than 4 pCi/L
- o Zone 2 counties have a predicted average screening level ≥ 2 pCi/L and ≤ 4 pCi/L
- o Zone 3 counties have a predicted average screening level < 2 pCi/L

The Zone designations were determined by assessing five factors that are known to be important indicators of radon potential: indoor radon measurements, geology, aerial radioactivity, soil parameters, and foundation types.

The predictions of average screening levels in each of the Zones is an expression of radon potential in the lowest liveable area of a structure. This map is unable to estimate actual exposures to radon. EPA recommends methods for testing and fixing individual homes based on an estimate of actual exposure to radon. For more information on testing and fixing elevated radon levels in homes consult these EPA publications: *A Citizen's Guide to Radon*, *the Consumer's Guide to Radon Reduction* and *the Home Buyer's and Seller's Guide to Radon*.

EPA believes that States, local governments and other organizations can achieve optimal risk reductions by targeting resources and program activities to high radon potential areas. Emphasizing targeted approaches (technical assistance, information and outreach efforts, promotion of real estate mandates and policies and building codes, etc.) in such areas addresses the greatest potential risks first.

EPA also believes that the use of passive radon control systems in the construction of new homes in Zone 1 counties, and the activation of those systems if necessitated by follow-up testing, is a cost effective approach to achieving significant radon risk reduction.

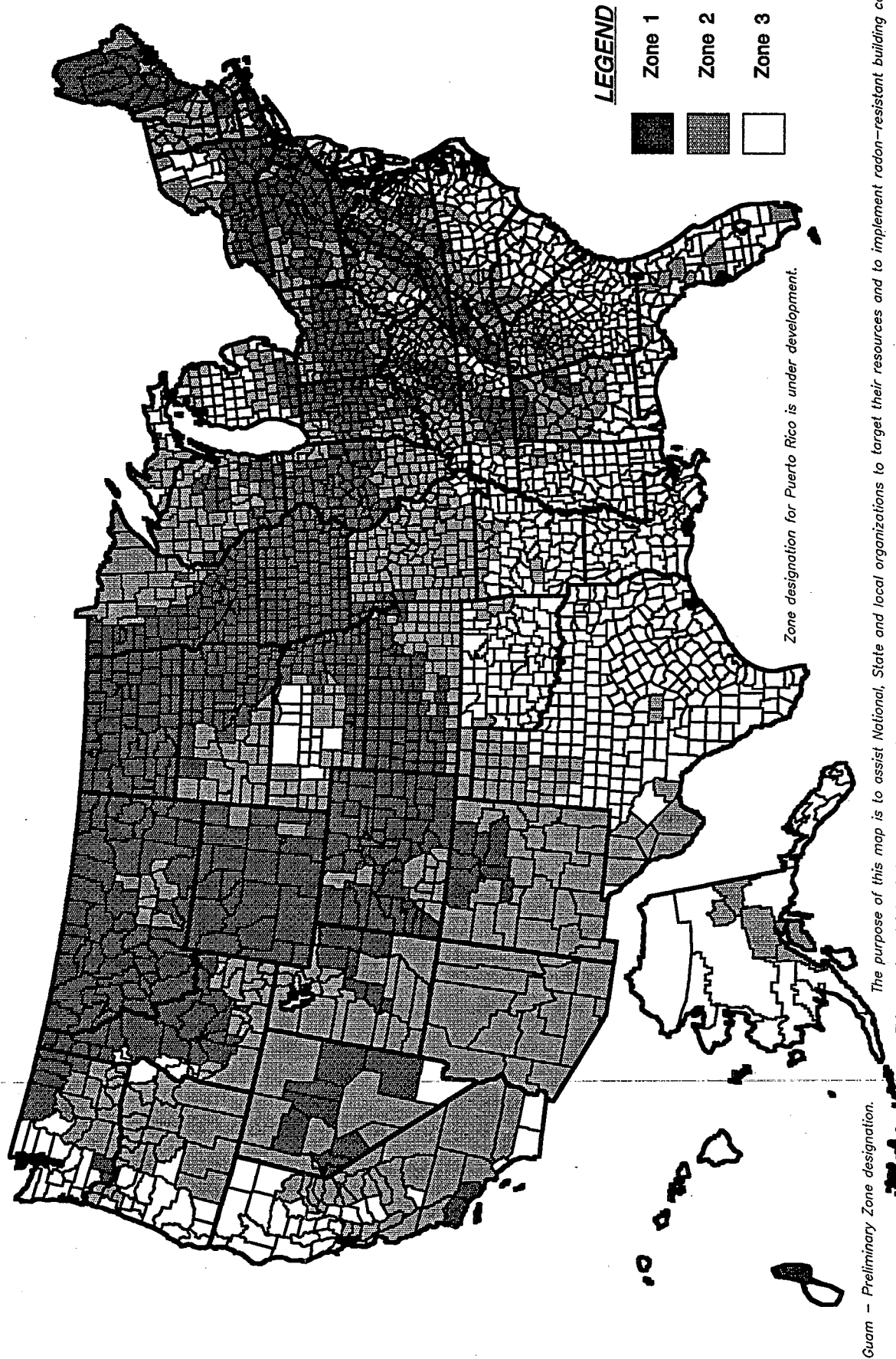
The Map of Radon Zones and its supporting documentation establish no regulatory requirements. Use of this map by State or local radon programs and building code officials is voluntary. The information presented on the Map of Radon Zones and in the supporting documentation is not applicable to radon in water.

Development of the Map of Radon Zones

The technical foundation for the Map of Radon Zones is the USGS Geologic Radon Province Map. In order to examine the radon potential for the United States, the USGS began by identifying approximately 360 separate geologic provinces for the U.S. The provinces are shown on the USGS Geologic Radon Province Map (Figure 2). Each of the geologic provinces was evaluated by examining the available data for that area: indoor radon measurements, geology, aerial radioactivity, soil parameters, and foundation types. As stated previously, these five factors are considered to be of basic importance in assessing radon

Figure 1

EPA Map of Radon Zones



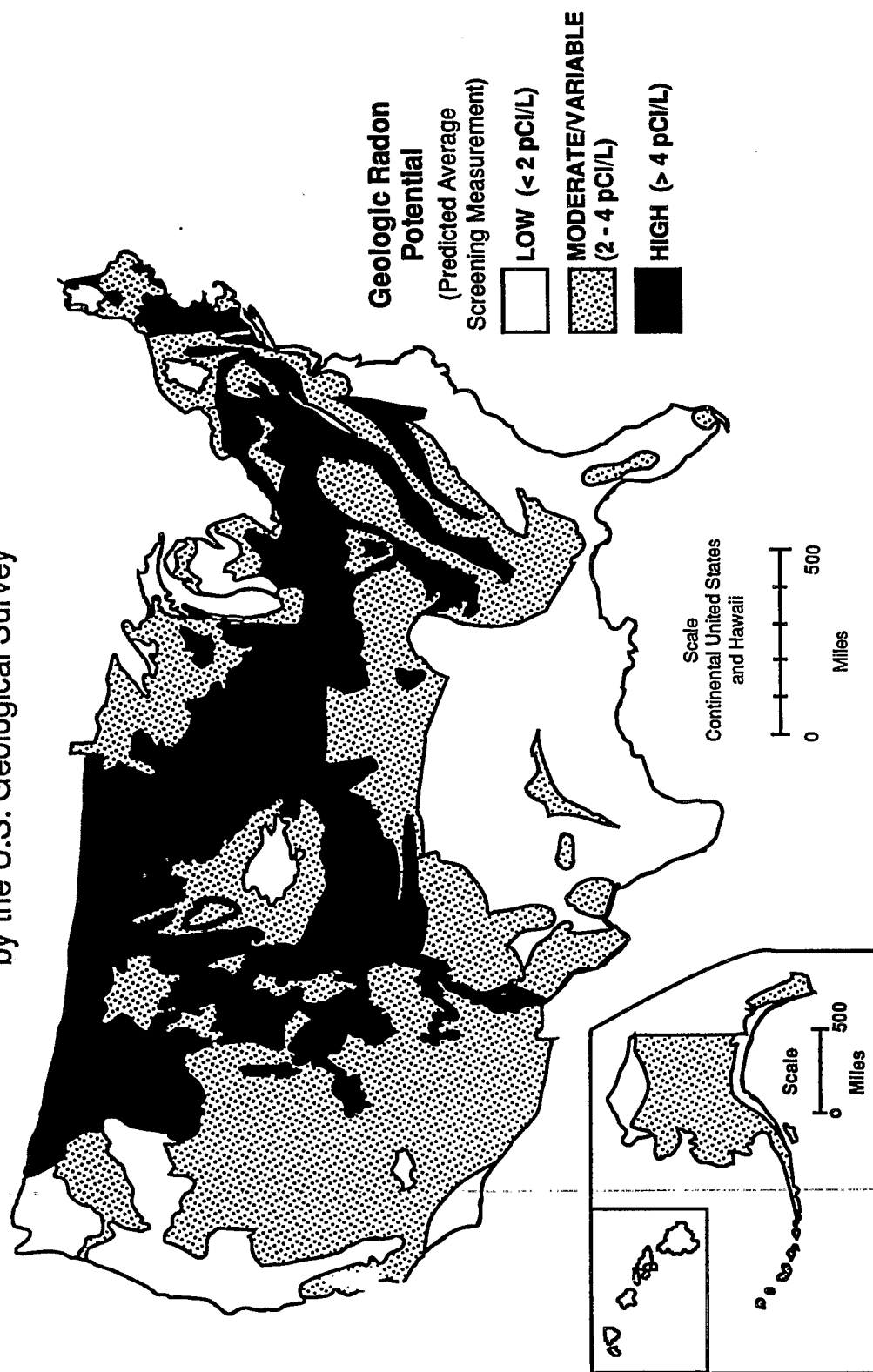
Guam - Preliminary Zone designation.

The purpose of this map is to assist National, State and local organizations to target their resources and to implement radon-resistant building codes. This map is not intended to be used to determine if a home in a given zone should be tested for radon. Homes with elevated levels of radon have been found in all three zones. All homes should be tested, regardless of geographic location.

IMPORTANT: Consult the EPA Map of Radon Zones document (EPA-402-R-93-071) before using this map. This document contains information on radon potential variations within counties. EPA also recommends that this map be supplemented with any available local data in order to further understand and predict the radon potential of a specific area.

Figure 2

GENERALIZED GEOLOGIC RADON POTENTIAL OF THE UNITED STATES by the U.S. Geological Survey



potential and some data are available for each of these factors in every geologic province. The province boundaries do not coincide with political borders (county and state) but define areas of general radon potential. The five factors were assigned numerical values based on an assessment of their respective contribution to radon potential, and a confidence level was assigned to each contributing variable. The approach used by USGS to estimate the radon potential for each province is described in Part II of this document.

EPA subsequently developed the Map of Radon Zones by extrapolating from the province level to the county level so that all counties in the U.S. were assigned to one of three radon zones. EPA assigned each county to a given zone based on its provincial radon potential. For example, if a county is located within a geologic province that has a predicted average screening level greater than 4 pCi/L, it was assigned to Zone 1. Likewise, counties located in provinces with predicted average screening levels ≥ 2 pCi/L and ≤ 4 pCi/L, and less than 2 pCi/L, were assigned to Zones 2 and 3, respectively.

If the boundaries of a county fall in more than one geologic province, the county was assigned to a zone based on the predicted radon potential of the province in which most of the area lies. For example, if three different provinces cross through a given county, the county was assigned to the zone representing the radon potential of the province containing most of the county's land area. (In this case, it is not technically correct to say that the predicted average screening level applies to the entire county since the county falls in multiple provinces with differing radon potentials.)

Figures 3 and 4 demonstrate an example of how EPA extrapolated the county zone designations for Nebraska from the USGS geologic province map for the State. As figure 3 shows, USGS has identified 5 geologic provinces for Nebraska. Most of the counties are extrapolated "straight" from their corresponding provinces, but there are counties "partitioned" by several provinces -- for example, Lincoln County. Although Lincoln county falls in multiple provinces, it was assigned to Zone 3 because most of its area falls in the province with the lowest radon potential.

It is important to note that EPA's extrapolation from the province level to the county level may mask significant "highs" and "lows" within specific counties. In other words, within-county variations in radon potential are not shown on the Map of Radon Zones. EPA recommends that users who may need to address specific within-county variations in radon potential (e.g., local government officials considering the implementation of radon-resistant construction codes) consult USGS' Geologic Radon Province Map and the State chapters provided with this map for more detailed information, as well as any locally available data.

Map Validation

The Map of Radon Zones is intended to represent a preliminary assessment of radon potential for the entire United States. The factors that are used in this effort -- indoor radon data, geology, aerial radioactivity, soils, and foundation type -- are basic indicators for radon potential. It is important to note, however, that the map's county zone designations are not "statistically valid" predictions due to the nature of the data available for these 5 factors at the county level. In order to validate the map in light of this lack of statistical confidence, EPA conducted a number of analyses. These analyses have helped EPA to identify the best situations in which to apply the map, and its limitations.

Figure 3

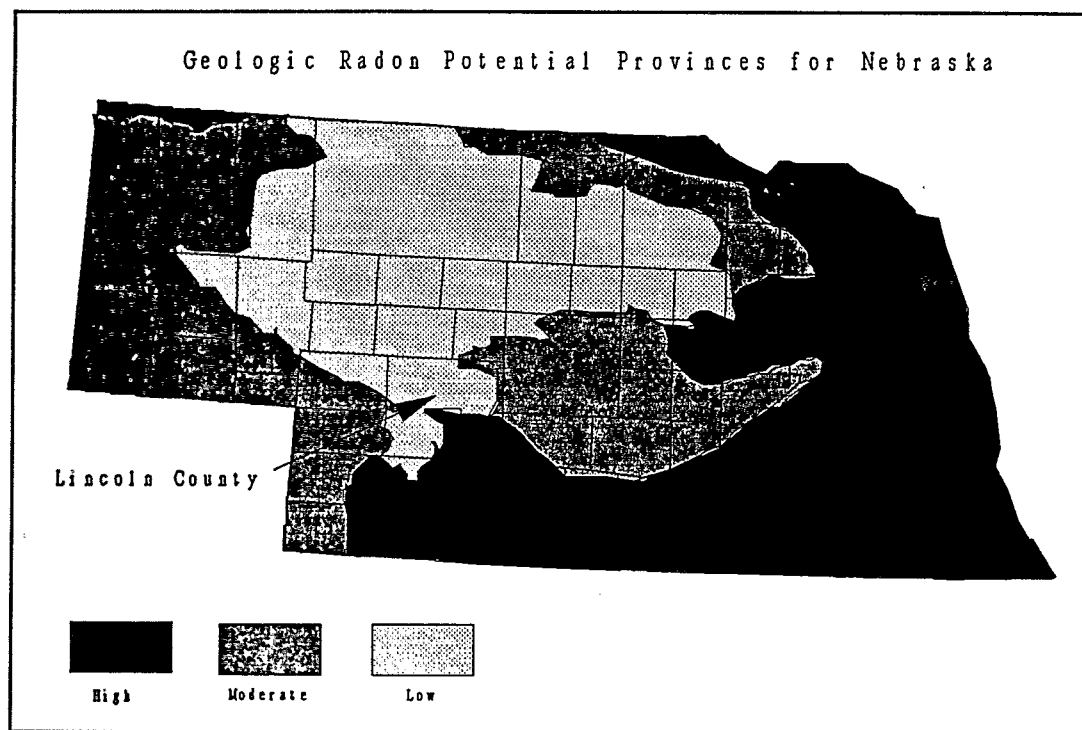
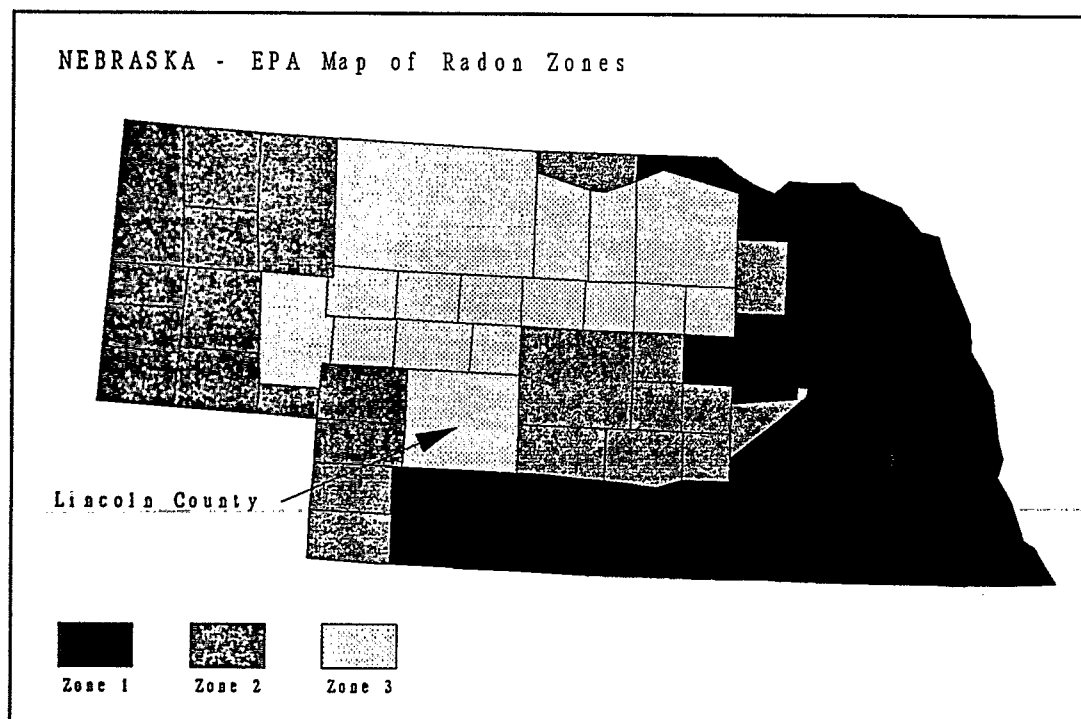


Figure 4



One such analysis involved comparing county zone designations to indoor radon measurements from the State/EPA Residential Radon Surveys (SRRS). Screening averages for counties with at least 100 measurements were compared to the counties' predicted radon potential as indicated by the Map of Radon Zones. EPA found that 72% of the county screening averages were correctly reflected by the appropriate zone designations on the Map. In all other cases, they only differed by 1 zone.

Another accuracy analysis used the annual average data from the National Residential Radon Survey (NRRS). The NRRS indicated that approximately 6 million homes in the United States have annual averages greater than or equal to 4 pCi/L. By cross checking the county location of the approximately 5,700 homes which participated in the survey, their radon measurements, and the zone designations for these counties, EPA found that approximately 3.8 million homes of the 5.4 million homes with radon levels greater than or equal to 4 pCi/L will be found in counties designated as Zone 1. A random sampling of an equal number of counties would have only found approximately 1.8 million homes greater than 4 pCi/L. In other words, this analysis indicated that the map approach is three times more efficient at identifying high radon areas than random selection of zone designations.

Together, these analyses show that the approach EPA used to develop the Map of Radon Zones is a reasonable one. In addition, the Agency's confidence is enhanced by results of the extensive State review process -- the map generally agrees with the States' knowledge of and experience in their own jurisdictions. However, the accuracy analyses highlight two important points: the fact that elevated levels will be found in Zones 2 and 3, and that there will be significant numbers of homes with lower indoor radon levels in all of the Zones. For these reasons, users of the Map of Radon Zones need to supplement the Map with locally available data whenever possible. Although all known "hot spots", i.e., localized areas of consistently elevated levels, are discussed in the State-specific chapters, accurately defining the boundaries of the "hot spots" on this scale of map is not possible at this time. Also, unknown "hot spots" do exist.

The Map of Radon Zones is intended to be a starting point for characterizing radon potential because our knowledge of radon sources and transport is always growing. Although this effort represents the best data available at this time, EPA will continue to study these parameters and others such as house construction, ventilation features and meteorology factors in order to better characterize the presence of radon in U.S homes, especially in high risk areas. These efforts will eventually assist EPA in refining and revising the conclusions of the Map of Radon Zones. And although this map is most appropriately used as a targeting tool by the aforementioned audiences -- **the Agency encourages all residents to test their homes for radon, regardless of geographic location or the zone designation of the county in which they live. Similarly, the Map of Radon Zones should not to be used in lieu of testing during real estate transactions.**

Review Process

The Map of Radon Zones has undergone extensive review within EPA and outside the Agency. The Association of American State Geologists (AASG) played an integral role in this review process. The AASG individual State geologists have reviewed their State-specific information, the USGS Geologic Radon Province Map, and other materials for their geologic content and consistency.

In addition to each State geologist providing technical comments, the State radon offices were asked to comment on their respective States' radon potential evaluations. In particular, the States were asked to evaluate the data used to assign their counties to specific zones. EPA and USGS worked with the States to resolve any issues concerning county zone designations. In a few cases, States have requested changes in county zone designations. The requests were based on additional data from the State on geology, indoor radon measurements, population, etc. Upon reviewing the data submitted by the States, EPA did make some changes in zone designations. These changes, which do not strictly follow the methodology outlined in this document, are discussed in the respective State chapters.

EPA encourages the States and counties to conduct further research and data collection efforts to refine the Map of Radon Zones. EPA would like to be kept informed of any changes the States, counties, or others make to the maps. Updates and revisions will be handled in a similar fashion to the way the map was developed. States should notify EPA of any proposed changes by forwarding the changes through the Regional EPA offices that are listed in Part II. Depending on the amount of new information that is presented, EPA will consider updating this map periodically. The State radon programs should initiate proper notification of the appropriate State officials when the Map of Radon Zones is released and when revisions or updates are made by the State or EPA.

THE USGS/EPA RADON POTENTIAL ASSESSMENTS: AN INTRODUCTION

by

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BACKGROUND

The Indoor Radon Abatement Act of 1988 (15 U.S.C. 2661-2671) 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.*

Booklets detailing the radon potential assessment for the U.S. have been developed for each State. USGS geologists are the authors of the geologic radon potential booklets. Each booklet consists of several components, the first being an overview to the mapping project (Part I), this introduction to the USGS assessment (Part II), including a general discussion of radon (occurrence, transport, etc.), and details concerning the types of data used. The third component is a summary chapter outlining the general geology and geologic radon potential of the EPA Region (Part III). The fourth component is an individual chapter for each state (Part IV). 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. Finally, the booklets contain EPA's map of radon zones for each state and an accompanying description (Part V).

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

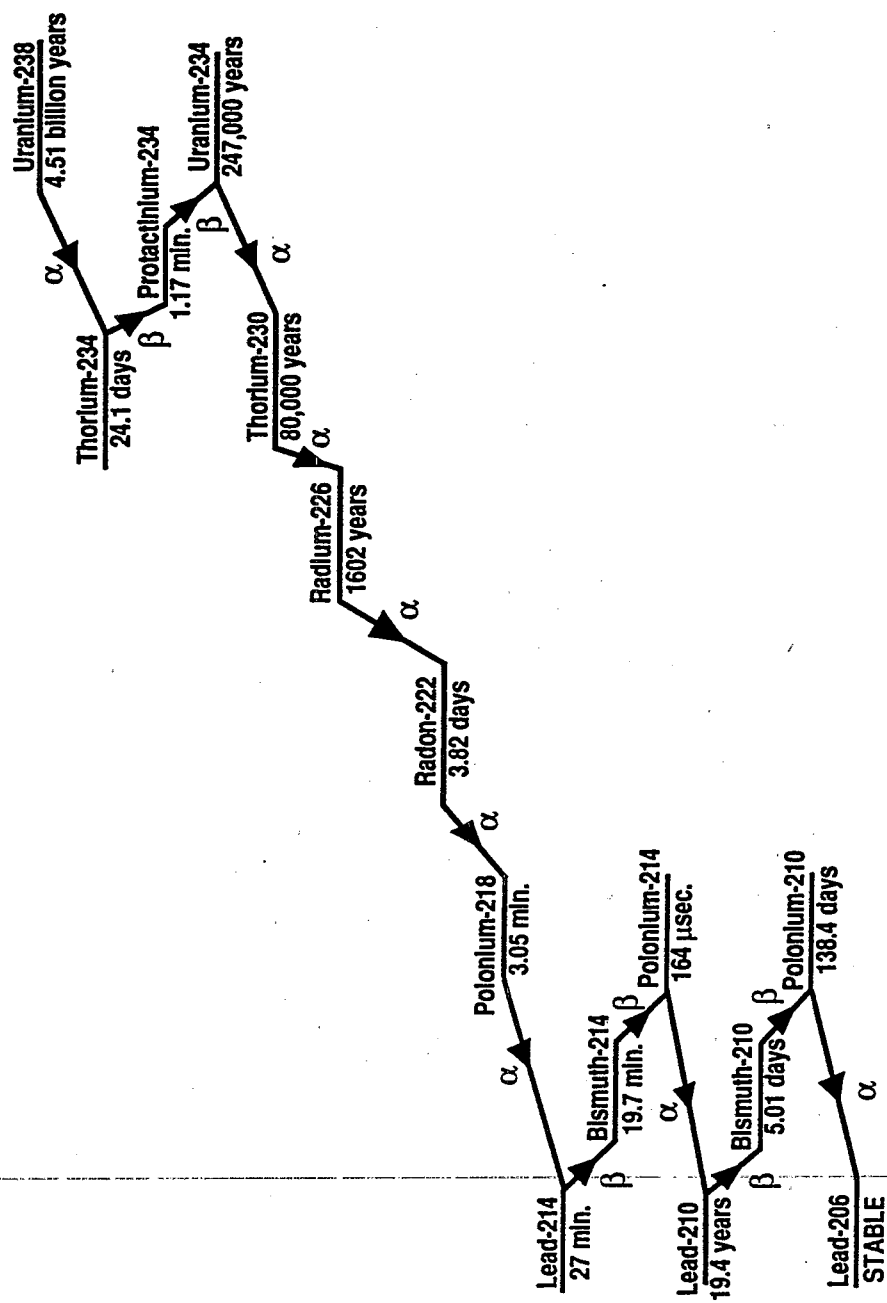


Figure 1. The uranium-238 decay series, showing the half-lives of elements and their modes of decay (after Wanty and Schoen, 1991). α denotes alpha decay, β denotes beta decay.

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 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 ($1 \text{ nm} = 10^{-9}$ 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.

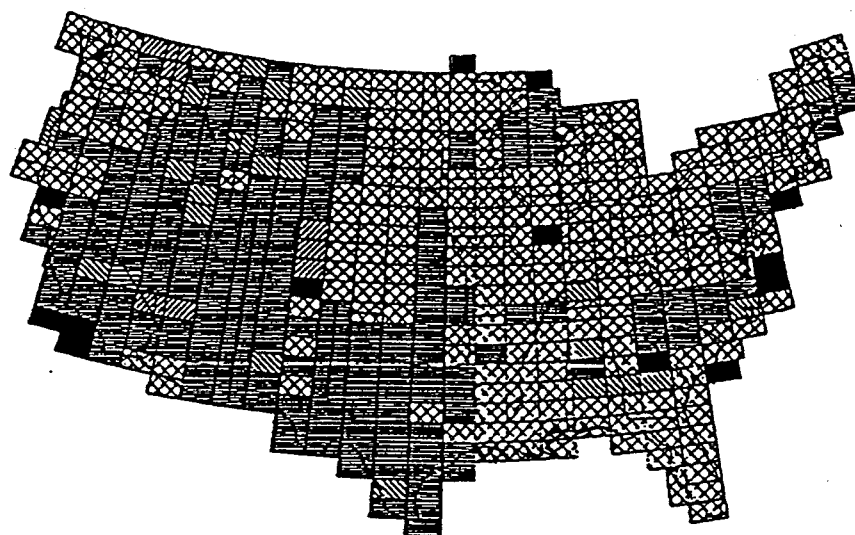
Although many cases of elevated indoor radon levels can be traced to high radium and (or) uranium concentrations in parent rocks, some structural features, most notably faults and shear zones, have been identified as sites of localized uranium concentrations (Deffeyes and MacGregor, 1980) and have been 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).

FLIGHT LINE SPACING OF NURE AERIAL SURVEYS



- 2 KM (1 MILE)
- 5 KM (3 MILES)
- 2 & 5 KM
- 10 KM (6 MILES)
- 5 & 10 KM
- NO 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.

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.

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.

STATE/EPA RESIDENTIAL RADON SURVEY SCREENING MEASUREMENTS

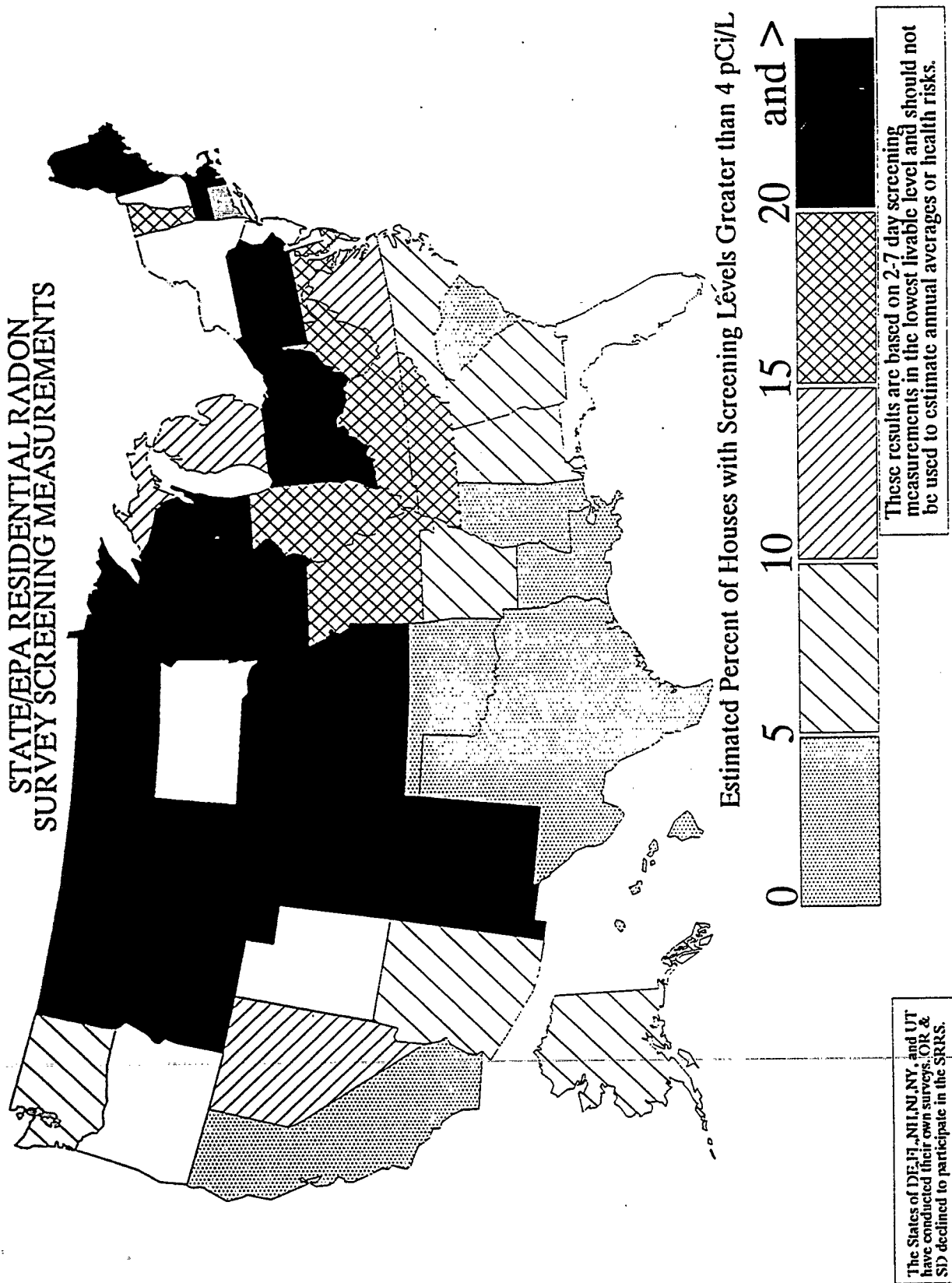


Figure 3. Percent of homes tested in the State/EPA Residential Radon Survey with screening indoor radon levels exceeding 4 pCi/L.

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 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

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.

FACTOR	<div> <div>INCREASING RADON POTENTIAL</div> <div>➔</div> </div> 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

FACTOR	<div> <div>INCREASING CONFIDENCE</div> <div>➔</div> </div> 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

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 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.

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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)	
				Oligocene		38 (34-38)	
			Paleogene ² Subperiod or Subsystem (Pt)	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 (Tr)		Late	Upper			
			Middle	Middle			
			Early	Lower	~240		
	Paleozoic ² (Pz)		Permian (P)		Late	Upper	
				Early	Lower	290 (290-305)	
		Carboniferous Systems (C)	Pennsylvanian (P)	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 (C)		Late	Upper		
				Middle	Middle		
				Early	Lower	~570 ³	
Proterozoic (E)	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-C), 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/m³ (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/m³.

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 ($\text{CaMg}(\text{CO}_3)_2$), 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	State	EPA Region
EPA Region 1 JFK Federal Building Boston, MA 02203 (617) 565-4502	Alabama.....	4
	Alaska.....	10
	Arizona.....	9
	Arkansas.....	6
	California.....	9
	Colorado.....	8
EPA Region 2 (2AIR:RAD) 26 Federal Plaza New York, NY 10278 (212) 264-4110	Connecticut.....	1
	Delaware.....	3
	District of Columbia.....	3
	Florida.....	4
	Georgia.....	4
	Hawaii.....	9
Region 3 (3AH14) 841 Chestnut Street Philadelphia, PA 19107 (215) 597-8326	Idaho.....	10
	Illinois.....	5
	Indiana.....	5
	Iowa.....	7
EPA Region 4 345 Courtland Street, N.E. Atlanta, GA 30365 (404) 347-3907	Kansas.....	7
	Kentucky.....	4
	Louisiana.....	6
	Maine.....	1
	Maryland.....	3
EPA Region 5 (5AR26) 77 West Jackson Blvd. Chicago, IL 60604-3507 (312) 886-6175	Massachusetts.....	1
	Michigan.....	5
	Minnesota.....	5
	Mississippi.....	4
	Missouri.....	7
EPA Region 6 (6T-AS) 1445 Ross Avenue Dallas, TX 75202-2733 (214) 655-7224	Montana.....	8
	Nebraska.....	7
	Nevada.....	9
	New Hampshire.....	1
EPA Region 7 726 Minnesota Avenue Kansas City, KS 66101 (913) 551-7604	New Jersey.....	2
	New Mexico.....	6
	New York.....	2
	North Carolina.....	4
	North Dakota.....	8
	Ohio.....	5
EPA Region 8 (8HWM-RP) 999 18th Street One Denver Place, Suite 1300 Denver, CO 80202-2413 (303) 293-1713	Oklahoma.....	6
	Oregon.....	10
	Pennsylvania.....	3
	Rhode Island.....	1
	South Carolina.....	4
	South Dakota.....	8
	Tennessee.....	4
EPA Region 9 (A-3) 75 Hawthorne Street San Francisco, CA 94105 (415) 744-1048	Texas.....	6
	Utah.....	8
	Vermont.....	1
	Virginia.....	3
EPA Region 10 1200 Sixth Avenue Seattle, WA 98101 (202) 442-7660	Washington.....	10
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	Wisconsin.....	5
	Wyoming.....	8

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May, 1993

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EPA REGION 3 GEOLOGIC RADON POTENTIAL SUMMARY

by
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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 Bringham 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

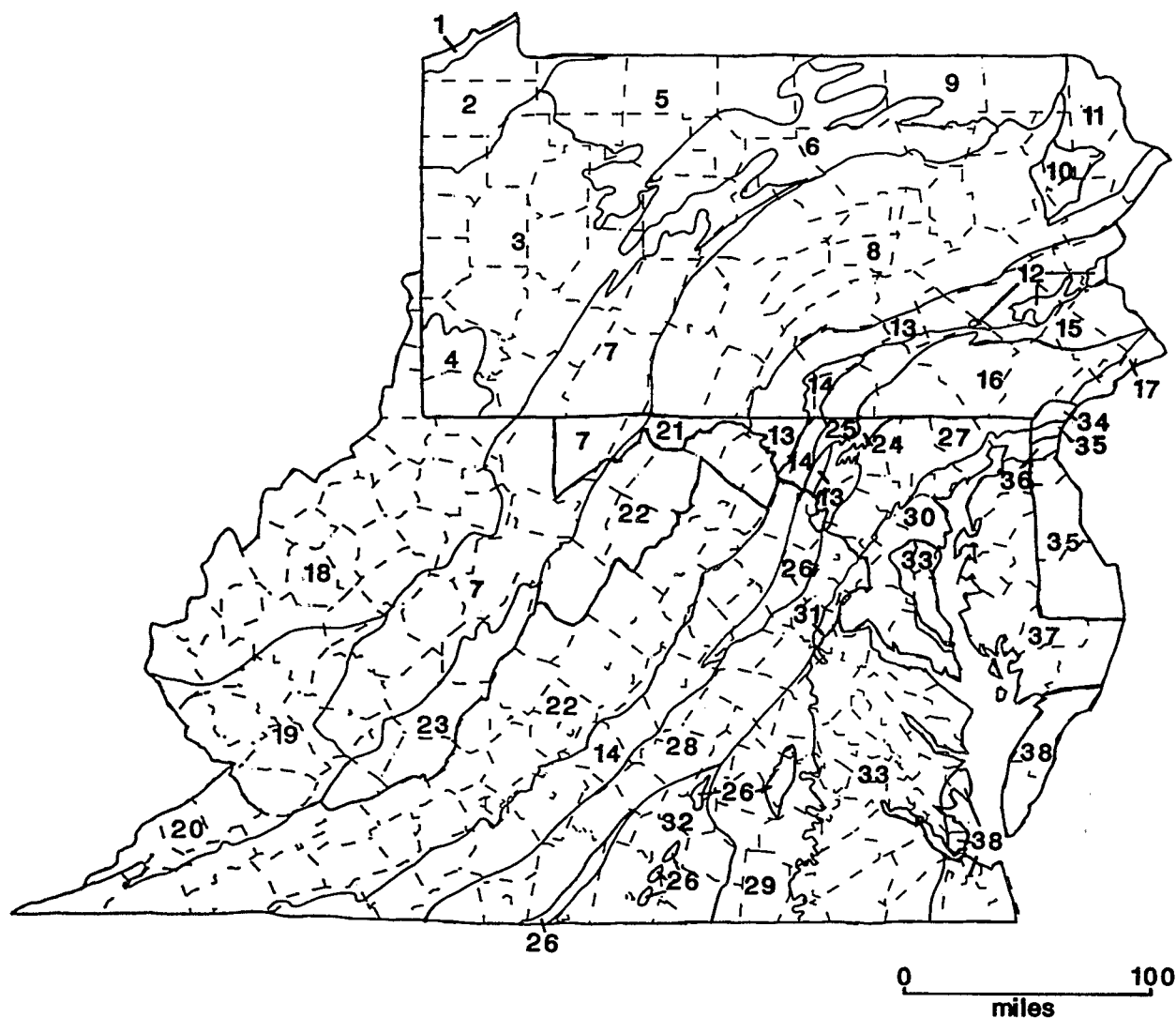
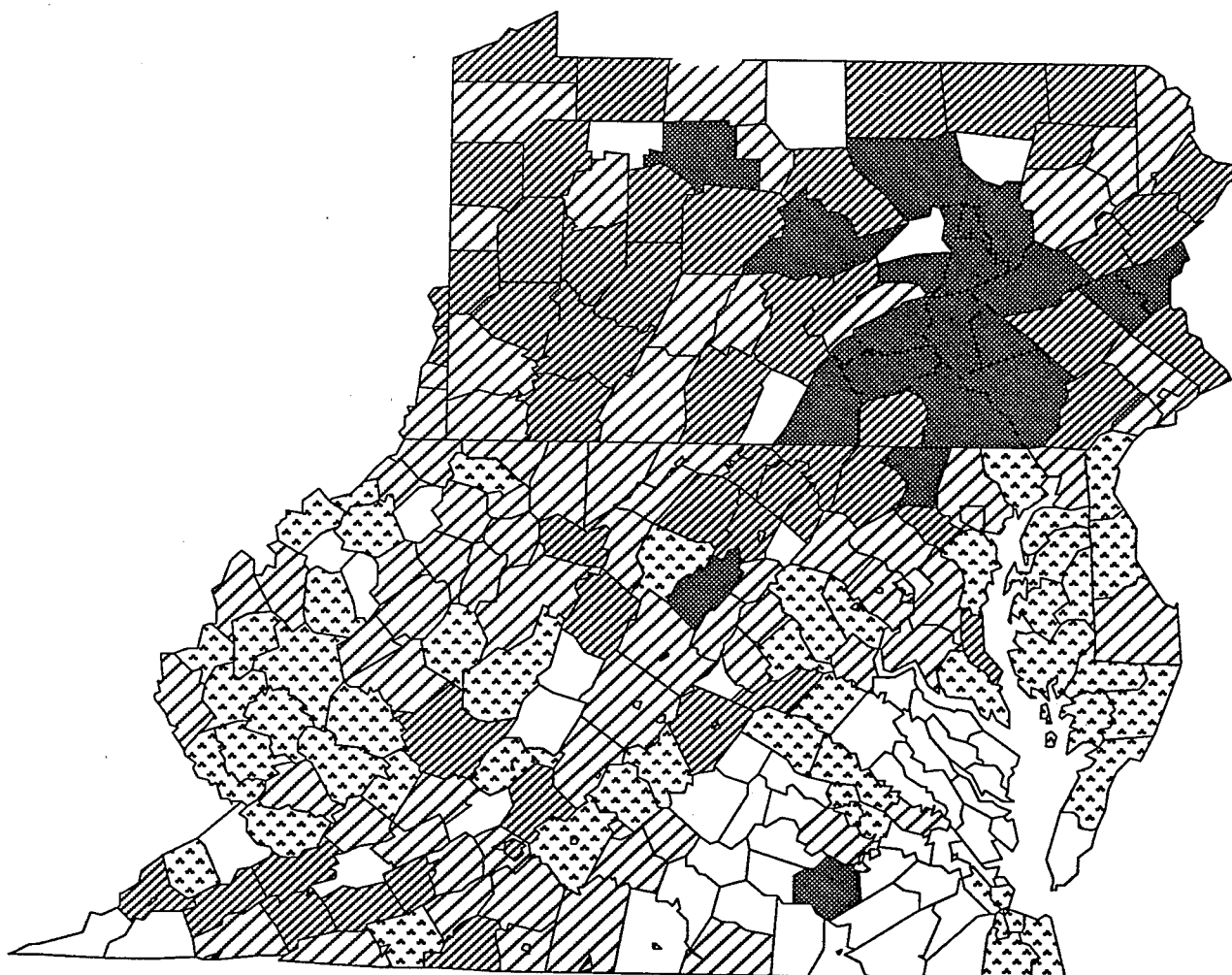


Figure 1. Geologic radon potential areas of EPA Region 3. 1-Central Lowland; 2-Glaciaded Pittsburgh Plateau; 3-Pennsylvanian rocks of the Pittsburgh Low Plateau; 4-Permian rocks of the Pittsburgh Low Plateau; 5-High Plateau Section; 6-Mountainous High Plateau; 7-Allegheny Plateau and Mountains; 8-Appalachian Mountains; 9-Glaciaded Low Plateau, Western Portion; 10-Glaciaded Pocono Plateau; 11-Glaciaded 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.



100 Miles

Indoor Radon Screening
Measurements: Average (pCi/L)

61		0.0 to 1.9
81		2.0 to 4.0
57		4.1 to 10.0
20		10.1 to 32.6
65		Missing Data or < 5 measurements

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.

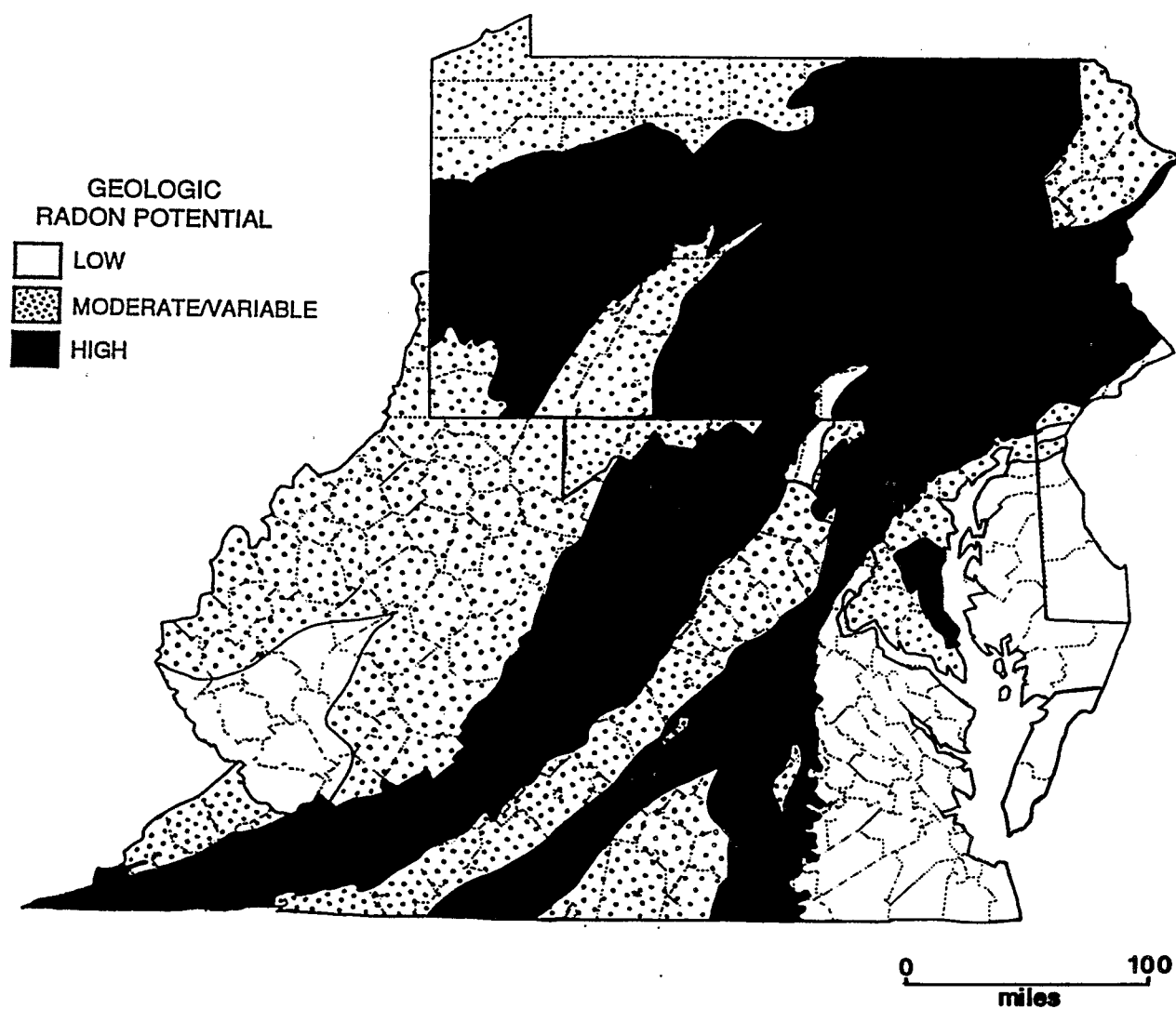


Figure 3. Geologic radon potential of EPA Region 3. For more detail, refer to individual state radon potential chapters.

rapid permeability. Limited aerial 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 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.

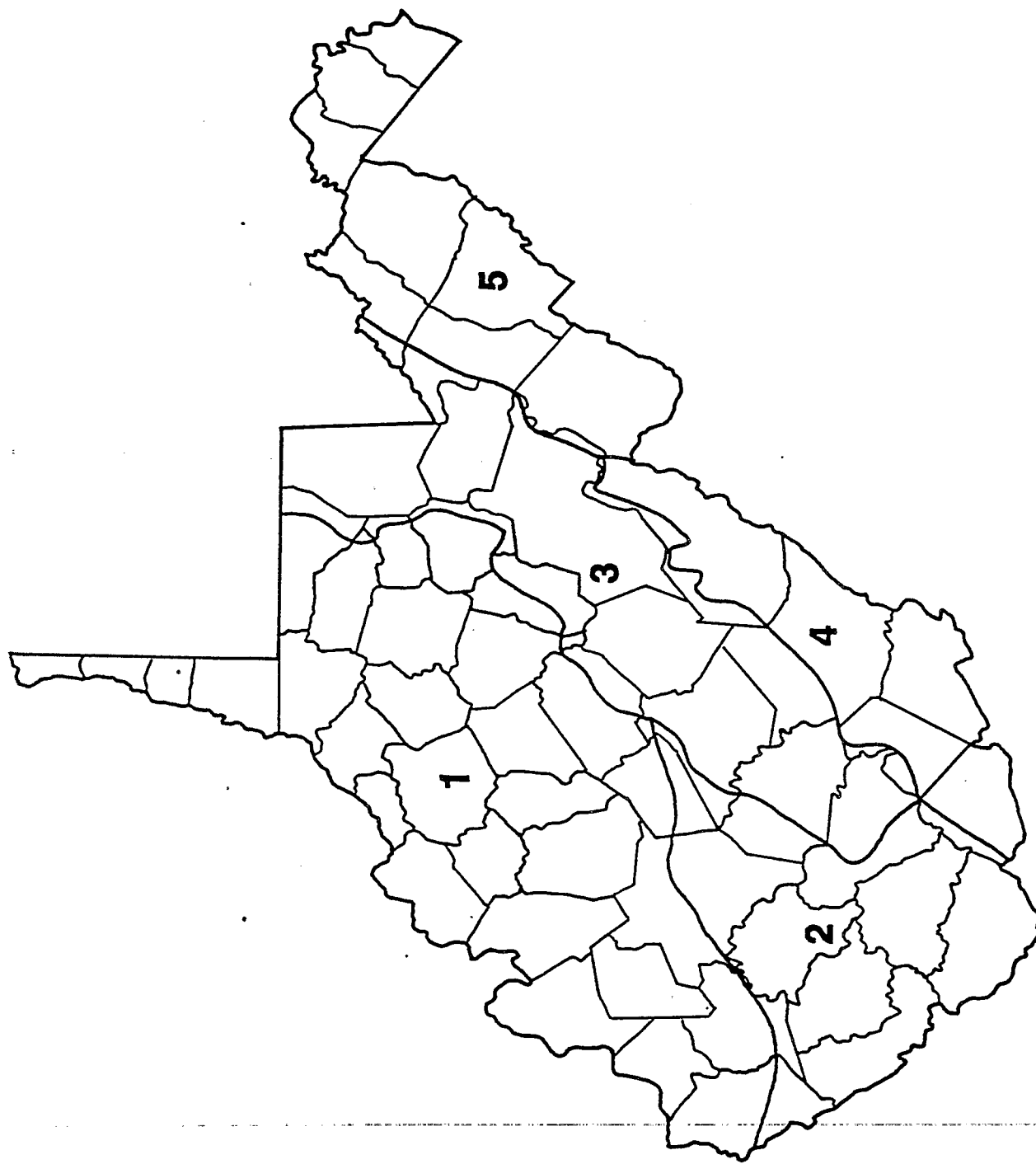


Fig. 1- Physiographic regions of West Virginia. After Soil Conservation Service (1979). 1- Central Allegheny Plateau; 2- Cumberland Plateau and Mountains; 3- Eastern Allegheny Plateau and Mountains; 4- Southern Appalachian Ridge and Valley; and 5- Northern Appalachian Ridge and Valley.

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.

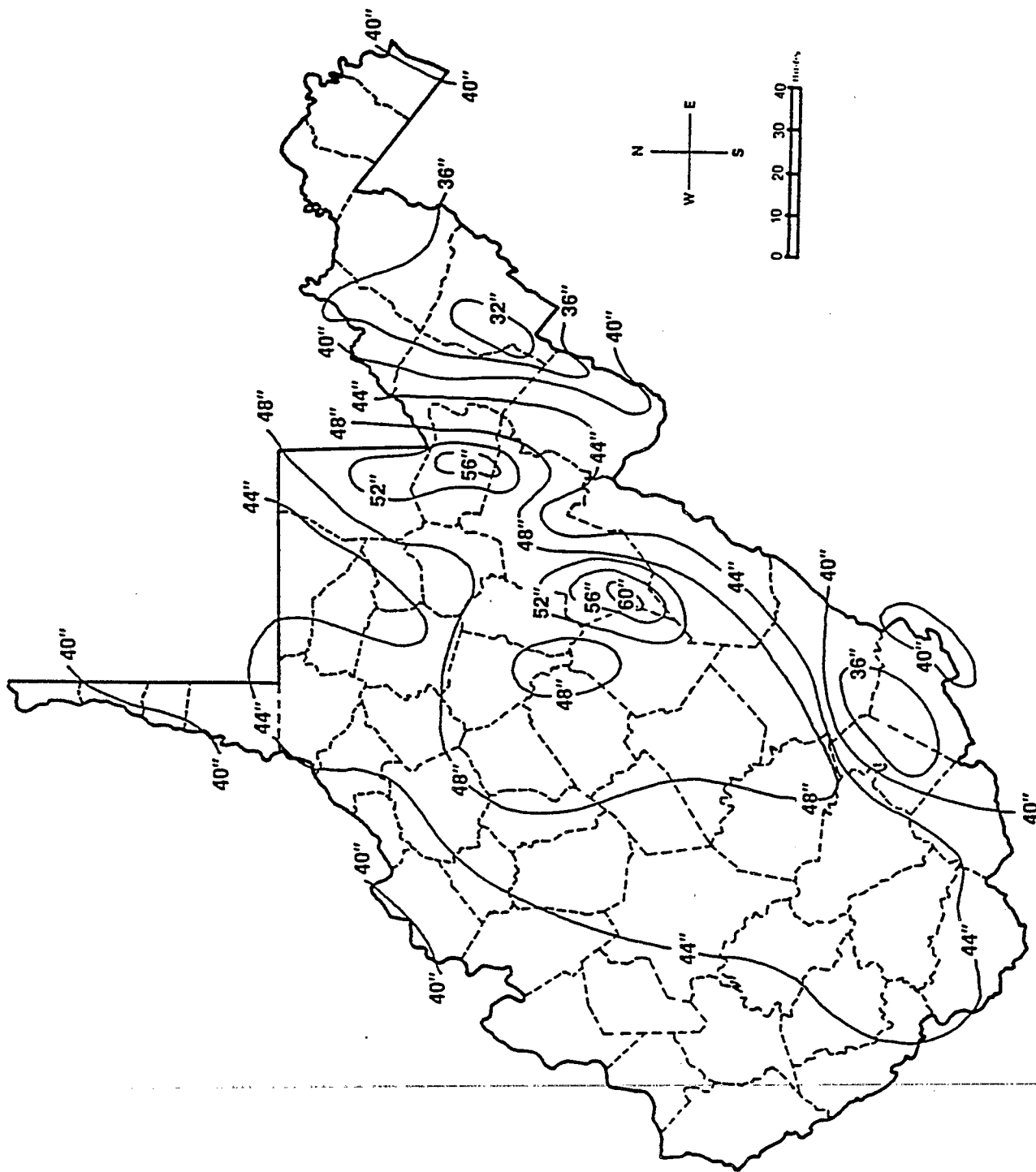


Fig. 2- Map showing average annual precipitation in West Virginia. From Facts on File, Inc., 1984.

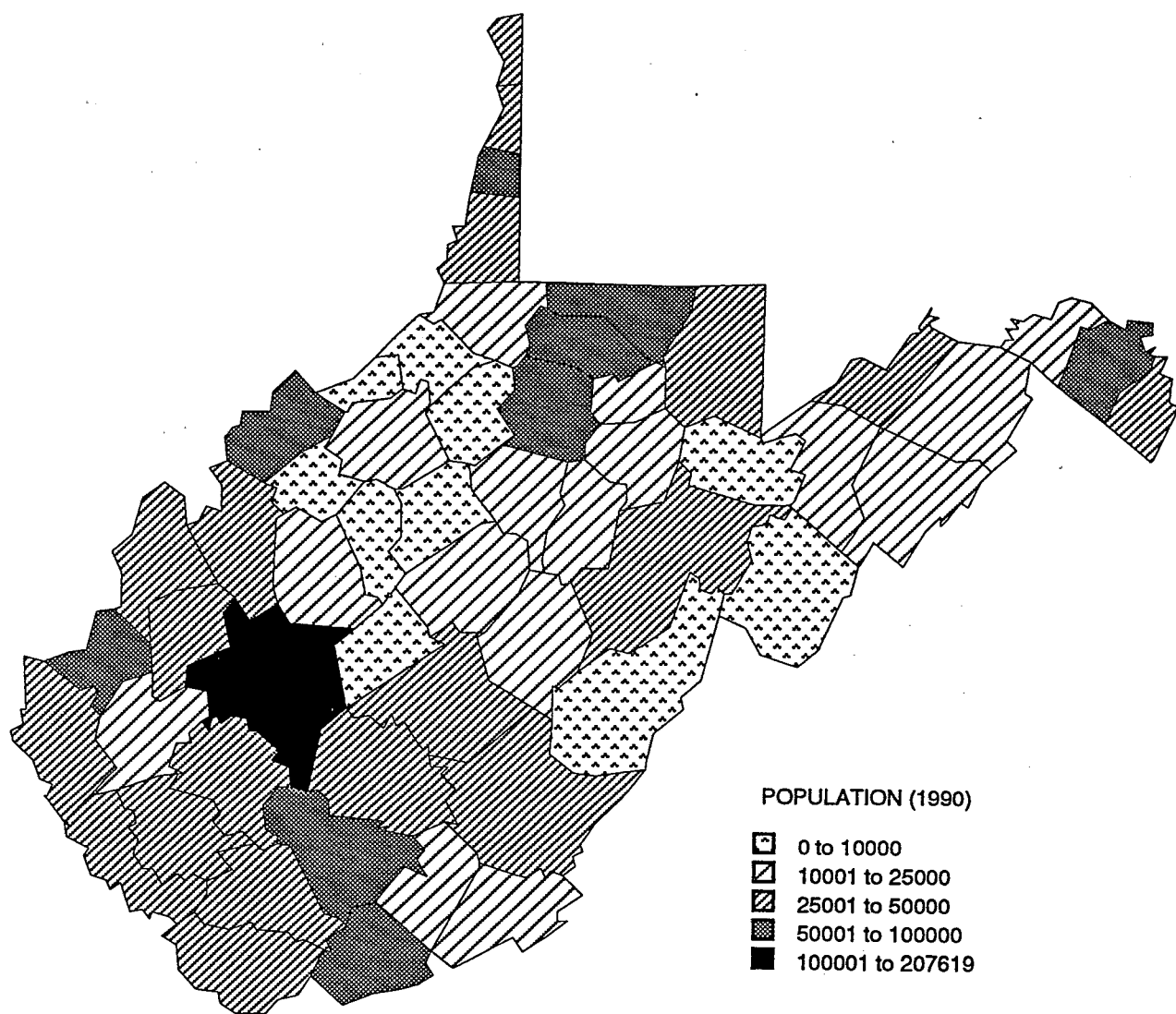


Figure 3. Population of counties in West Virginia (1990 U.S. Census data).

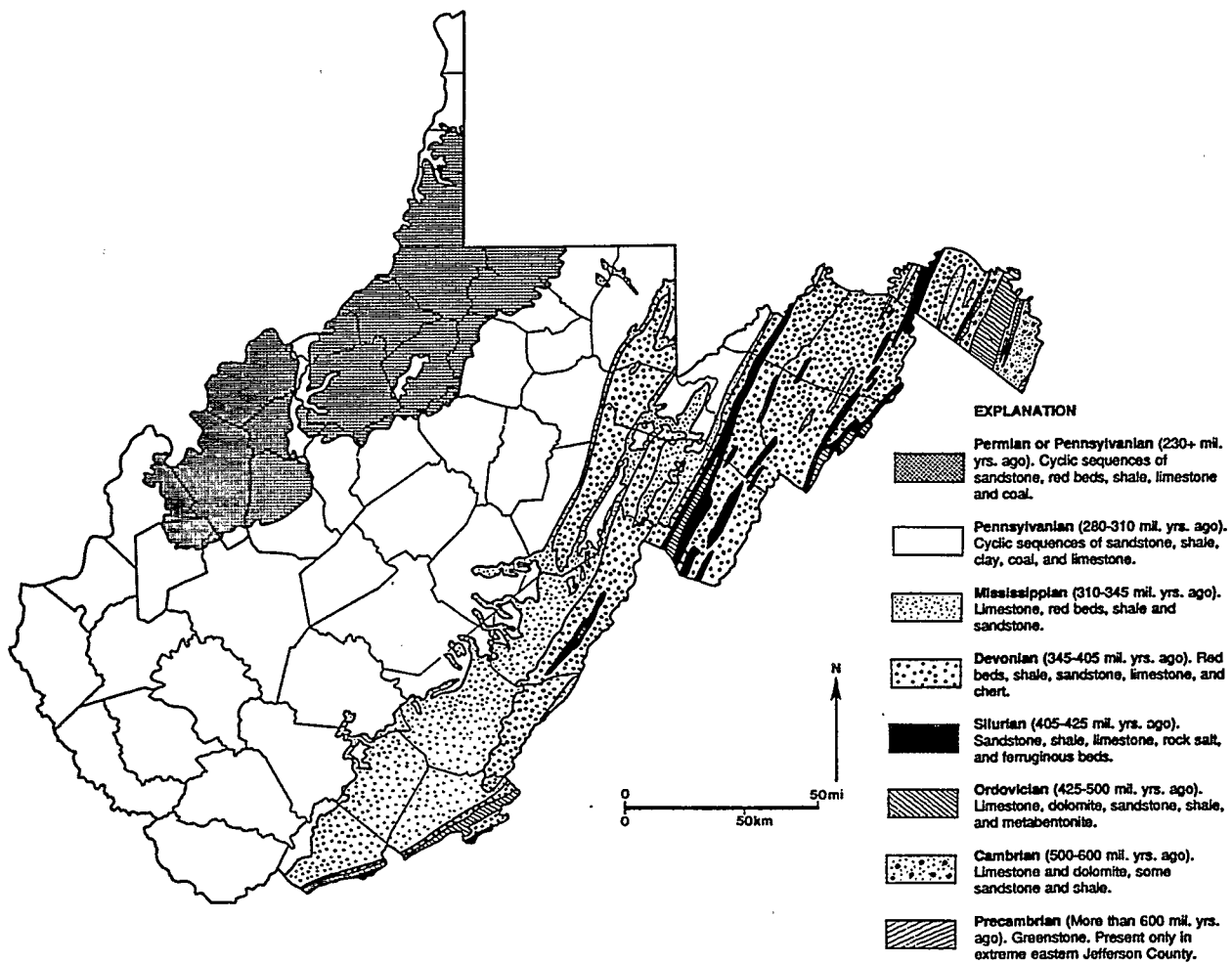


Fig. 4- Generalized bedrock geologic map of West Virginia. From Erwin, 1969.

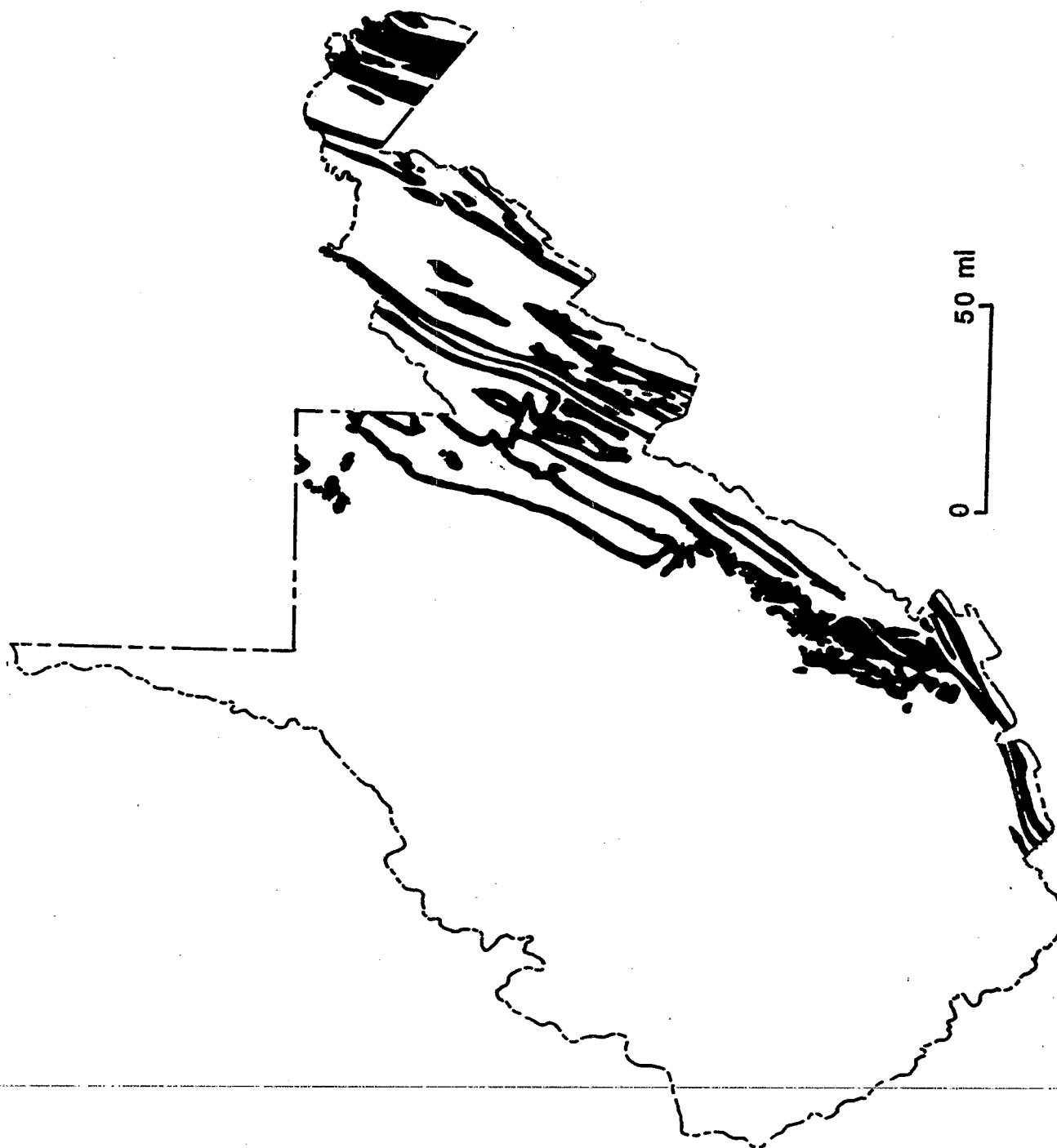


Fig. 5- Map showing the major outcrop areas of Cambrian through Mississippian limestone in West Virginia. These are areas that may contain karst and/or thick residual soils enriched in uranium and radium. The most important area of karst occurs in Greenbrier County (see Fig.6 for location) where historical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

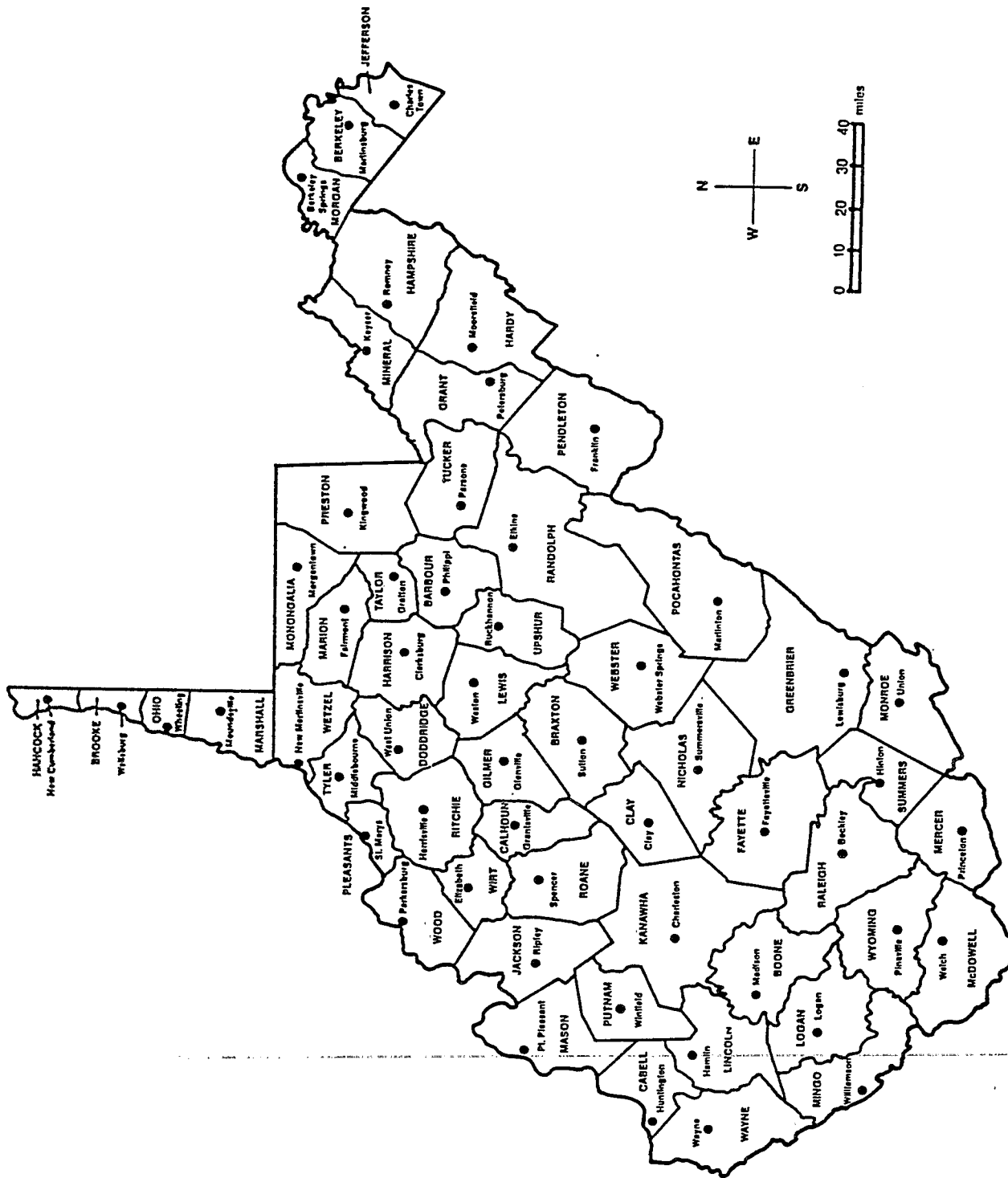


Fig. 6- Map showing counties in West Virginia. From Facts on File, Inc., 1984.

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 except 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).

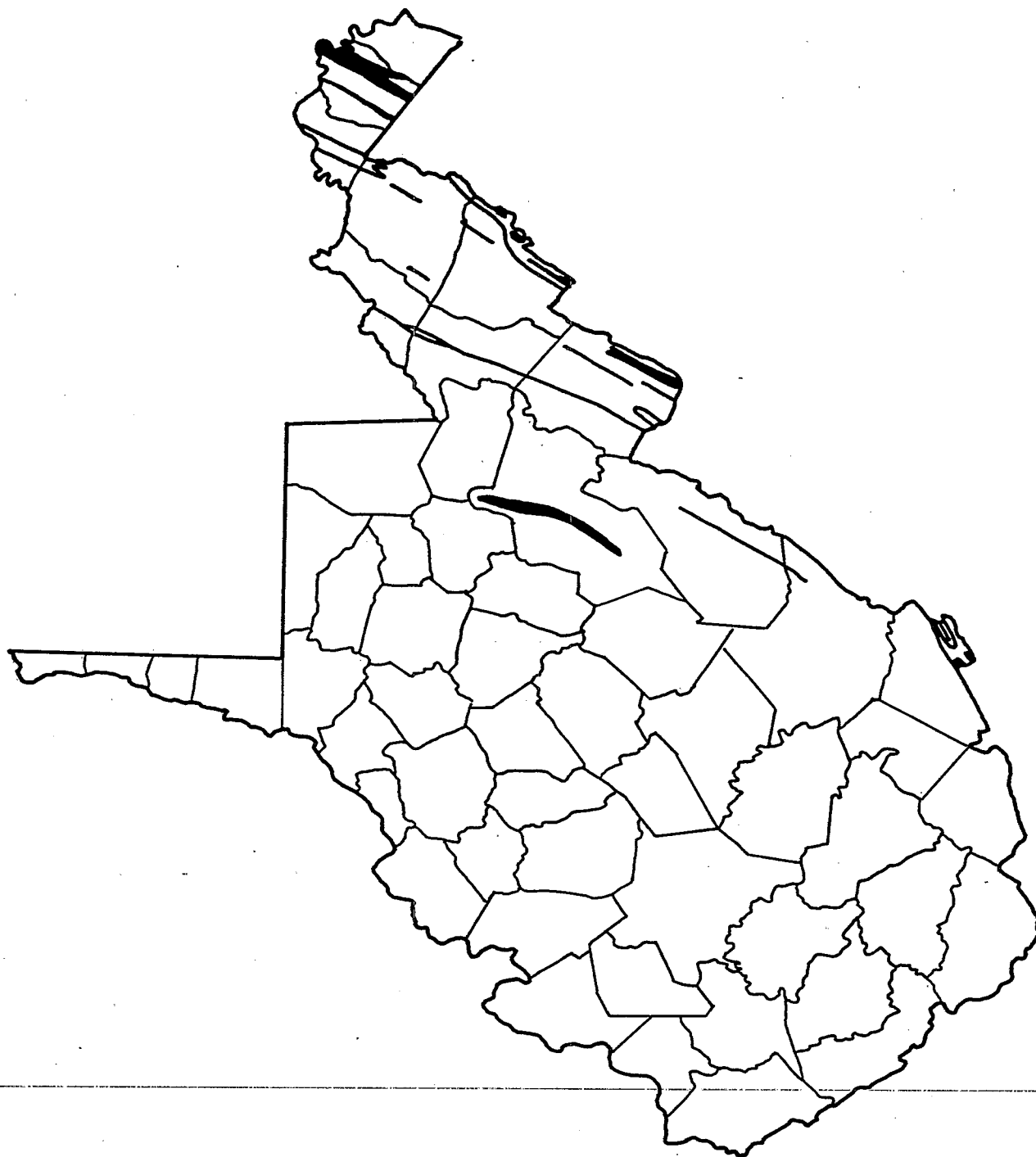


Fig. 8- Map showing the approximate location of outcrop belts of sedimentary rocks containing dark gray to black shales in West Virginia. For more precise location information and generalized descriptions of these uraniferous shale-bearing units see Cardwell and others, 1968.

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.

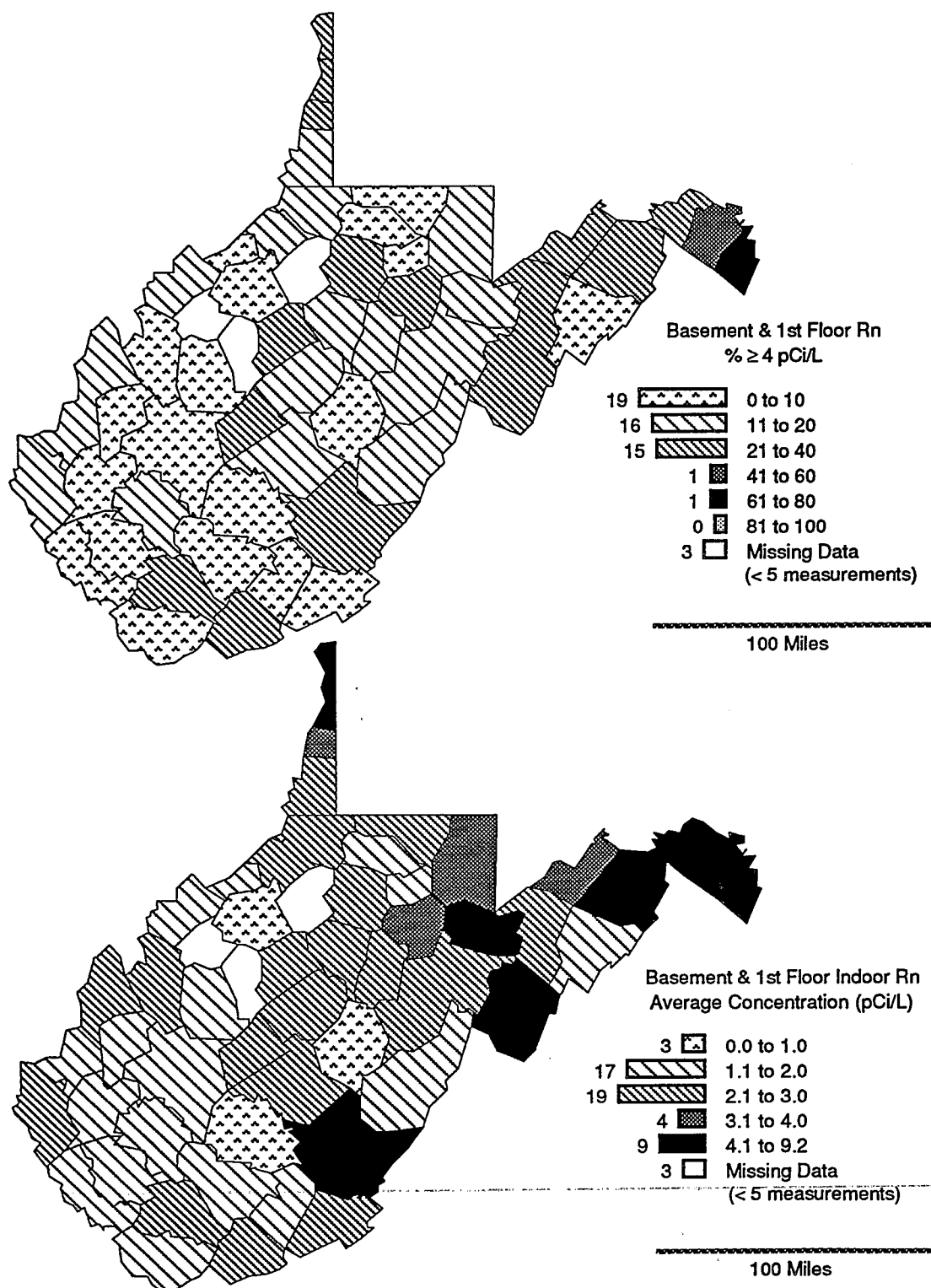


Figure 9. Screening indoor radon data from the EPA/State Residential radon Survey of West Virginia, 1988-89, for counties with 5 or more measurements. Data are from 2-7 day charcoal canister tests. Histograms in map legends show the number of counties in each category. The number of samples in each county (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 (Greenman 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.

FACTOR	Central Allegheny Plateau		Cumberland Plateau & Mountains		Eastern Allegheny Plateau & Mts	
	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

FACTOR	Southern Appalachian Ridge & Valley		Northern Appalachian Ridge & Valley	
	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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EPA's Map of Radon Zones

The USGS' Geologic Radon Province Map is the technical foundation for EPA's Map of Radon Zones. The Geologic Radon Province Map defines the radon potential for approximately 360 geologic provinces. EPA has adapted this information to fit a county boundary map in order to produce the Map of Radon Zones.

The Map of Radon Zones is based on the same range of predicted screening levels of indoor radon as USGS' Geologic Radon Province Map. EPA defines the three zones as follows: Zone One areas have an average predicted indoor radon screening potential greater than 4 pCi/L. Zone Two areas are predicted to have an average indoor radon screening potential between 2 pCi/L and 4 pCi/L. Zone Three areas are predicted to have an average indoor radon screening potential less than 2 pCi/L.

Since the geologic province boundaries cross state and county boundaries, a strict translation of counties from the Geologic Radon Province Map to the Map of Radon Zones was not possible. For counties that have variable radon potential (i.e., are located in two or more provinces of different rankings), the counties were assigned to a zone based on the predicted radon potential of the province in which most of its area lies. (See Part I for more details.)

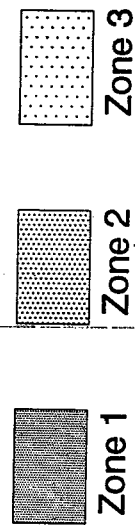
WEST VIRGINIA MAP OF RADON ZONES

The West Virginia Map of Radon Zones and its supporting documentation (Part IV of this report) have received extensive review by West Virginia geologists and radon program experts. The map for West Virginia generally reflects current State knowledge about radon for its counties. Some States have been able to conduct radon investigations in areas smaller than geologic provinces and counties, so it is important to consult locally available data.

Several West Virginia counties do not strictly follow the methodology for adapting geologic provinces to county boundaries. EPA and the West Virginia Department of Health have designated Hancock, Brooke, Ohio, Wetzel, Monongalia, Marshall, Preston, Greenbrier, Mercer, Summers, Monroe, and Pocahontas counties as Zone 1. Although most areas of these counties have moderate geologic radon potential, supplemental indoor radon data for these counties estimate that significant percentages of homes are above 4 pCi/L.

Although the information provided in Part IV of this report -- the State chapter entitled "Preliminary Geologic Radon Potential Assessment of West Virginia" -- may appear to be quite specific, it cannot be applied to determine the radon levels of a neighborhood, housing tract, individual house, etc. **THE ONLY WAY TO DETERMINE IF A HOUSE HAS ELEVATED INDOOR RADON IS TO TEST.** Contact the Region 3 EPA office or the West Virginia radon program for information on testing and fixing homes. Telephone numbers and addresses can be found in Part II of this report.

This map is not intended to determine if a home in a given zone should be tested for radon. Homes with elevated levels of radon have been found in all three zones. **All homes should be tested, regardless of zone designation.**



IMPORTANT: Consult the publication entitled "Preliminary Geologic Radon Potential Assessment of West Virginia" before using this map. This document contains information on radon potential variations within counties. EPA also recommends that this map be supplemented with any available local data in order to further understand and predict the radon potential of a specific area.

