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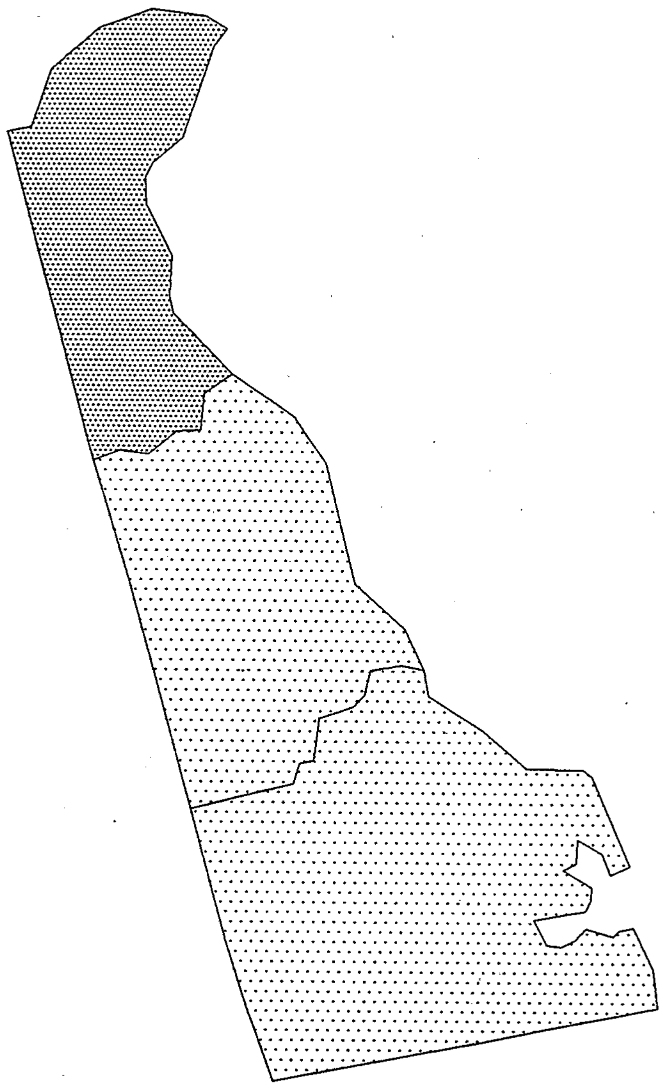
EPA's Map of Radon Zones

DELAWARE



EPA'S MAP OF RADON ZONES
DELAWARE

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

SEPTEMBER, 1993

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ORIA would also like to recognize the efforts of all the EPA Regional Offices in coordinating the reviews with the State programs and the Association of American State Geologists (AASG) for providing a liaison with the State geological surveys. In addition, appreciation is expressed to all of the State radon programs and geological surveys for their technical input and review of the Map of Radon Zones.

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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:

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

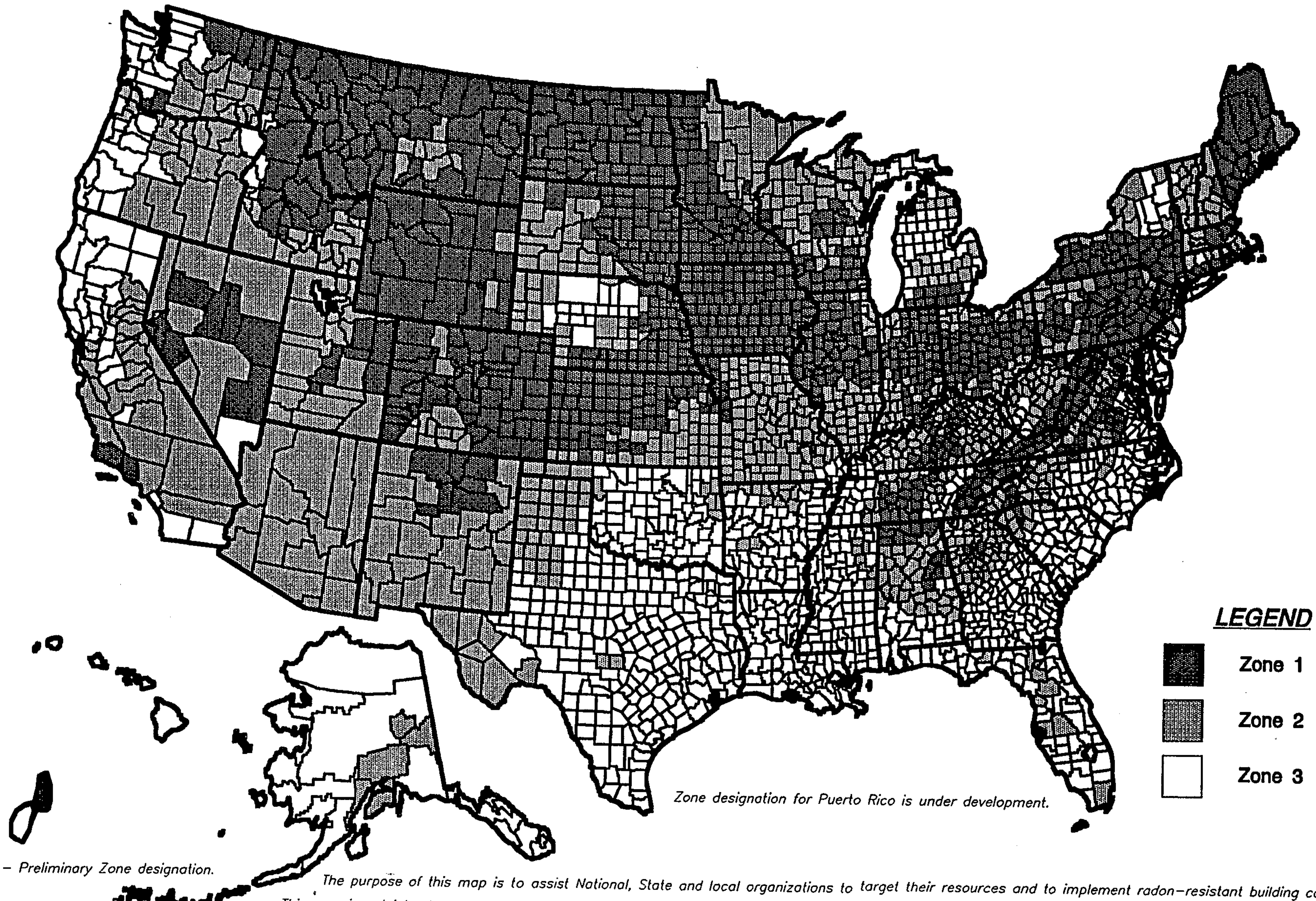
The Map of Radon Zones and its supporting documentation establish no regulatory requirements. Use of this map by State or local radon programs and building code officials is voluntary. The information presented on the Map of Radon Zones and in the supporting documentation is not applicable to radon in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



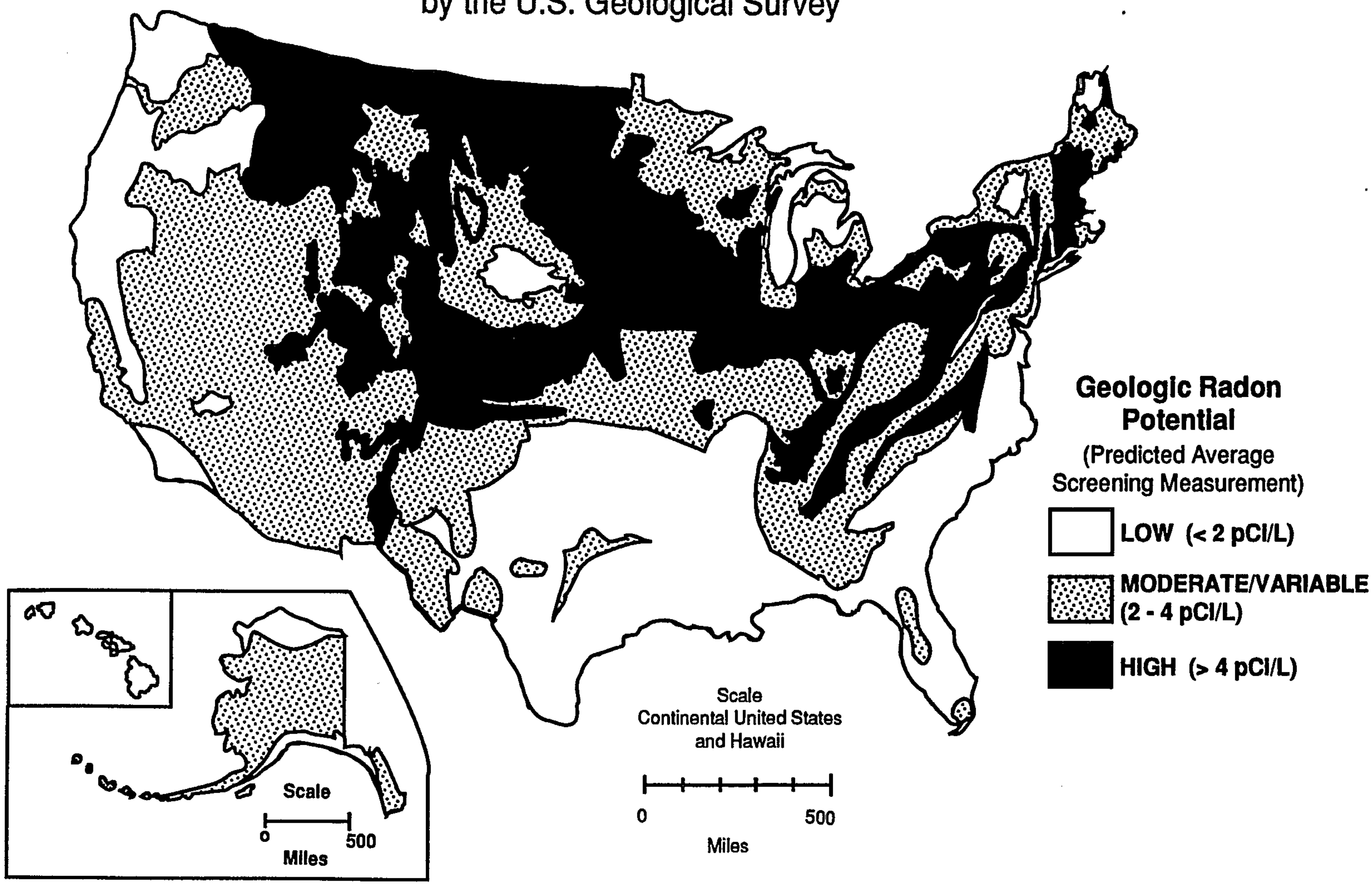
The purpose of this map is to assist National, State and local organizations to target their resources and to implement radon–resistant building codes. This map is not intended to be used to determine if a home in a given zone should be tested for radon. Homes with elevated levels of radon have been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



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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

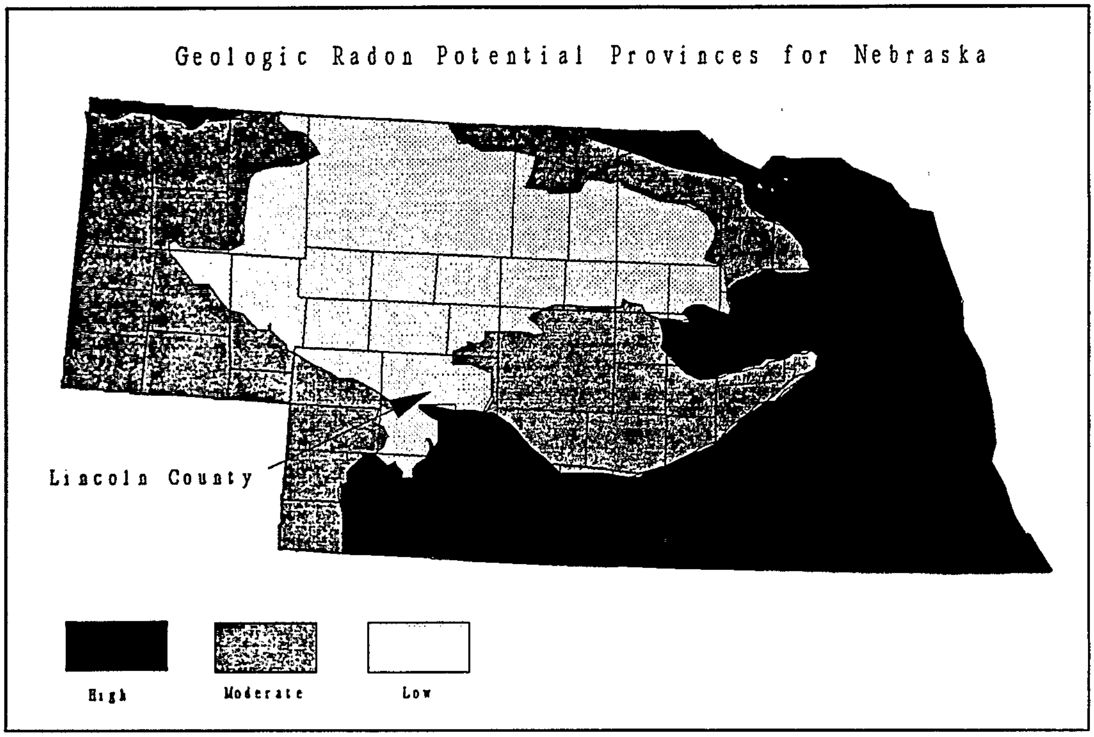
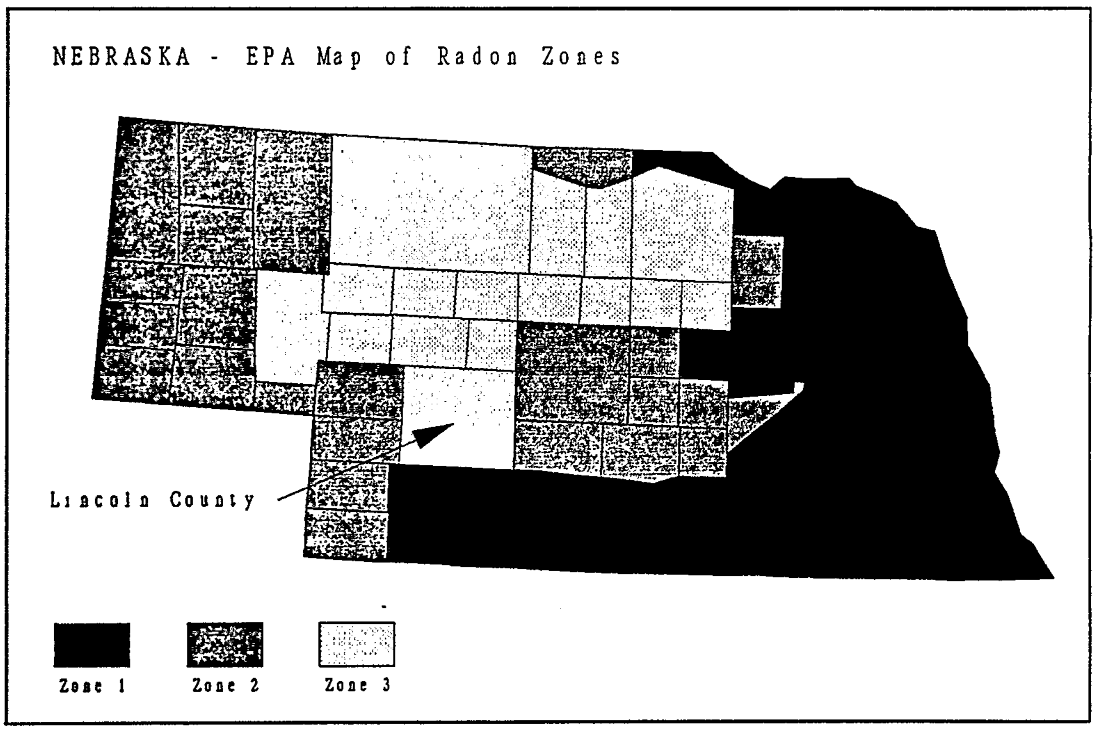


Figure 4



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

BACKGROUND

The Indoor Radon Abatement Act of 1988 (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

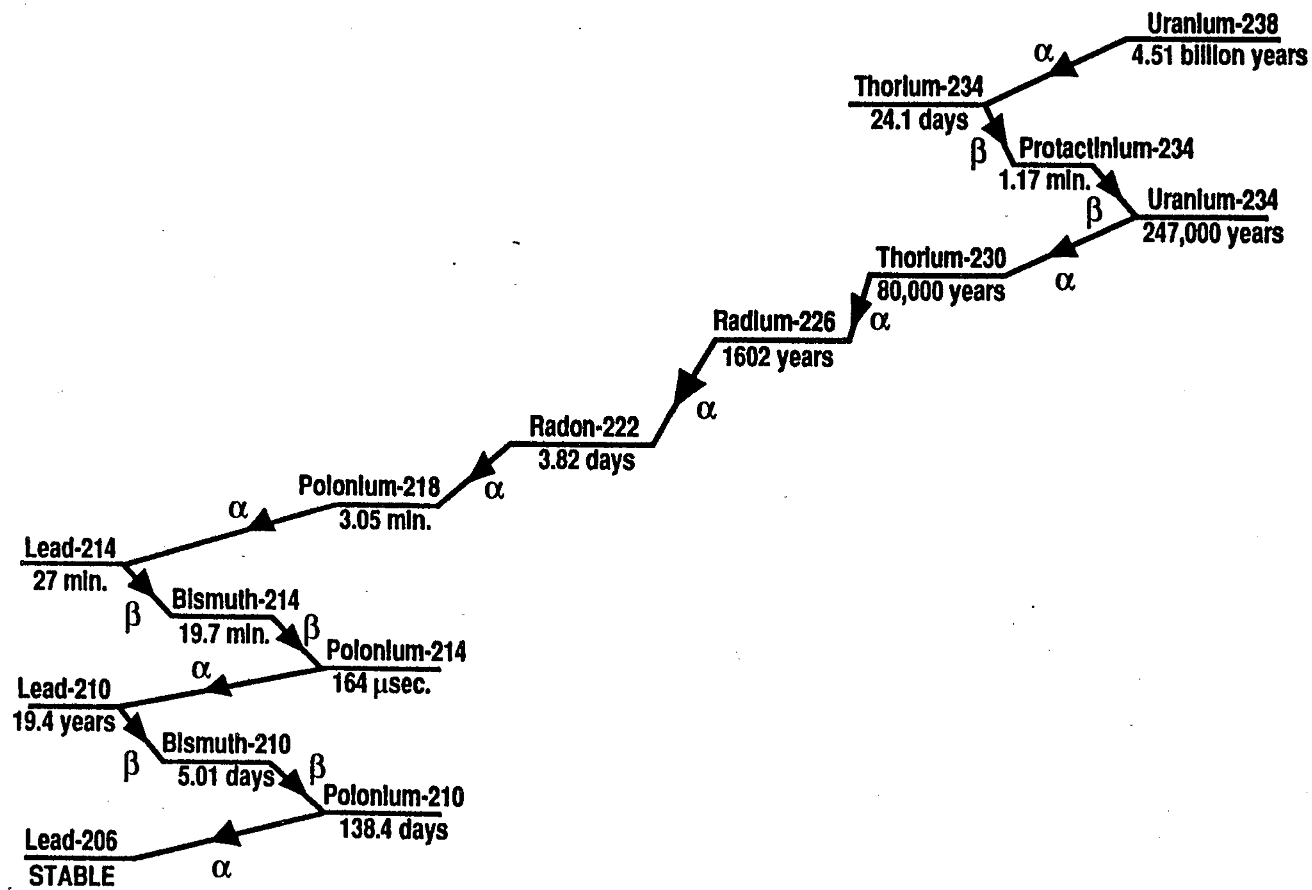


Figure 1. The uranium-238 decay series, showing the half-lives of elements and their modes of decay (after Wanty and Schoen, 1991). α denotes alpha decay, β denotes beta decay.

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 nm = 10^{-9} meters), or about 2×10^{-6} inches—this is known as alpha recoil (Tanner, 1980). Moisture in the soil lessens the chance of a recoiling radon atom becoming imbedded in an adjacent grain. Because water is more dense than air, a radon atom will travel a shorter distance in a water-filled pore than in an air-filled pore, thus increasing the likelihood that the radon atom will remain in the pore space. Intermediate moisture levels enhance radon emanation but do not significantly affect permeability. However, high moisture levels can significantly decrease the gas permeability of the soil and impede radon movement through the soil.

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

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

RADON ENTRY INTO BUILDINGS

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

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

METHODS AND SOURCES OF DATA

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

GEOLOGIC DATA

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

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

NURE Aerial Radiometric Data

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

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

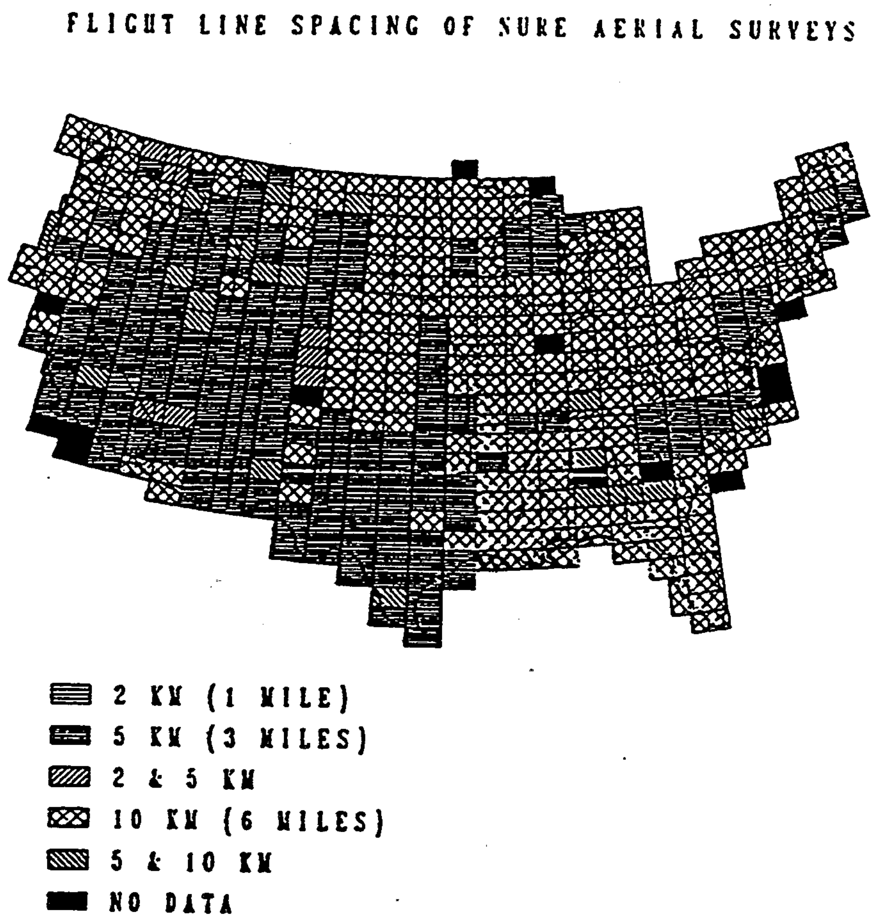


Figure 2. Nominal flightline spacings for NURE aerial gamma-ray surveys covering the contiguous United States (from Duval and others, 1990). Rectangles represent 1°x2° quadrangles.

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.

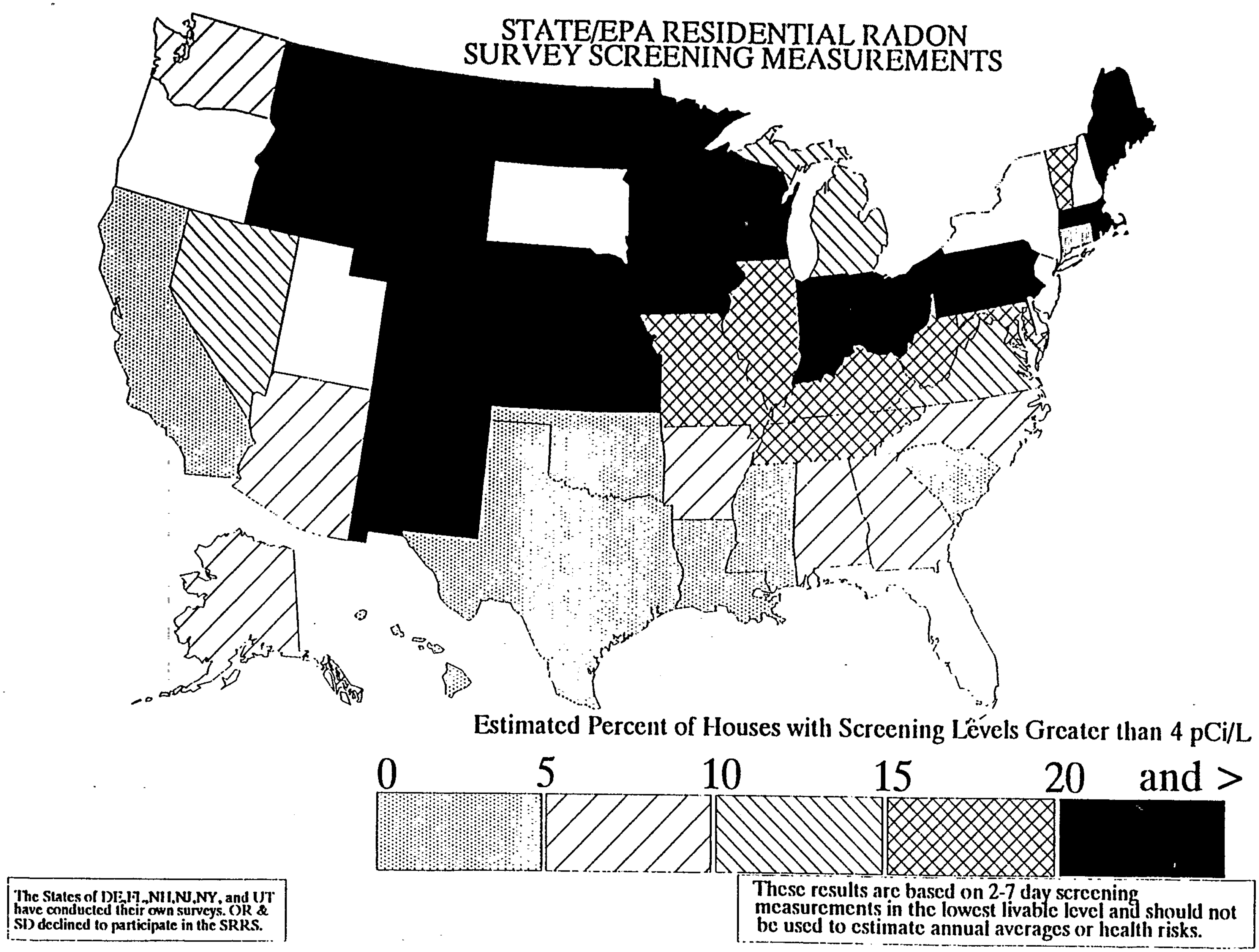


Figure 3. Percent of homes tested in the State/EPA Residential Radon Survey with screening indoor radon levels exceeding 4 pCi/L.

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.

INCREASING RADON POTENTIAL →

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

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

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

SCORING:

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

POSSIBLE RANGE OF POINTS = 3 to 17

TABLE 2. CONFIDENCE INDEX MATRIX

INCREASING CONFIDENCE →

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

SCORING:

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

POSSIBLE RANGE OF POINTS = 4 to 12

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, localizeddistribution 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.

REFERENCES CITED

Akerblom, G., Anderson, P., and Clavensjo, B., 1984, Soil gas radon--A source for indoor radon daughters: Radiation Protection Dosimetry, v. 7, p. 49-54.

Deffeyes, K.S., and MacGregor, I.D., 1980, World uranium resources: Scientific American, v. 242, p. 66-76.

Durrance, E.M., 1986, Radioactivity in geology: Principles and applications: New York, N.Y., Wiley and Sons, 441 p.

Duval, J.S., 1989, Radioactivity and some of its applications in geology: Proceedings of the symposium on the application of geophysics to engineering and environmental problems (SAGEEP), Golden, Colorado, March 13-16, 1989: Society of Engineering and Mineral Exploration Geophysicists, p. 1-61.

Duval, J.S., Cook, B.G., and Adams, J.A.S., 1971, Circle of investigation of an airborne gamma-ray spectrometer: Journal of Geophysical Research, v. 76, p. 8466-8470.

Duval, J.S., Jones, W.J., Riggle, F.R., and Pitkin, J.A., 1989, Equivalent uranium map of conterminous United States: U.S. Geological Survey Open-File Report 89-478, 10 p.

Duval, J.S., Reimer, G.M., Schumann, R.R., Owen, D.E., and Otton, J.K., 1990, Soil-gas radon compared to aerial and ground gamma-ray measurements at study sites near Greeley and Fort Collins, Colorado: U.S. Geological Survey Open-File Report 90-648, 42 p.

Dziuban, J.A., Clifford, M.A., White, S.B., Bergstein, J.W., and Alexander, B.V., 1990, Residential radon survey of twenty-three States, *in* Proceedings of the 1990 International Symposium on Radon and Radon Reduction Technology, Vol. III: Preprints: U.S. Environmental Protection Agency report EPA/600/9-90/005c, Paper IV-2, 17 p.

Gammage, R.B., Wilson, D.L., Saultz, R.J., and Bauer, B.C., 1993, Subtereanean transport of radon and elevated indoor radon in hilly karst terranes: Atmospheric Environment (in press).

Gundersen, L.C.S., Reimer, G.M., and Agard, S.S., 1988a, Correlation between geology, radon in soil gas, and indoor radon in the Reading Prong, *in* Marikos, M.A., and Hansman, R.H., eds., Geologic causes of natural radionuclide anomalies: Missouri Department of Natural Resources Special Publication 4, p. 91-102.

Gundersen, L.C.S, Reimer, G.M., Wiggs, C.R., and Rice, C.A., 1988b, Map showing radon potential of rocks and soils in Montgomery County, Maryland: U.S. Geological Survey Miscellaneous Field Studies Map MF-2043, scale 1:62,500.

Gundersen, Linda C.S., 1991, Radon in sheared metamorphic and igneous rocks, *in* Gundersen, Linda C.S., and Richard B. Wanty, eds., Field studies of radon in rocks, soils, and water: U.S. Geol. Survey Bulletin no. 1971, p. 39-50.

Henry, Mitchell E., Kaeding, Margret E., and Monteverde, Donald, 1991, Radon in soil gas and gamma-ray activity of rocks and soils at the Mulligan Quarry, Clinton, New Jersey, *in* Gundersen, Linda C.S., and Richard B. Wanty, eds., Field studies of radon in rocks, soils, and water: U.S. Geol. Survey Bulletin no. 1971, p. 65-75.

Klusman, R. W., and Jaacks, J. A., 1987, Environmental influences upon mercury, radon, and helium concentrations in soil gases at a site near Denver, Colorado: Journal of Geochemical Exploration, v. 27, p. 259-280.

Kovach, E.M., 1945, Meteorological influences upon the radon content of soil gas: Transactions, American Geophysical Union, v. 26, p. 241-248.

Kunz, C., Laymon, C.A., and Parker, C., 1989, Gravelly soils and indoor radon, *in* Osborne, M.C., and Harrison, J., eds., Proceedings of the 1988 EPA Symposium on Radon and Radon Reduction Technology, Volume 1: U.S. Environmental Protection Agency Report EPA/600/9-89/006A, p. 5-75--5-86.

Muessig, K., and Bell, C., 1988, Use of airborne radiometric data to direct testing for elevated indoor radon: Northeastern Environmental Science, v. 7, no. 1, p. 45-51.

Ronca-Battista, M., Moon, M., Bergsten, J., White, S.B., Holt, N., and Alexander, B., 1988, Radon-222 concentrations in the United States--Results of sample surveys in five states: Radiation Protection Dosimetry, v. 24, p. 307-312.

Rose, A.W., Washington, J.W., and Greeman, D.J., 1988, Variability of radon with depth and season in a central Pennsylvania soil developed on limestone: Northeastern Environmental Science, v. 7, p. 35-39.

Schery, S.D., Gaeddert, D.H., and Wilkening, M.H., 1984, Factors affecting exhalation of radon from a gravelly sandy loam: Journal of Geophysical Research, v. 89, p. 7299-7309.

Schumann, R.R., and Owen, D.E., 1988, Relationships between geology, equivalent uranium concentration, and radon in soil gas, Fairfax County, Virginia: U.S. Geological Survey Open-File Report 88-18, 28 p.

Schumann, R.R., and Gundersen, L.C.S., 1991, Regional differences in radon emanation coefficients in soils: Geological Society of America Abstracts With Programs, v. 23, no. 1, p. 125.

Schumann, R.R., Peake, R.T., Schmidt, K.M., and Owen, D.E., 1991, Correlations of soil-gas and indoor radon with geology in glacially derived soils of the northern Great Plains, *in* Proceedings of the 1990 International Symposium on Radon and Radon Reduction Technology, Volume 2, Symposium Oral Papers: U.S. Environmental Protection Agency report EPA/600/9-91/026b, p. 6-23--6-36.

Schumann, R.R., Owen, D.E., and Asher-Bolinder, S., 1992, Effects of weather and soil characteristics on temporal variations in soil-gas radon concentrations, *in* Gates, A.E., and Gundersen, L.C.S., eds., Geologic controls on radon: Geological Society of America Special Paper 271, p. 65-72.

Sextro, R.G., Moed, B.A., Nazaroff, W.W., Revzan, K.L., and Nero, A.V., 1987, Investigations of soil as a source of indoor radon, *in* Hopke, P.K., ed., Radon and its decay products: American Chemical Society Symposium Series 331, p. 10-29.

Sterling, R., Meixel, G., Shen, L., Labs, K., and Bligh, T., 1985, Assessment of the energy savings potential of building foundations research: Oak Ridge, Tenn., U.S. Department of Energy Report ORNL/SUB/84-0024/1.

Smith, R.C., II, Reilly, M.A., Rose, A.W., Barnes, J.H., and Berkheiser, S.W., Jr., 1987, Radon: a profound case: Pennsylvania Geology, v. 18, p. 1-7.

Tanner, A.B., 1964, Radon migration in the ground: a review, *in* Adams, J.A.S., and Lowder, W.M., eds., The natural radiation environment: Chicago, Ill., University of Chicago Press, p. 161-190.

Tanner, A.B., 1980, Radon migration in the ground: a supplementary review, *in* Gesell, T.F., and Lowder, W.M. (eds), Natural radiation environment III, Symposium proceedings, Houston, Texas, v. 1, p. 5-56.

U.S. Department of Agriculture, 1987, Principal kinds of soils: Orders, suborders, and great groups: U.S. Geological Survey, National Atlas of the United States of America, sheet 38077-BE-NA-07M-00, scale 1:7,500,000.

U.S. Department of Energy, 1976, National Uranium Resource Evaluation preliminary report, prepared by the U.S. Energy Research and Development Administration, Grand Junction, Colo.: GJO-11(76).

Wanty, Richard B., and Schoen, Robert, 1991, A review of the chemical processes affecting the mobility of radionuclides in natural waters, with applications, *in* Gundersen, Linda C.S., and Richard B. Wanty, eds., Field studies of radon in rocks, soils, and water: U.S. Geological Survey Bulletin no. 1971, p. 183-194.

Washington, J.W., and Rose, A.W., 1990, Regional and temporal relations of radon in soil gas to soil temperature and moisture: Geophysical Research Letters, v. 17, p. 829-832.

White, S.B., Bergsten, J.W., Alexander, B.V., and Ronca-Battista, M., 1989, Multi-State surveys of indoor ^{222}Rn: Health Physics, v. 57, p. 891-896.

APPENDIX A
GEOLOGIC TIME SCALE

Subdivisions (and their symbols)						Age estimates of boundaries in mega-annum (Ma)[1]
Eon or Eonothem	Era or Erathem	Period, System, Subperiod, Subsystem		Epoch or Series		
Phanerozoic[2]	Cenozoic[2] (Cz)	Quaternary[2] (Q)		Holocene		0.010
				Pleistocene		1.6 (1.6–1.9)
		Tertiary (T)	Neogene[2] Subperiod or Subsystem (N)	Pliocene		5 (4.9–5.3)
				Miocene		24 (23–26)
			Paleogene[2] Subperiod or Subsystem (Pε)	Oligocene		38 (34–38)
				Eocene		55 (54–56)
				Paleocene		66 (63–66)
	Mesozoic[2] (Mz)	Cretaceous (K)		Late	Upper	96 (95–97)
				Early	Lower	138 (135–141)
		Jurassic (J)		Late	Upper	
				Middle	Middle	
				Early	Lower	205 (200–215)
		Triassic (Ŧ)		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 (Є)		Late	Upper	
				Middle	Middle	
				Early	Lower	~570[3]
Proterozoic (Ꝑ)	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 (pЄ), 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/m^3.

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

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

Geologic terms and terms related to the study of radon

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

eolian Pertaining to sediments deposited by the wind.

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

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

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

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

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

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

formation A mappable body of rock having similar characteristics.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

nlacer deposit See heavy minerals

residual Formed by weathering of a material in place.

residuum Deposit of residual material.

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

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

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

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

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

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

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

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

shrink-swell clay See clay mineral.

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

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

slope An inclined part of the earth's surface.

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

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

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

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

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

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

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

uraniferous Containing uranium, usually more than 2 ppm.

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

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

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

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

APPENDIX C
EPA REGIONAL OFFICES

EPA Regional Offices
EPA Region 1 JFK Federal Building Boston, MA 02203 (617) 565-4502
EPA Region 2 (2AIR:RAD) 26 Federal Plaza New York, NY 10278 (212) 264-4110
Region 3 (3AH14) 841 Chestnut Street Philadelphia, PA 19107 (215) 597-8326
EPA Region 4 345 Courtland Street, N.E. Atlanta, GA 30365 (404) 347-3907
EPA Region 5 (5AR26) 77 West Jackson Blvd. Chicago, IL 60604-3507 (312) 886-6175
EPA Region 6 (6T-AS) 1445 Ross Avenue Dallas, TX 75202-2733 (214) 655-7224
EPA Region 7 726 Minnesota Avenue Kansas City, KS 66101 (913) 551-7604
EPA Region 8 (8HWM-RP) 999 18th Street One Denver Place, Suite 1300 Denver, CO 80202-2413 (303) 293-1713
EPA Region 9 (A-3) 75 Hawthorne Street San Francisco, CA 94105 (415) 744-1048
EPA Region 10 1200 Sixth Avenue Seattle, WA 98101 (202) 442-7660

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

STATE RADON CONTACTS

May, 1993

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

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

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

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

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

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

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

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

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

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

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

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

Idaho
Pat McGavarn
Office of Environmental Health
450 West State Street
Boise, ID 83720
(208) 334-6584
1-800-445-8647 in state

Illinois
Richard Allen
Illinois Department of Nuclear Safety
1301 Outer Park Drive
Springfield, IL 62704
(217) 524-5614
1-800-325-1245 in state

Indiana
Lorand Magyar
Radiological Health Section
Indiana State Department of Health
1330 West Michigan Street
P.O. Box 1964
Indianapolis, IN 46206
(317) 633-8563
1-800-272-9723 In State

Iowa
Donald A. Flater
Bureau of Radiological Health
Iowa Department of Public Health
Lucas State Office Building
Des Moines, IA 50319-0075
(515) 281-3478
1-800-383-5992 In State

Kansas
Harold Spiker
Radiation Control Program
Kansas Department of Health and Environment
109 SW 9th Street
6th Floor Mills Building
Topeka, KS 66612
(913) 296-1561

Kentucky
Jeana Phelps
Radiation Control Branch
Department of Health Services
Cabinet for Human Resources
275 East Main Street
Frankfort, KY 40601
(502) 564-3700

Louisiana
Matt Schlenker
Louisiana Department of Environmental Quality
P.O. Box 82135
Baton Rouge, LA 70884-2135
(504) 925-7042
1-800-256-2494 in state

Maine
Bob Stilwell
Division of Health Engineering
Department of Human Services
State House, Station 10
Augusta, ME 04333
(207) 289-5676
1-800-232-0842 in state

Maryland
Leon J. Rachuba
Radiological Health Program
Maryland Department of the Environment
2500 Broening Highway
Baltimore, MD 21224
(410) 631-3301
1-800-872-3666 In State

Massachusetts
William J. Bell
Radiation Control Program
Department of Public Health
23 Service Center
Northampton, MA 01060
(413) 586-7525
1-800-445-1255 in state

Michigan
Sue Hendershott
Division of Radiological Health
Bureau of Environmental and Occupational Health
3423 North Logan Street
P.O. Box 30195
Lansing, MI 48909
(517) 335-8194

Minnesota
Laura Oatmann
Indoor Air Quality Unit
925 Delaware Street, SE
P.O. Box 59040
Minneapolis, MN 55459-0040
(612) 627-5480
1-800-798-9050 in state

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

STATE GEOLOGICAL SURVEYS

May, 1993

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

EPA REGION 3 GEOLOGIC RADON POTENTIAL SUMMARY

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

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

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

DELAWARE

Piedmont

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

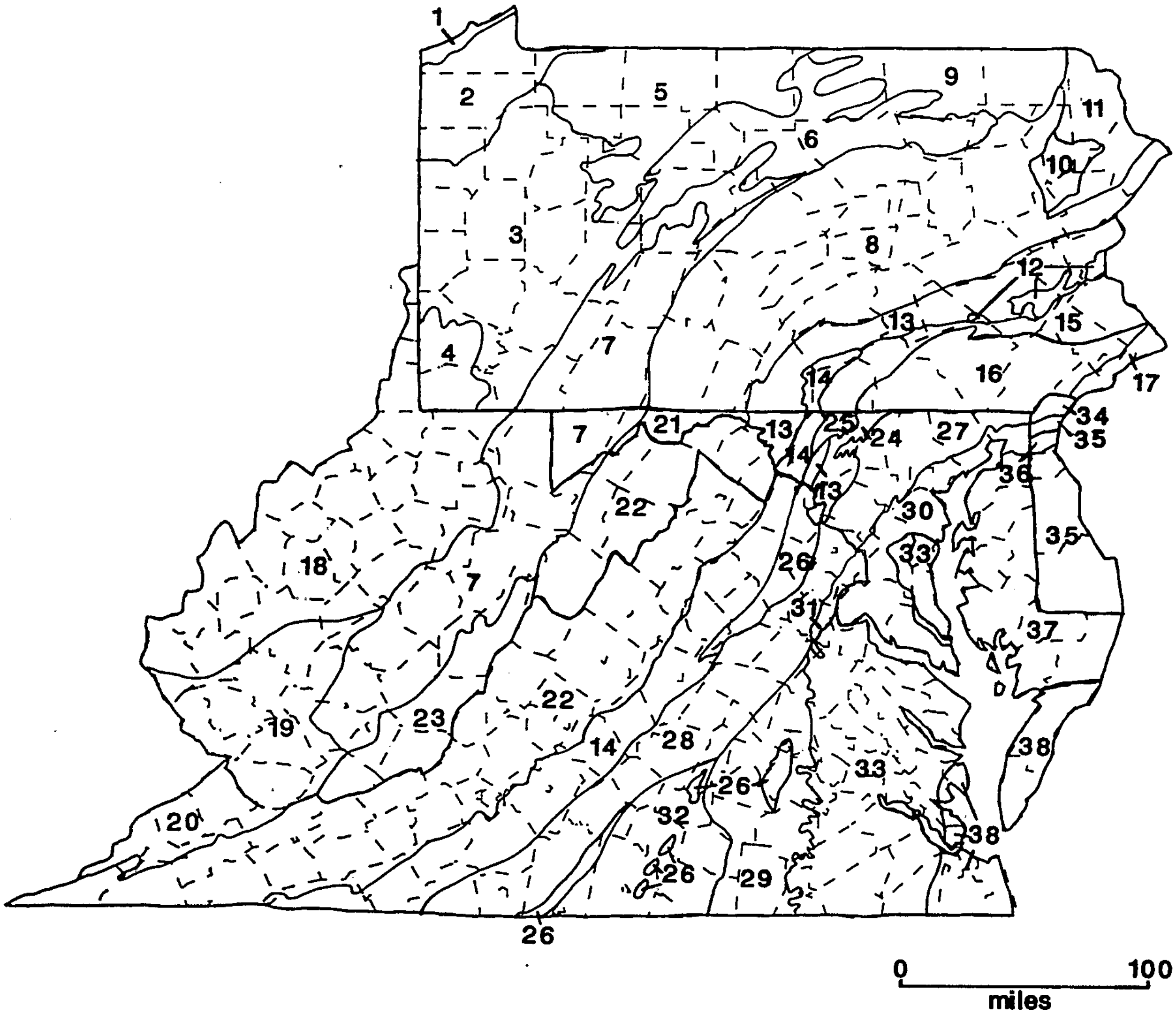


Figure 1. Geologic radon potential areas of EPA Region 3. 1–Central Lowland; 2–Glaciated Pittsburgh Plateau; 3–Pennsylvanian rocks of the Pittsburgh Low Plateau; 4–Permian rocks of the Pittsburgh Low Plateau; 5–High Plateau Section; 6–Mountainous High Plateau; 7–Allegheny Plateau and Mountains; 8–Appalachian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

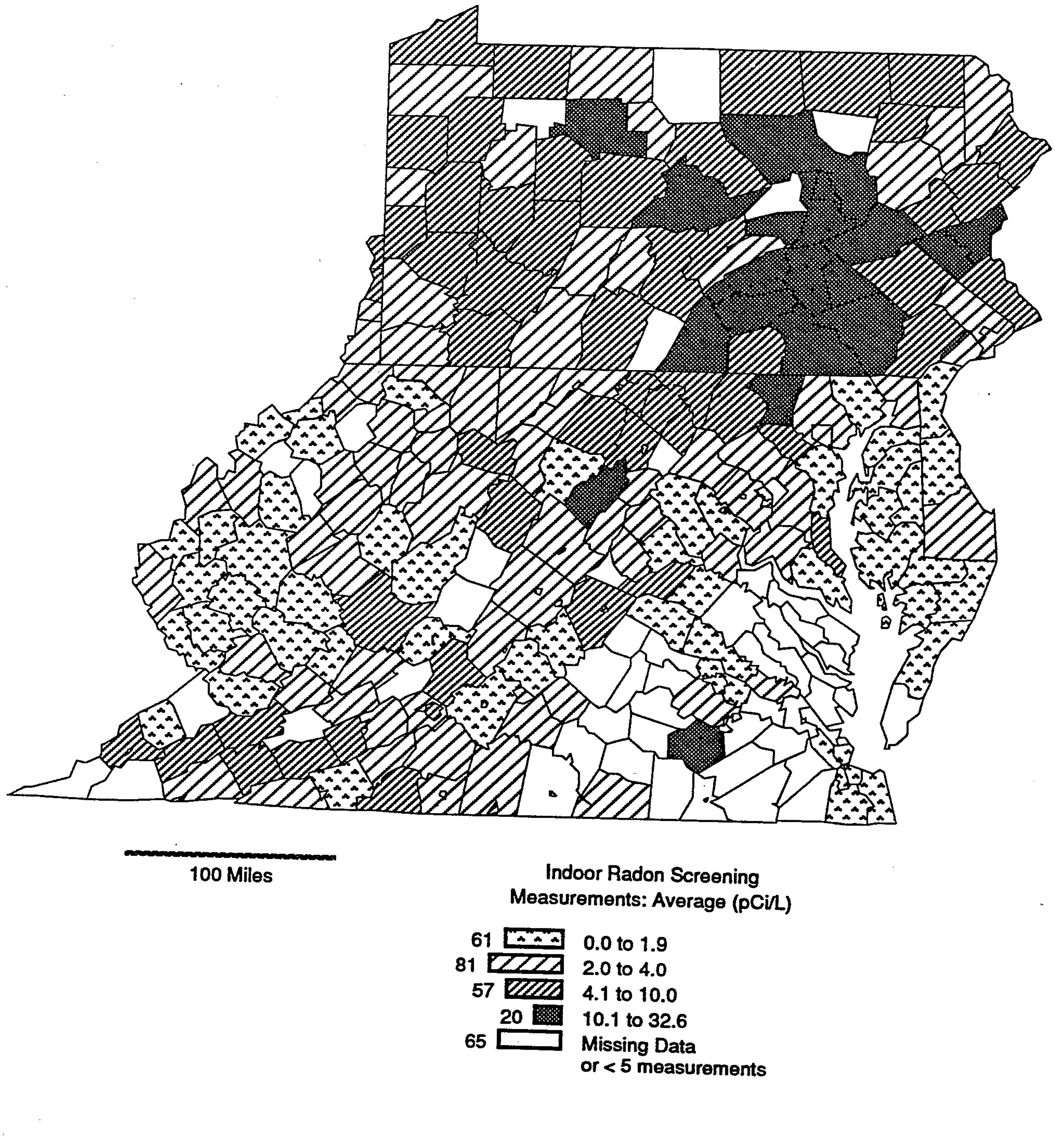


Figure 2. Screening indoor radon averages for counties with 5 or more measurements in EPA Region 3. Data for Maryland, Pennsylvania, Virginia, and West Virginia are from the State/EPA Residential Radon Survey. Data for Delaware were compiled by the Delaware Department of Health and Social Services. Histograms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

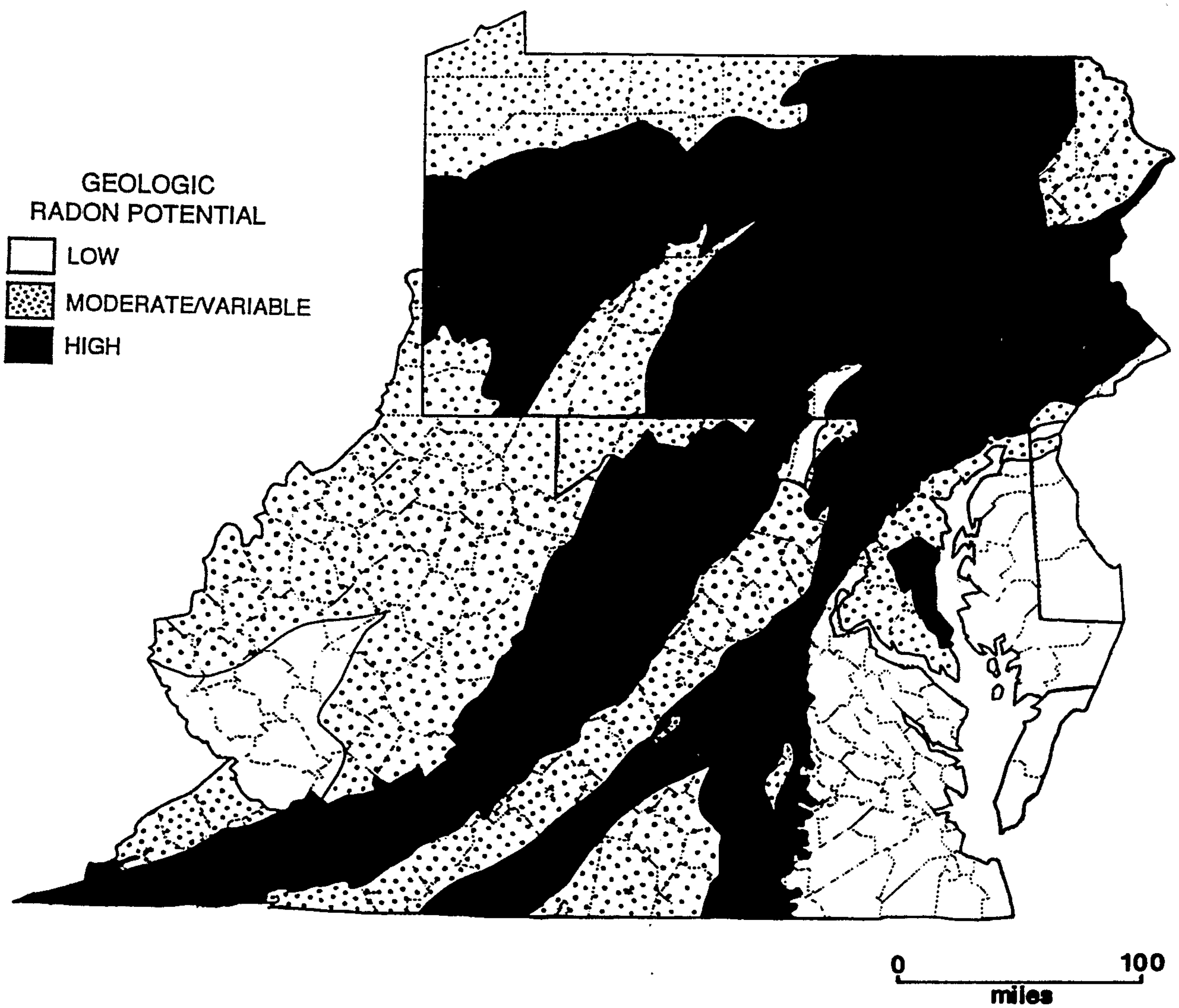


Figure 3. Geologic radon potential of EPA Region 3. For more detail, refer to individual state radon potential chapters.

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

Coastal Plain

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

MARYLAND

Coastal Plain

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

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

Piedmont

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

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

Appalachian Mountains

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

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

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

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

PENNSYLVANIA

New England Province

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

Piedmont

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

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

Blue Ridge

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

Ridge and Valley and Appalachian Plateaus

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

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

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

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

Coastal Plain

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

Glaciated Areas of Pennsylvania

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

VIRGINIA

Coastal Plain

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

Piedmont

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

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

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

Valley and Ridge

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

Appalachian Plateaus

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

WEST VIRGINIA

Allegheny Plateau

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

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

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

Ridge and Valley Province

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

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

PRELIMINARY GEOLOGIC RADON POTENTIAL ASSESSMENT OF DELAWARE

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

INTRODUCTION

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

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

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

PHYSIOGRAPHIC AND GEOGRAPHIC SETTING

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

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

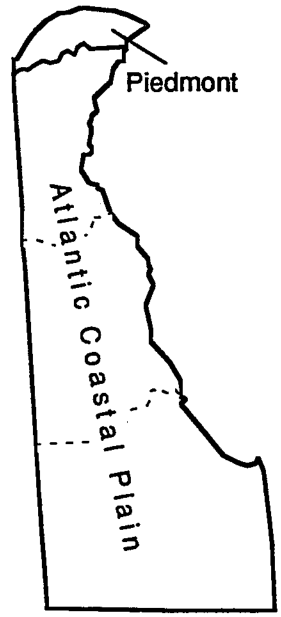


Figure 1. Physiographic areas of Delaware.

GEOLOGY AND SOILS

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

The Piedmont

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

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

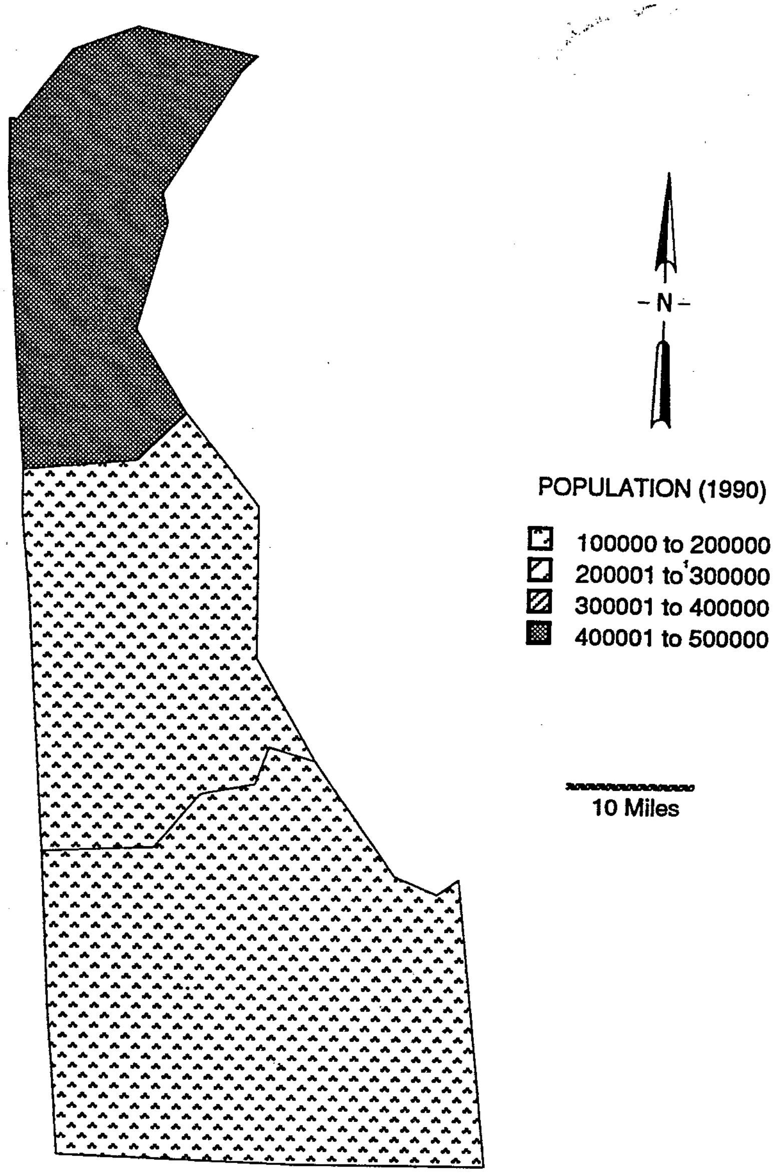


Figure 2. Population of counties in Delaware (1990 U.S. Census data).

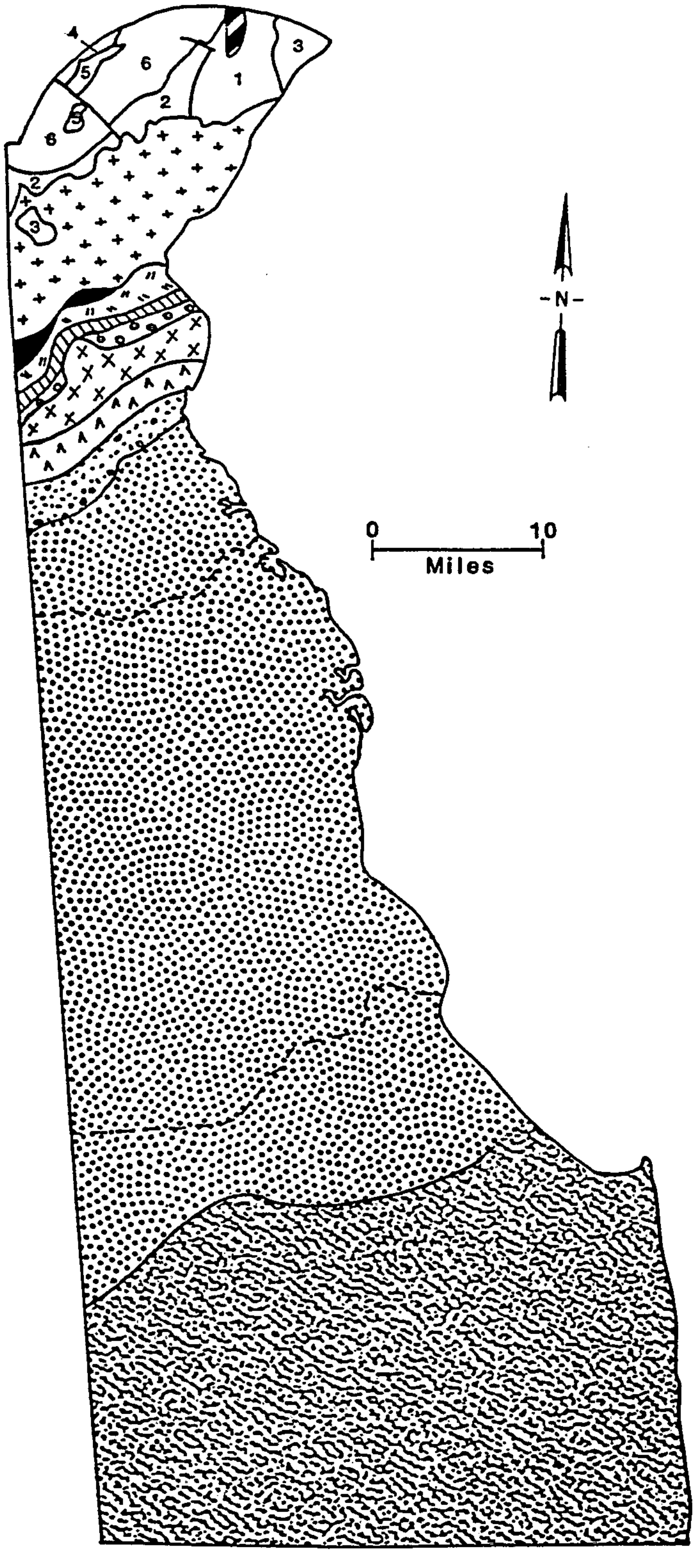


Figure 3. Generalized geologic map of Delaware showing rock units ranging in age from Precambrian to Tertiary (after Pickett, 1976). Quaternary units are shown on the surficial geologic map (fig. 5).

GENERALIZED GEOLOGIC MAP OF DELAWARE (PRECAMBRIAN-TERTIARY)
EXPLANATION

TERTIARY

PLIOCENE

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

PLIOCENE?

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

MIOCENE-PLIOCENE(?)

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

PALEOCENE-EOCENE(?)

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

CRETACEOUS-PALEOCENE

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

CRETACEOUS

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

Matawan Group

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

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

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

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

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

PRECAMBRIAN-PALEOZOIC

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

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

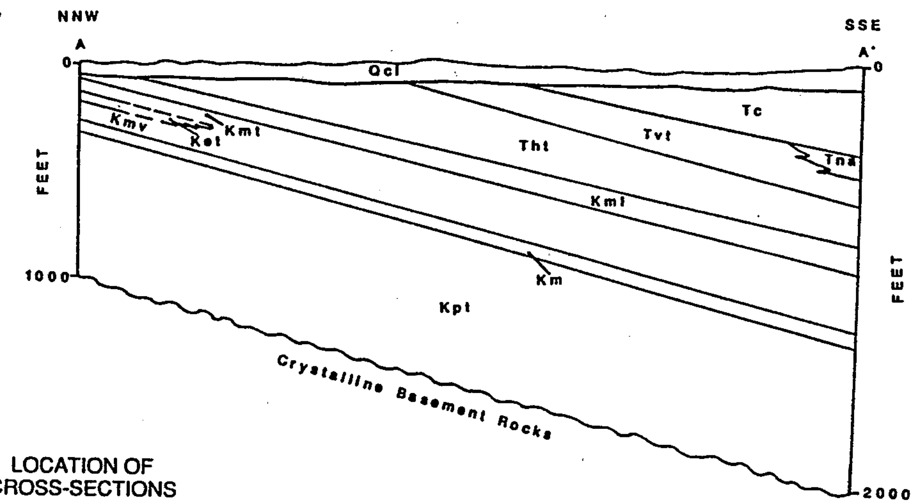
4 **Baltimore Gneiss** - Feldspathic biotite gneiss and minor schist.

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

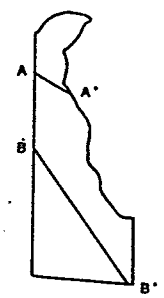
2 **James Run Formation** - Amphibolite; hypersthene gneiss and minor pelitic gneiss.

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

A.



LOCATION OF CROSS-SECTIONS



EXPLANATION

- **Qhl** - Holocene Deposits
- **QToml, Qomu** - Omar Formation
- **Qcl** - Columbia Formation
- **Tbd** - Beaverdam Formation
- **Tbt** - Bethany Formation
- **Tma, Tmb** - Manokin Formation
- **Tsm** - St. Marys Formation
- **Tch** - Choptank Formation
- **Tc** - Calvert Formation
- **Tna** - Nanjemoy Formation
- **Tvt** - Vincentown Formation
- **Tht** - Hornerstown Formation
- **Kml** - Mount Laurel Formation
- **Kmt** - Marshalltown Formation
- **Ket** - Englishtown Formation
- **Kmv** - Merchantville Formation
- **Km** - Magothy Formation
- **Kpt** - Potomac Formation

B.

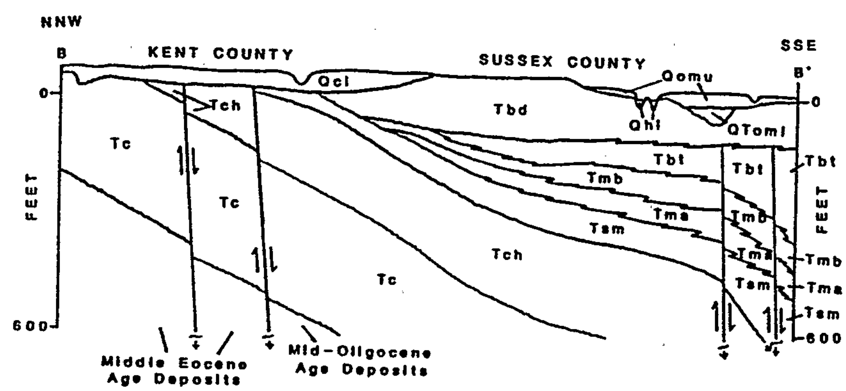


Figure 4. Diagrammatic geologic cross-sections of (A) the Middletown-Odessa area, New Castle County (after Pickett and Spoljaric, 1971), and (B) Kent and Sussex counties, southern Delaware (after Ramsey and Schenck, 1990).

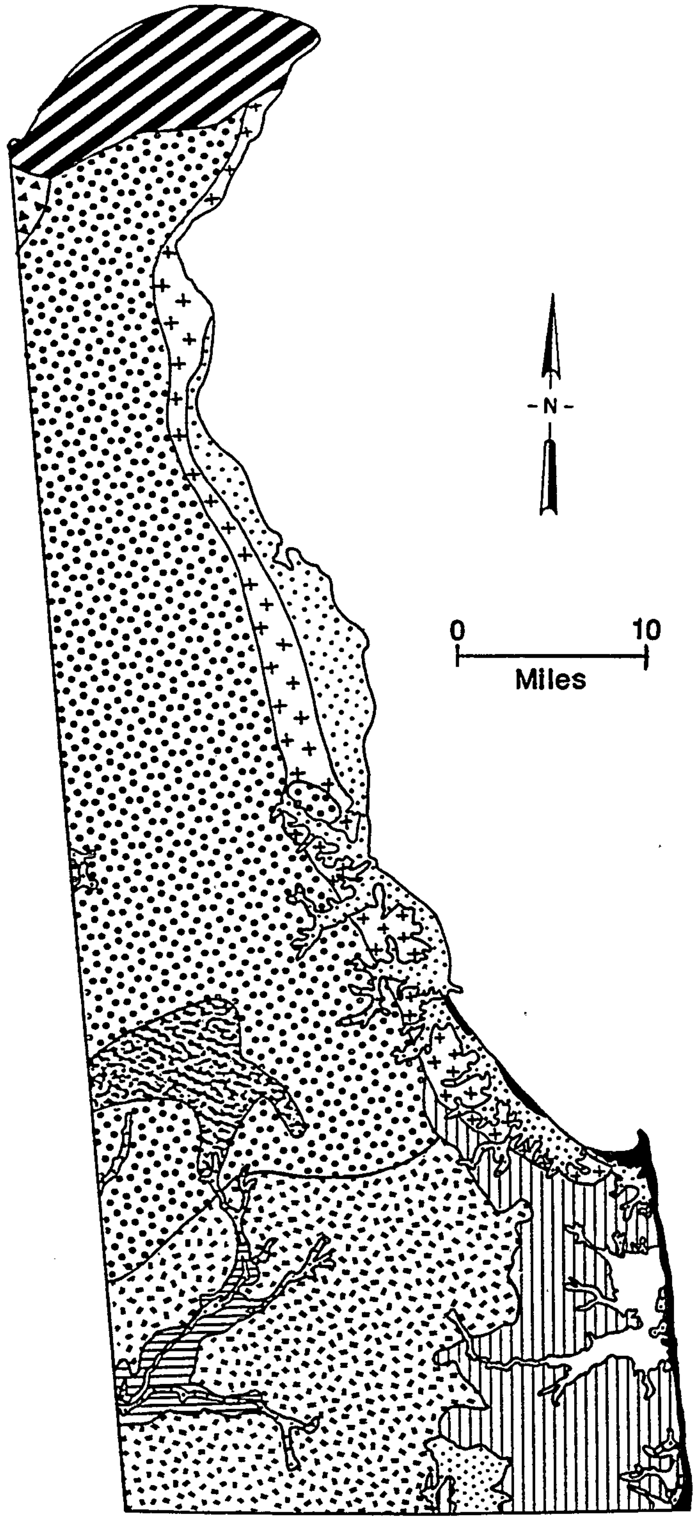


Figure 5. Generalized surficial geologic map of Delaware (after Richmond and others, 1987, and Ramsey and Schenck, 1990).

GENERALIZED SURFICIAL GEOLOGIC MAP OF DELAWARE
EXPLANATION

(After Richmond and others, 1987, and Ramsey and Schenck, 1990)

HOLOCENE

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

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

PLEISTOCENE

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

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

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

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

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

QUATERNARY AND TERTIARY

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

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

TERTIARY

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

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

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

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

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

The Coastal Plain

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

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

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

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

RADIOACTIVITY

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

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

INDOOR RADON DATA

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

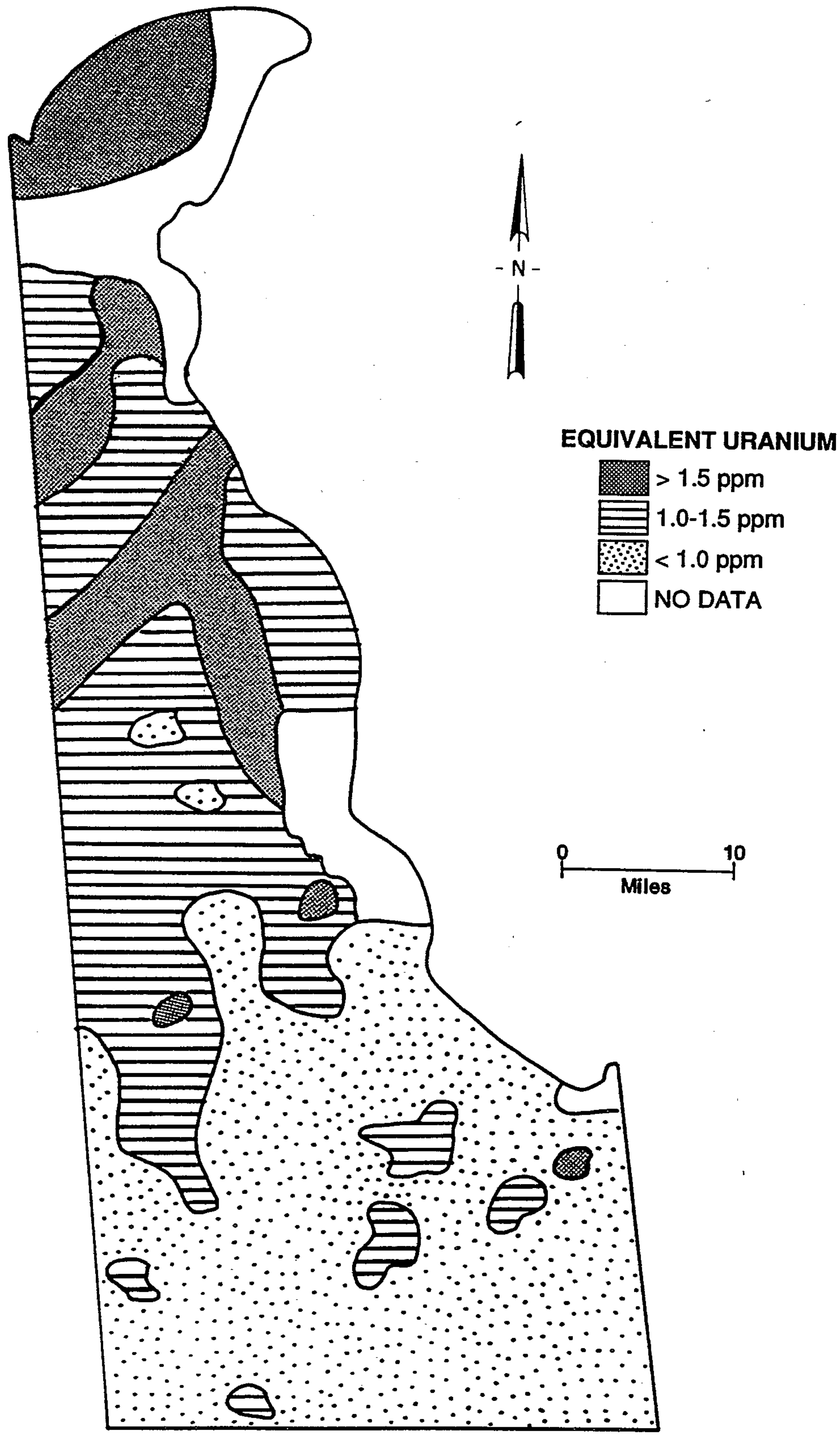


Figure 6. Aerial radiometric map of Delaware (after Duval and others, 1989).

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

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

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

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

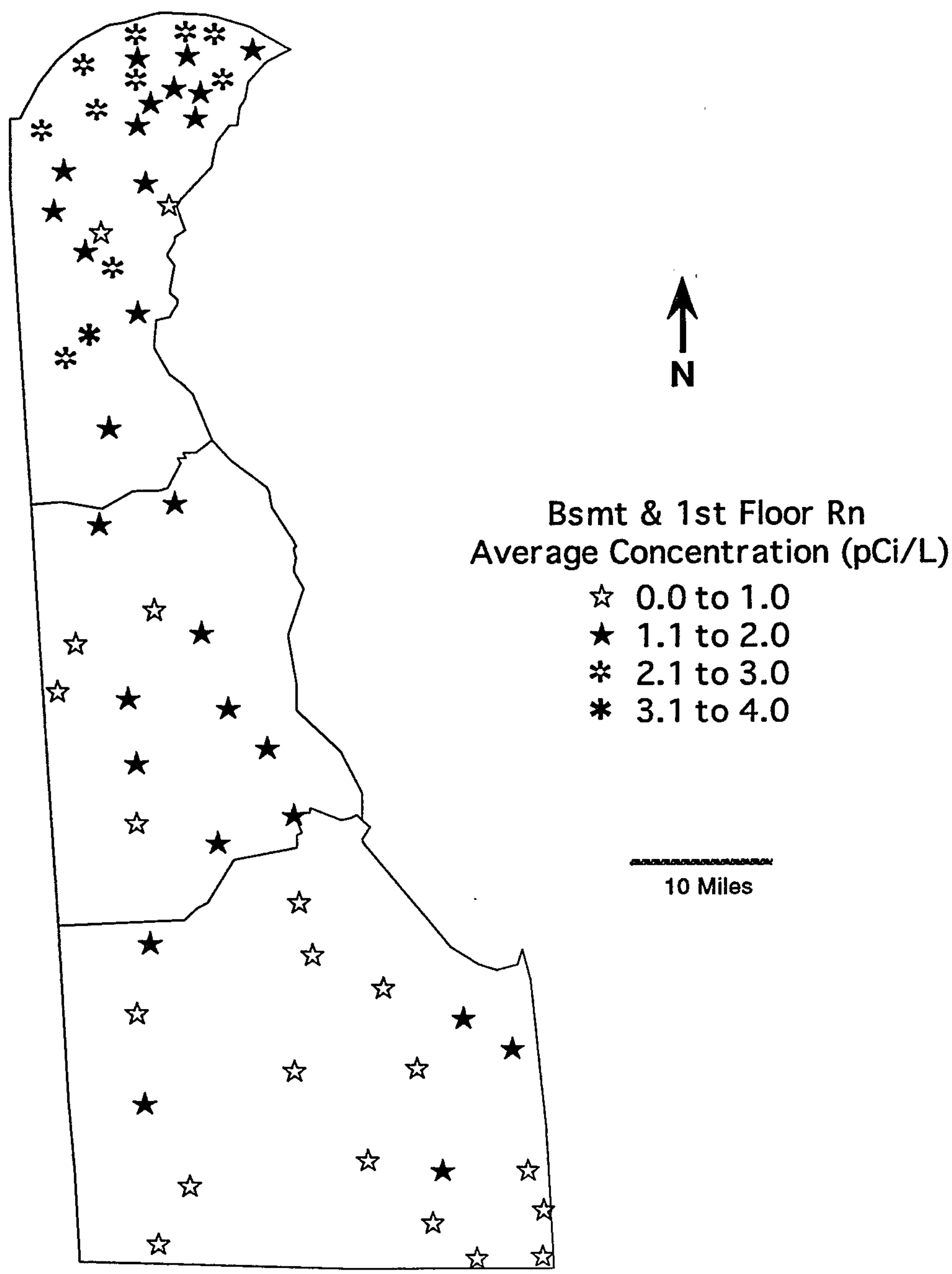


Figure 7a. Average indoor radon levels of homes sampled in each zip code area, plotted by zip code centroid. Points are plotted only for those zip code areas containing 5 or more measurements. Points representing the average indoor radon reading are plotted at the center of each zip code area. Data compiled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

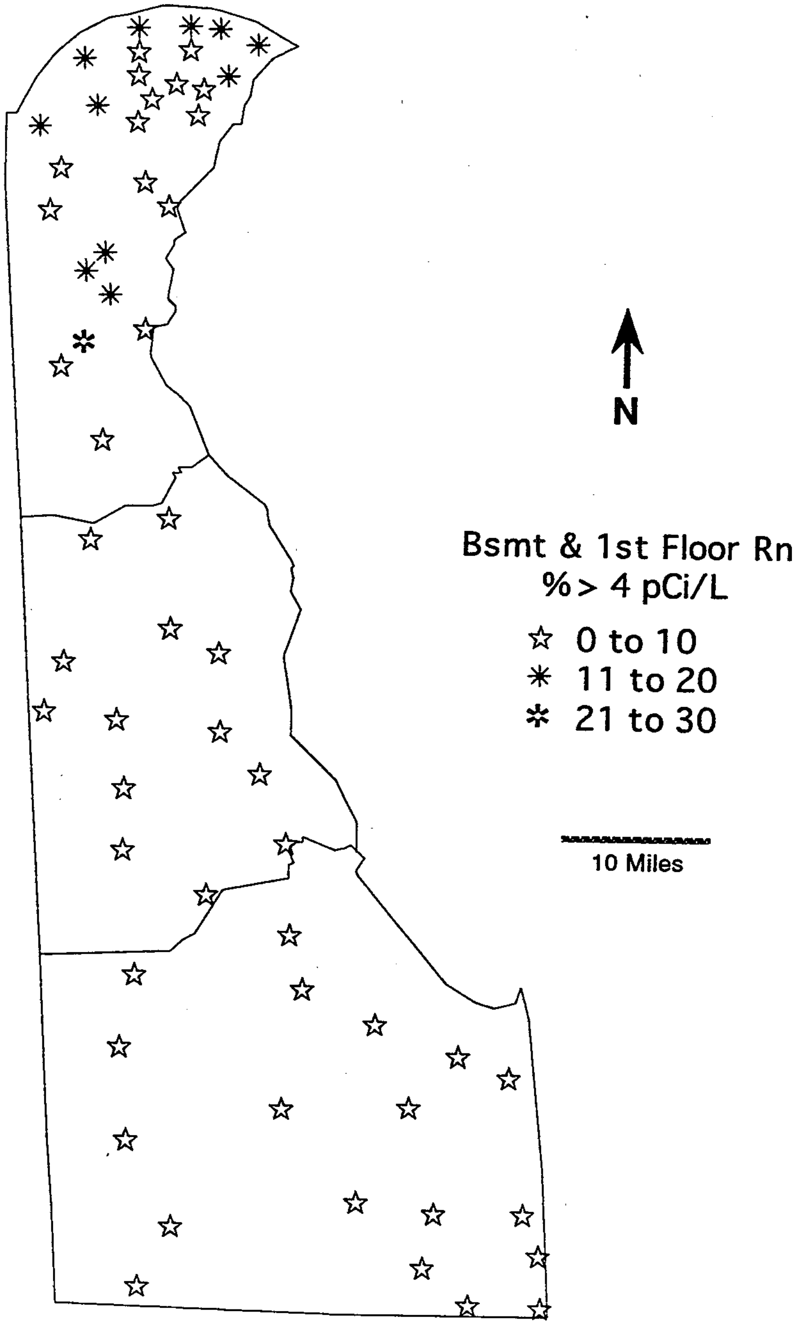


Figure 7b. Percent of homes tested with indoor radon measurements greater than 4 pCi/L, plotted by zip code centroid. Points are plotted only for those zip code areas with 5 or more measurements. Points representing the percent of readings greater than 4 pCi/L are plotted at the center of each zip code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

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

GEOLOGIC RADON POTENTIAL

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

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

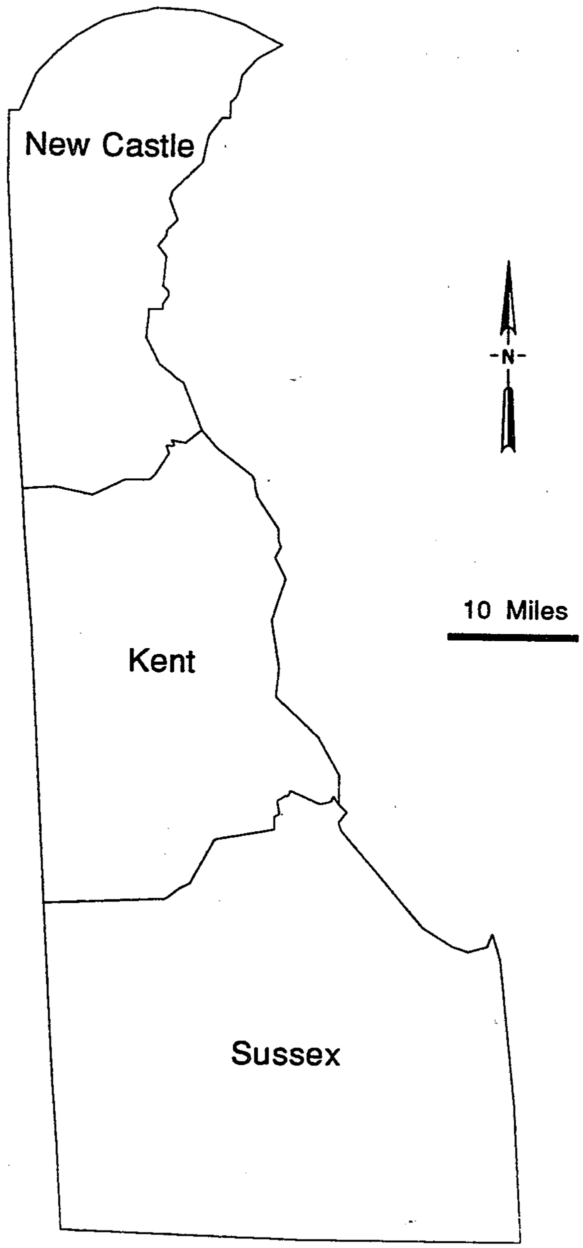
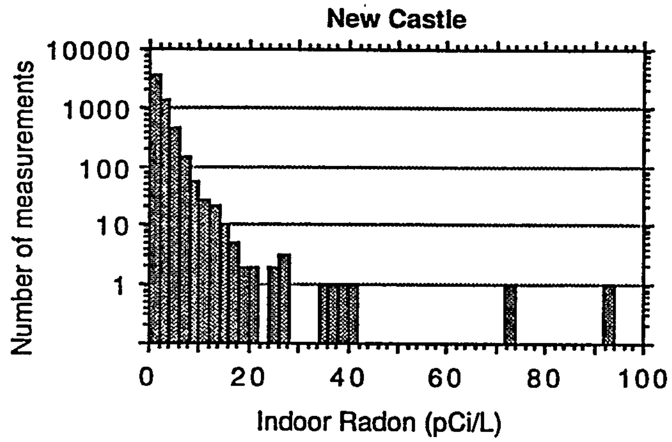
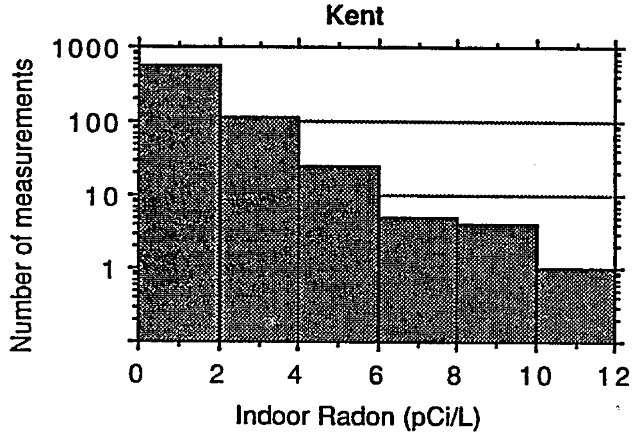


Figure 8. Counties in Delaware.





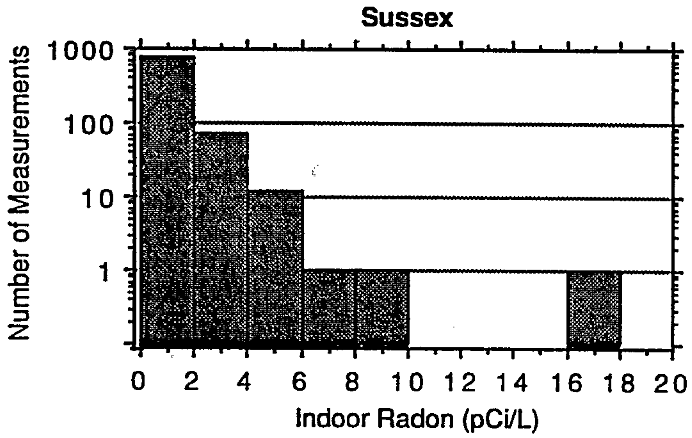


Figure 9. Histograms showing frequency distribution of indoor radon readings by county in Delaware. A log-scale vertical axis was used for ease of presentation. In order to better distinguish lower values on the graph, the histogram for New Castle County excludes a single reading of 163.9 pCi/L. Data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

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

SUMMARY

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

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

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

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

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

RADON INDEX SCORING:

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

Possible range of points = 3 to 17

CONFIDENCE INDEX SCORING:

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

Possible range of points = 4 to 12

REFERENCES CITED IN THIS REPORT
AND GENERAL REFERENCES PERTAINING TO RADON IN DELAWARE

Andres, A.S., 1986, Stratigraphy and depositional history of the post-Choptank Chesapeake Group: Delaware Geological Survey, Report of Investigations No. 42, 39 p.

Benson, R.N., and Pickett, T.E., 1986, Geology of south central Kent County, Delaware: Delaware Geological Survey, Geologic Map Series No. 7, scale 1:24,000.

Duval, J.S., Jones, W.J., Riggle, F.R., and Pitkin, J.A., 1989, Equivalent uranium map of conterminous United States: U.S. Geological Survey Open-File Report 89-478, 10 p.

Eichler, Thomas P, and Wright, Lester N., 1991, The Delaware Radon Program: Department of Health and Social Services, Division of Public Health, Authority on Radiation Protection, 29 p.

Elsinger, R.J., 1982, Estuarine geochemistry of 224 Ra, 228 Ra, 226 Ra, and 222 Rn: Doctoral Thesis, Univ. of South Carolina, Columbia, SC, 95 p.

Gundersen, L. C.S, Peake, R.T., Latske, G.D., Hauser, L.M., and Wiggs,C.R., 1991, A statistical summary of uranium and radon in soils from the Coastal Plain of Texas, Alabama, and New Jersey, *in* Proceedings of the 1990 International Symposium on Radon and Radon Reduction Technology,Volume 2: Symposium Oral Papers, U.S. EPA report EPA-600/9-91/026b, p. CVI4-1-13.

Gundersen, L.C.S., Reimer, G.M., Wiggs, C.R. and Rice, C.A., 1988, Radon Potential of Rocks and Soils in Montgomery County, Maryland: U. S. Geological Survey Miscellaneous Field Studies Map 88-2043, scale 1:62,000.

Hammond, D., Simpson, H.J., and Mathieu, G., 1976, Distribution of radon-222 in the Delaware and Hudson estuaries as an indicator of migration rates of dissolved species across the sediment-water interface: Eos, Transactions of the American Geophysical Union, v. 57, p. 151.

Ireland, W., Jr., and Matthews, E.D., 1974, Soil survey of Sussex County, Delaware: U.S. Department of Agriculture, Soil Conservatiion Service, 74 p.

Jordan, R.R., 1962, Stratigraphy of the sedimentary rocks of Delaware: Delaware Geological Survey, Bulletin No. 9, 51 p.

Jordan, R.R., 1964, Columbia (Pleistocene) sediments of Delaware: Delaware Geological Survey, Bulletin No. 12, 61 p.

Jordan, R.R., 1974, Pleistocene deposits of Delaware, *in* Oakes, R.Q., and Dubar, J.R., eds., Post-Miocene Stratigraphy, Central and Southern Atlantic Coastal Plain: Logan, Utah, Utah State University Press, p. 30-52.

Jordan, R.R., 1983, Stratigraphic nomenclature of nonmarine Cretaceous rocks of inner margin of Coastal Plain in Delaware and adjacent states: Delaware Geological Survey, Report of Investigations No. 37, 43 p.

Kraft, J.C., and Carey, W., eds., 1980, Selected Papers on the Geology of Delaware: Special publication of the Delaware Geological Survey, 268 p.

Matthews, E.D., and Lavoie, O.L., 1970, Soil survey of New Castle County, Delaware: U.S. Department of Agriculture, Soil Conservatiion Service, 97 p.

Matthews, E.D., and Ireland, W., Jr., 1971, Soil survey of Kent County, Delaware: U.S. Department of Agriculture, Soil Conservatiion Service, 66 p.

Pickett, T.E., 1976, Generalized Geologic Map of Delaware: Delaware Geological Survey Special Publication No. 9, scale approx. 1:576,000.

Pickett, T.E., and Benson, R.N., 1977, Geology of the Smyrna-Clayton area, Delaware: Delaware Geological Survey, Geologic Map Series No. 6, scale 1:24,000.

Pickett, T.E., and Benson, R.N., 1983, Geology of the Dover area, Delaware: Delaware Geological Survey, Geologic Map Series No. 7, scale 1:24,000.

Pickett, T.E., and Spoljaric, N., 1971, Geology of the Middletown-Odessa area, Delaware: Delaware Geological Survey, Geologic Map Series No. 2, scale 1:24,000.

Pierce, A.P., 1956, Radon and helium studies: U.S. Geological Survey Rept. TEI-620, p. 305-309.

Ramsey, K.W., and Schenck, W.S., 1990, Geologic map of southern Delaware: Delaware Geological Survey, Open-File Report No. 32, scale 1:100,000.

Reimer, G.M., Gundersen, L.C.S., Szarzi, S.L., and Been, J.M., 1991, Reconnaissance approach using geology and soil-gas radon concentrations for rapid and preliminary estimates of radon potential, *in* Gundersen, L.C.S., and Wanty, R.B., eds., Field Studies of Radon in Rocks Soils and Water: U. S. Geological Survey Bulletin 1971, p. 177-181.

Richmond, G.M., Fullerton, D.S., and Weide, D.L., compilers, 1987, Quaternary geologic map of the Chesapeake Bay 4°x6° quadrangle, United States and Canada: U.S. Geological Survey Miscellaneous Investigations Map I-1420 (NJ-18), scale 1:1,000,000.

Spoljaric, N., 1980, The geology of the Delaware Coastal Plain, *in* Kraft, J.C., and Carey, W., eds., Selected Papers on the Geology of Delaware: Special publication of the Delaware Geological Survey, p. 87-114.

Talley, J.H., 1982, Geohydrology of the Milford area, Delaware: Delaware Geological Survey, Hydrologic Map Series No. 4, scale 1:24,000.

Talley, J.H., 1987, Geohydrology of the southern coastal area, Delaware: Delaware Geological Survey, Hydrologic Map Series No. 7, 2 sheets, scale 1:24,000.

Thompson, A.M., 1980, A summary of the geology of the Piedmont in Delaware, *in* Kraft, J.C., and Carey, W., eds., Selected Papers on the Geology of Delaware: Special publication of the Delaware Geological Survey, p. 115-134.

van Assendelft, A.C.E., and Sachs, H.M., 1982, Soil and regional uranium as controlling factors of indoor radon in eastern Pennsylvania: Princeton University, Center for Energy and Environmental Studies Report 145, 68 p.

Wagner, Mary Emma, Srogi, LeeAnn, Wiswell, C. Gil, and Alcock, James, 1991, Taconic collision in the Delaware-Pennsylvania Piedmont and implications for subsequent geologic history, *in* Schultz, A., and Compton-Gooding, E., eds., Geologic evolution of the eastern United States, Field trip guidebook, Geological Society of America, NE-SE section, p. 91-119.

Woodruff, K.D., 1980, Geohydrology of Delaware, *in* Kraft, J.C., and Carey, W., eds., Selected Papers on the Geology of Delaware: Special publication of the Delaware Geological Survey, p. 135-166.

Woodruff, K.D., 1985, Geohydrology of the Wilmington area, Delaware: Delaware Geological Survey, Hydrologic Map Series No. 3, 4 sheets, scale 1:24,000.

Woodruff, K.D., 1986, Geohydrology of the Chesapeake and Delaware Canal area, Delaware: Delaware Geological Survey, Hydrologic Map Series No. 6, 2 sheets, scale 1:24,000.

Woodruff, K.D., and Thompson, A.M., 1972, Geology of the Newark area, Delaware: Delaware Geological Survey, Geologic Map Series No. 3, scale 1:24,000.

Woodruff, K.D., and Thompson, A.M., 1975, Geology of the Wilmington area, Delaware: Delaware Geological Survey, Geologic Map Series No. 4, scale 1:24,000.

Woodruff, K.D., Ramsey, K.W., and Talley, J.H., 1992, Radon potential of the glauconitic sediments in the Coastal Plain of Delaware: Final Report to Delaware Department of Health and Social Services, Division of Public Health, Health Systems Protection, Radiation Control, Contract No. 92-105, 43 p.

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.)

DELAWARE MAP OF RADON ZONES

The Delaware Map of Radon Zones and its supporting documentation (Part IV of this report) have received extensive review by Delaware geologists and radon program experts. The map for Delaware 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.

Although the information provided in Part IV of this report -- the State chapter entitled "Preliminary Geologic Radon Potential Assessment of Delaware" -- 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 Delaware radon program for information on testing and fixing homes. Telephone numbers and addresses can be found in Part II of this report.

DELAWARE - EPA Map of Radon Zones

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 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 Delaware" 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.