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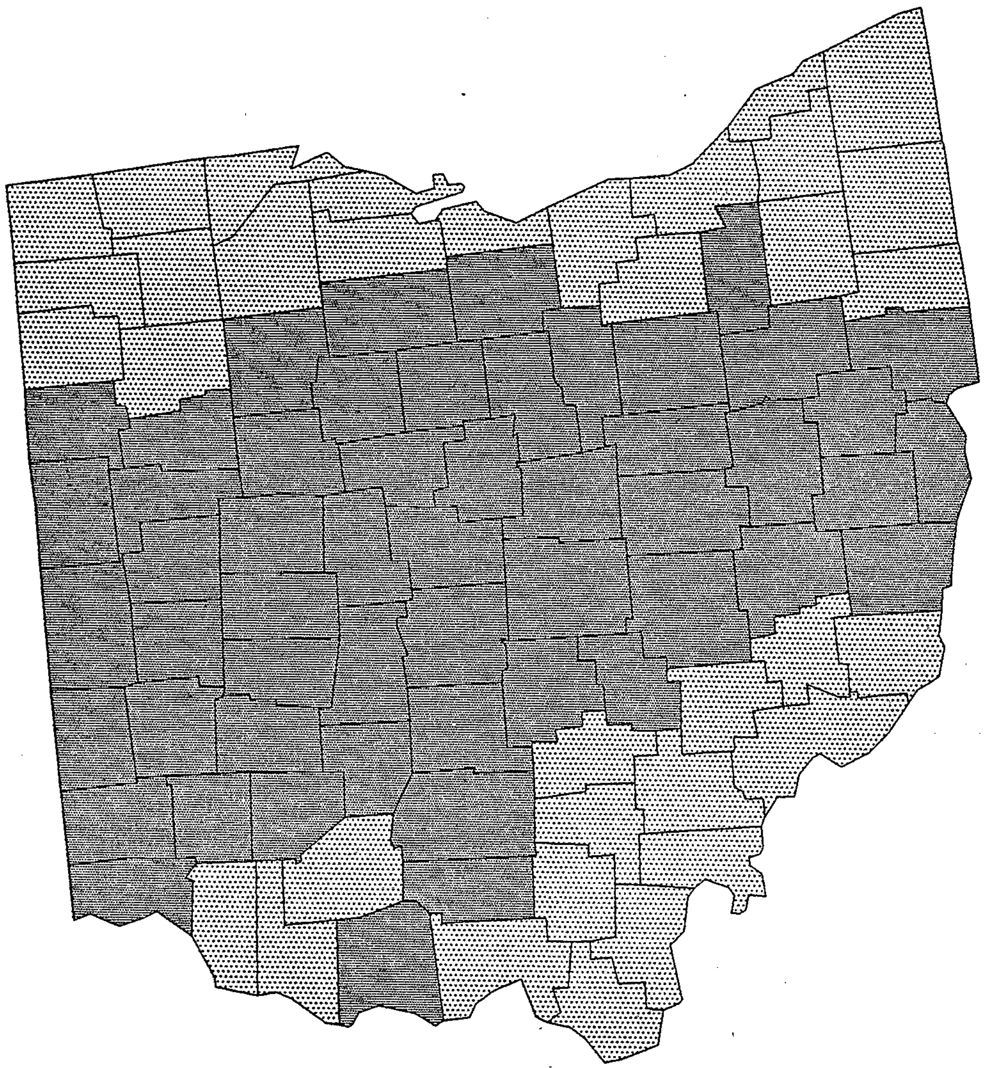
EPA's Map of Radon Zones

OHIO



EPA'S MAP OF RADON ZONES
OHIO

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

SEPTEMBER, 1993

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OVERVIEW

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

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

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

BACKGROUND

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

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

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

Purpose of the Map of Radon Zones

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

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

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

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

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

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

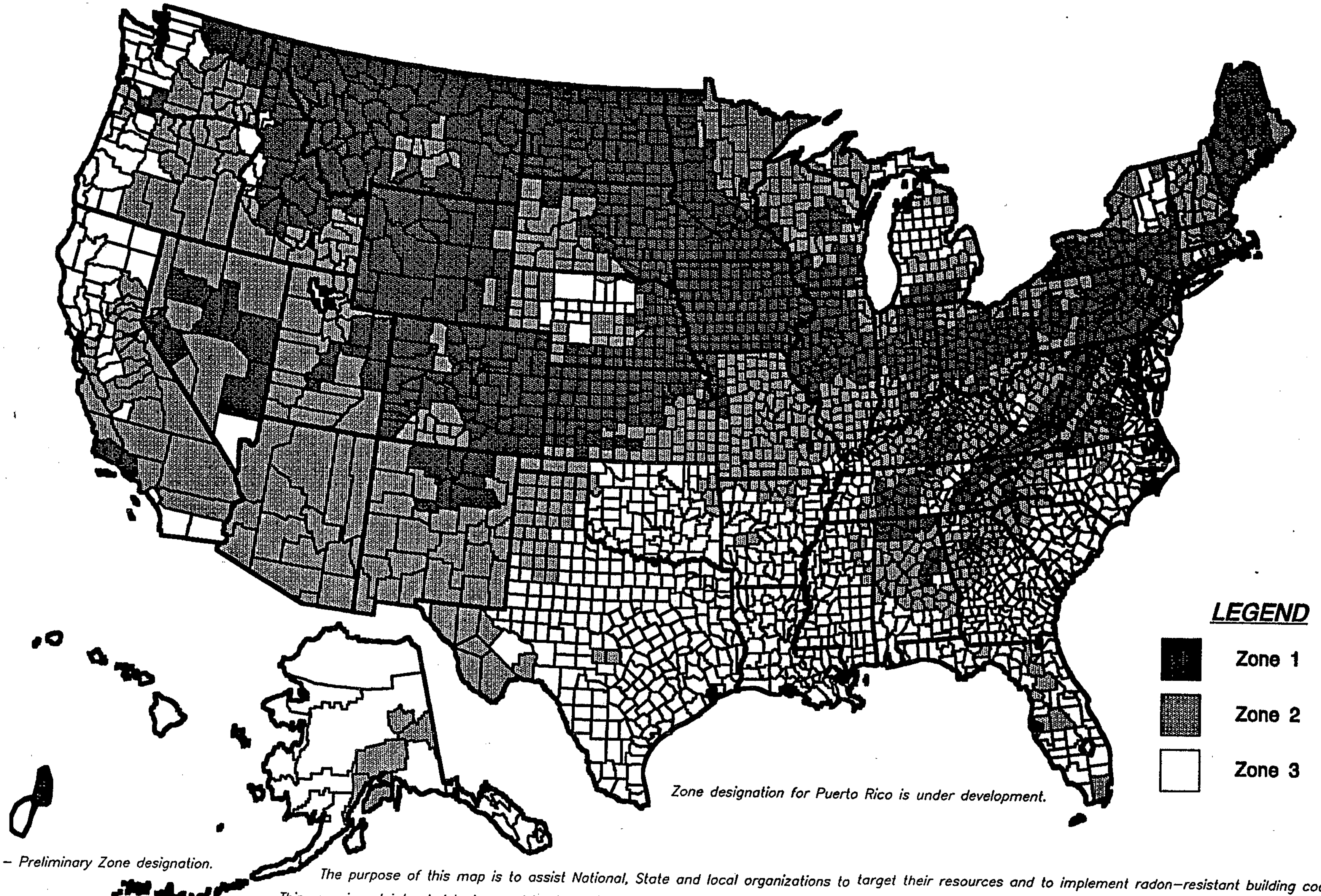
The Map of Radon Zones and its supporting documentation establish no regulatory requirements. Use of this map by State or local radon programs and building code officials is voluntary. The information presented on the Map of Radon Zones and in the supporting documentation is not applicable to radon in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

Development of the Map of Radon Zones

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

Figure 1

EPA Map of Radon Zones



The purpose of this map is to assist National, State and local organizations to target their resources and to implement radon–resistant building codes.

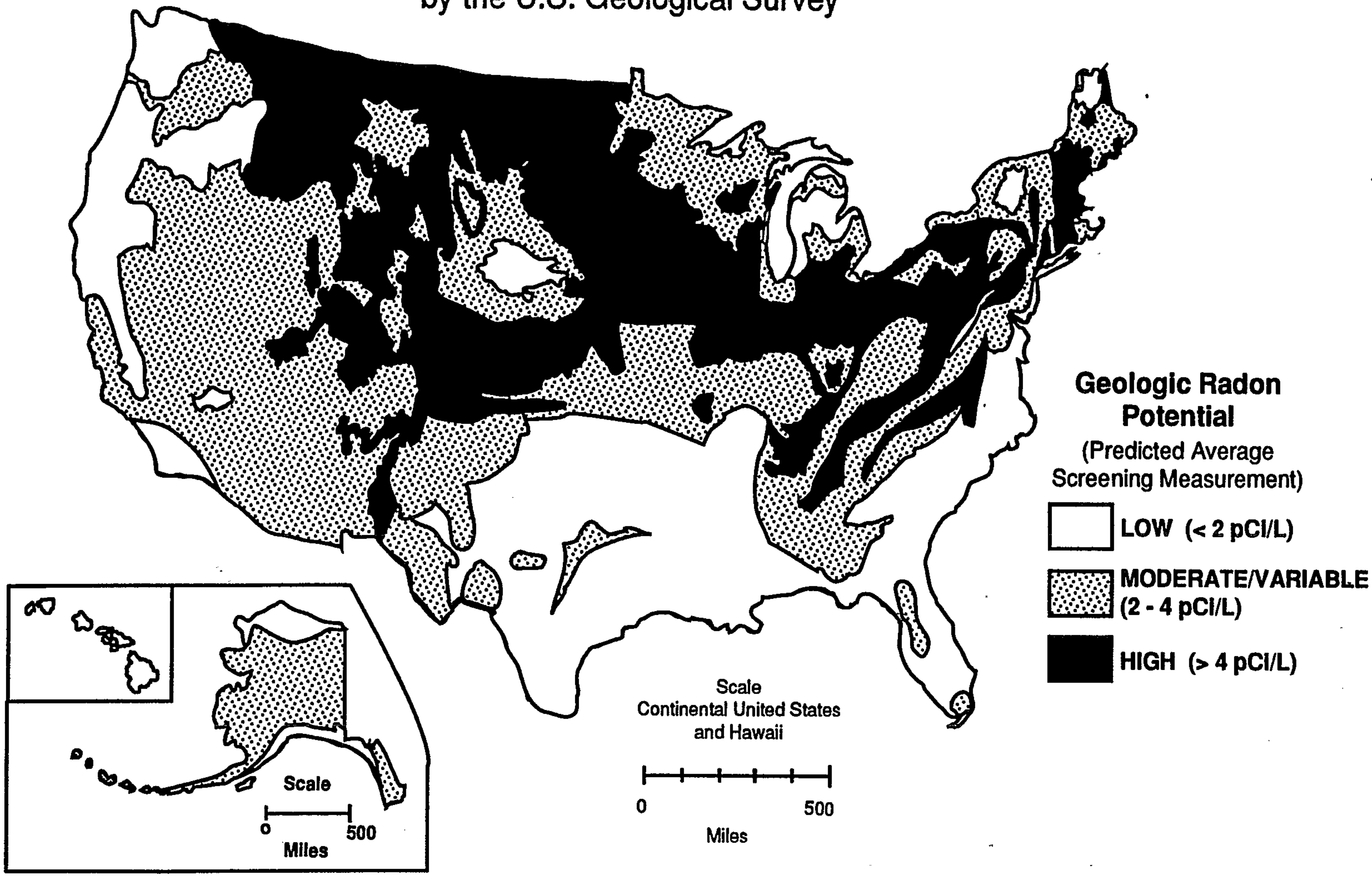
This map is not intended to be used to determine if a home in a given zone should be tested for radon. Homes with elevated levels of radon have been found in all three zones. ***All homes should be tested, regardless of geographic location.***

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

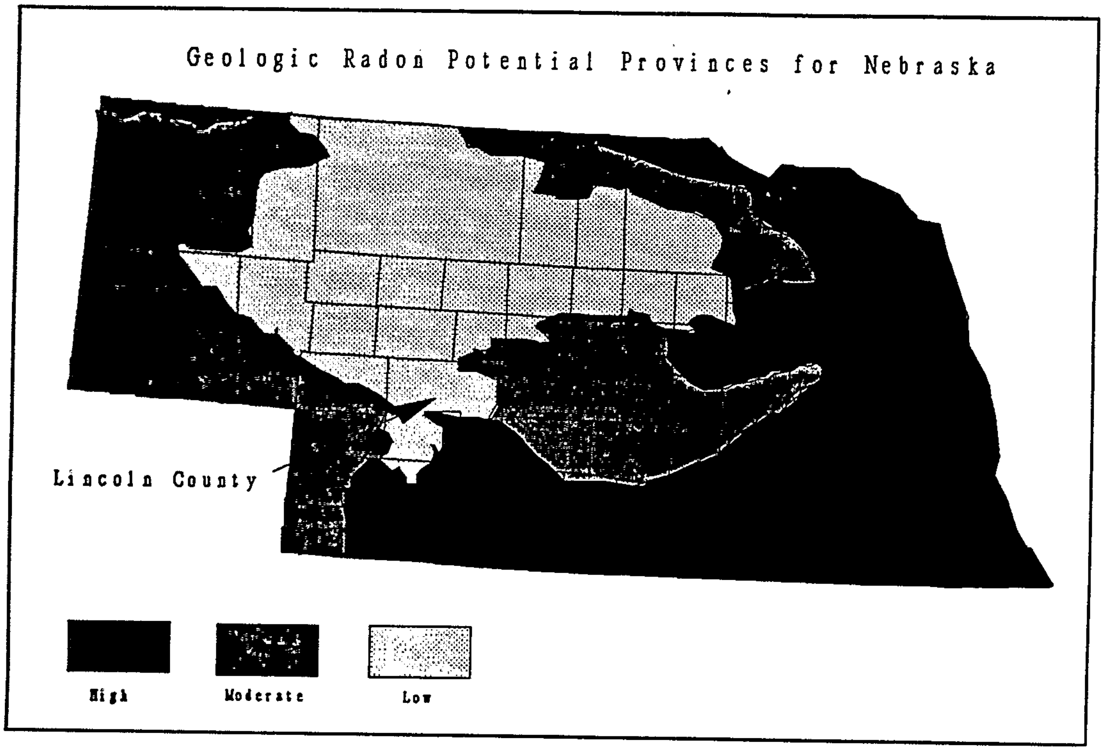
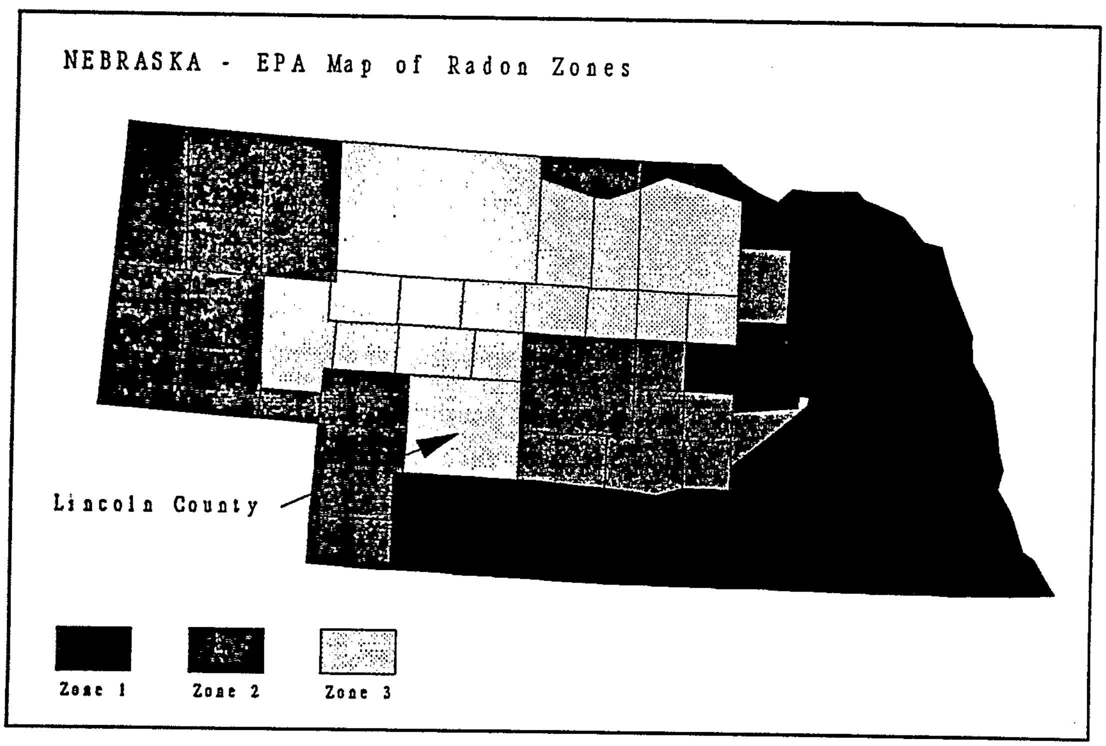


Figure 4



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
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BACKGROUND

The Indoor Radon Abatement Act of 1988 (15 U.S.C. 2661-2671) directed the U.S. Environmental Protection Agency (EPA) to identify areas of the United States that have the potential to produce harmful levels of indoor radon. These characterizations were to be based on both geological data and on indoor radon levels in homes and other structures. The EPA also was directed to develop model standards and techniques for new building construction that would provide adequate prevention or mitigation of radon entry. As part of an Interagency Agreement between the EPA and the U.S. Geological Survey (USGS), the USGS has prepared radon potential estimates for the United States. This report is one of ten booklets that document this effort. The purpose and intended use of these reports is to help identify areas where states can target their radon program resources, to provide guidance in selecting the most appropriate building code options for areas, and to provide general information on radon and geology for each state for federal, state, and municipal officials dealing with radon issues. *These reports are not intended to be used as a substitute for indoor radon testing, and they cannot and should not be used to estimate or predict the indoor radon concentrations of individual homes, building sites, or housing tracts. Elevated levels of indoor radon have been found in every State, and EPA recommends that all homes be tested for indoor radon.*

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

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

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

RADON GENERATION AND TRANSPORT IN SOILS

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

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

The shape and orientation of soil particles (soil structure) control permeability and affect water movement in the soil. Soils with blocky or granular structure have roughly equivalent permeabilities in the horizontal and vertical directions, and air and water can infiltrate the soil relatively easily. However, in soils with platy structure, horizontal permeability is much greater than vertical permeability, and air and moisture infiltration is generally slow. Soils with prismatic or columnar structure have dominantly vertical permeability. Platy and prismatic structures form in soils with high clay contents. In soils with shrink-swell clays, air

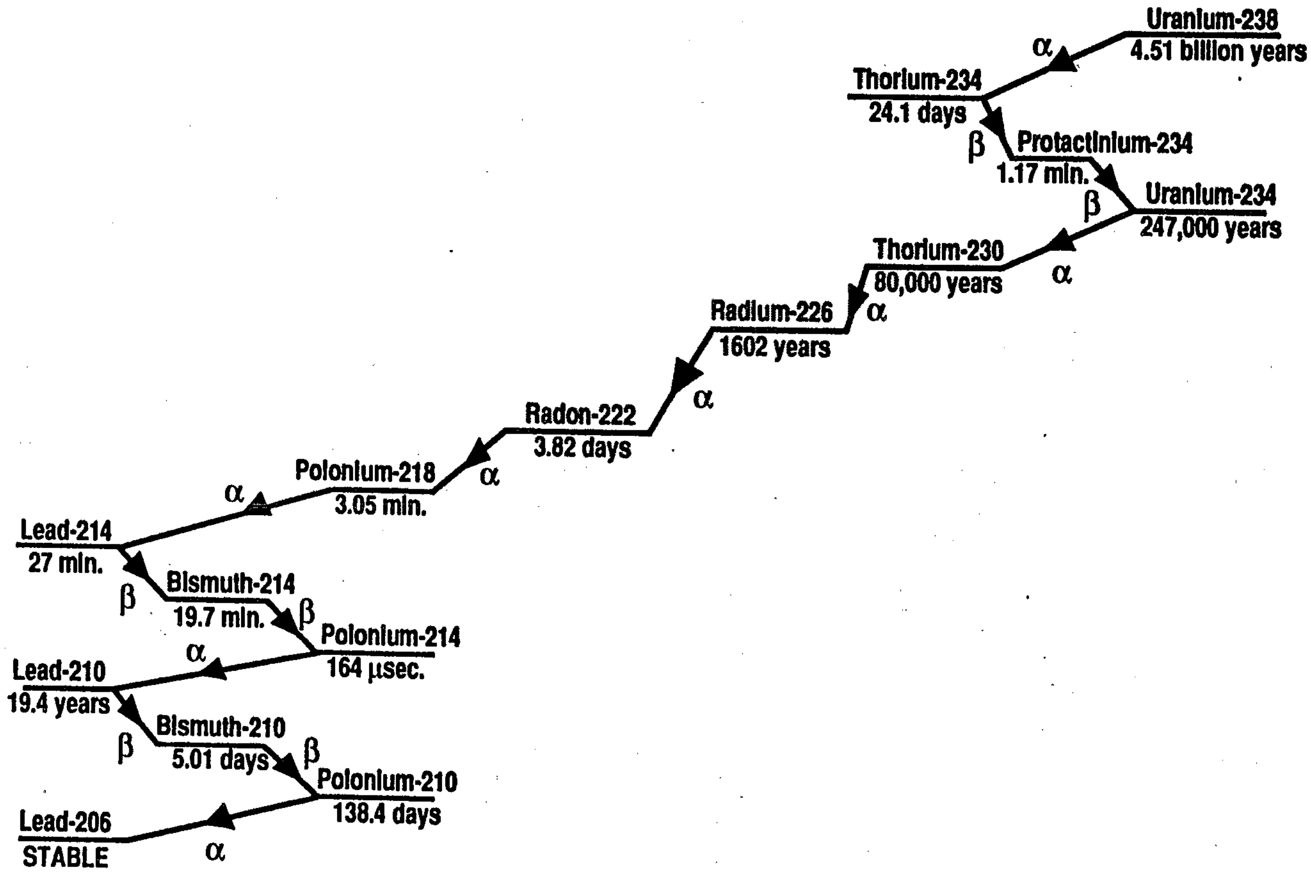

Figure 1. The uranium-238 decay series, showing the half-lives of elements and their modes of decay (after Wanty and Schoen, 1991). α denotes alpha decay, β denotes beta decay.

and moisture infiltration rates and depth of wetting may be limited when the cracks in the surface soil layers swell shut. Clay-rich B horizons, particularly those with massive or platy structure, can form a capping layer that impedes the escape of soil gas to the surface (Schumann and others, 1992). However, the shrinkage of clays can act to open or widen cracks upon drying, thus increasing the soil's permeability to gas flow during drier periods.

Radon transport in soils occurs by two processes: (1) diffusion and (2) flow (Tanner, 1964). Diffusion is the process whereby radon atoms move from areas of higher concentration to areas of lower concentration in response to a concentration gradient. Flow is the process by which soil air moves through soil pores in response to differences in pressure within the soil or between the soil and the atmosphere, carrying the radon atoms along with it. Diffusion is the dominant radon transport process in soils of low permeability, whereas flow tends to dominate in highly permeable soils (Sextro and others, 1987). In low-permeability soils, much of the radon may decay before it is able to enter a building because its transport rate is reduced. Conversely, highly permeable soils, even those that are relatively low in radium, such as those derived from some types of glacial deposits, have been associated with high indoor radon levels in Europe and in the northern United States (Akerblom and others, 1984; Kunz and others, 1989; Sextro and others, 1987). In areas of karst topography formed in carbonate rock (limestone or dolomite) environments, solution cavities and fissures can increase soil permeability at depth by providing additional pathways for gas flow.

Not all radium contained in soil grains and grain coatings will result in mobile radon when the radium decays. Depending on where the radium is distributed in the soil, many of the radon atoms may remain imbedded in the soil grain containing the parent radium atom, or become imbedded in adjacent soil grains. The portion of radium that releases radon into the pores and fractures of rocks and soils is called the emanating fraction. When a radium atom decays to radon, the energy generated is strong enough to send the radon atom a distance of about 40 nanometers (1 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).

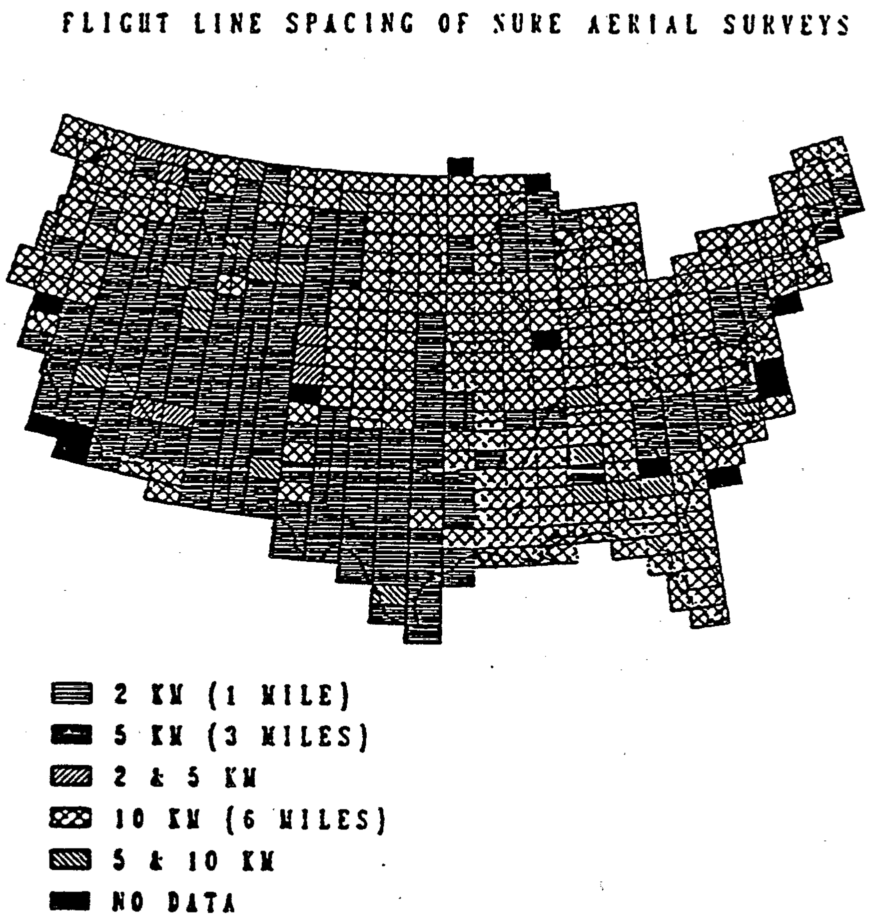

Figure 2. Nominal flightline spacings for NURE aerial gamma-ray surveys covering the contiguous United States (from Duval and others, 1990). Rectangles represent 1°x2° quadrangles.

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.

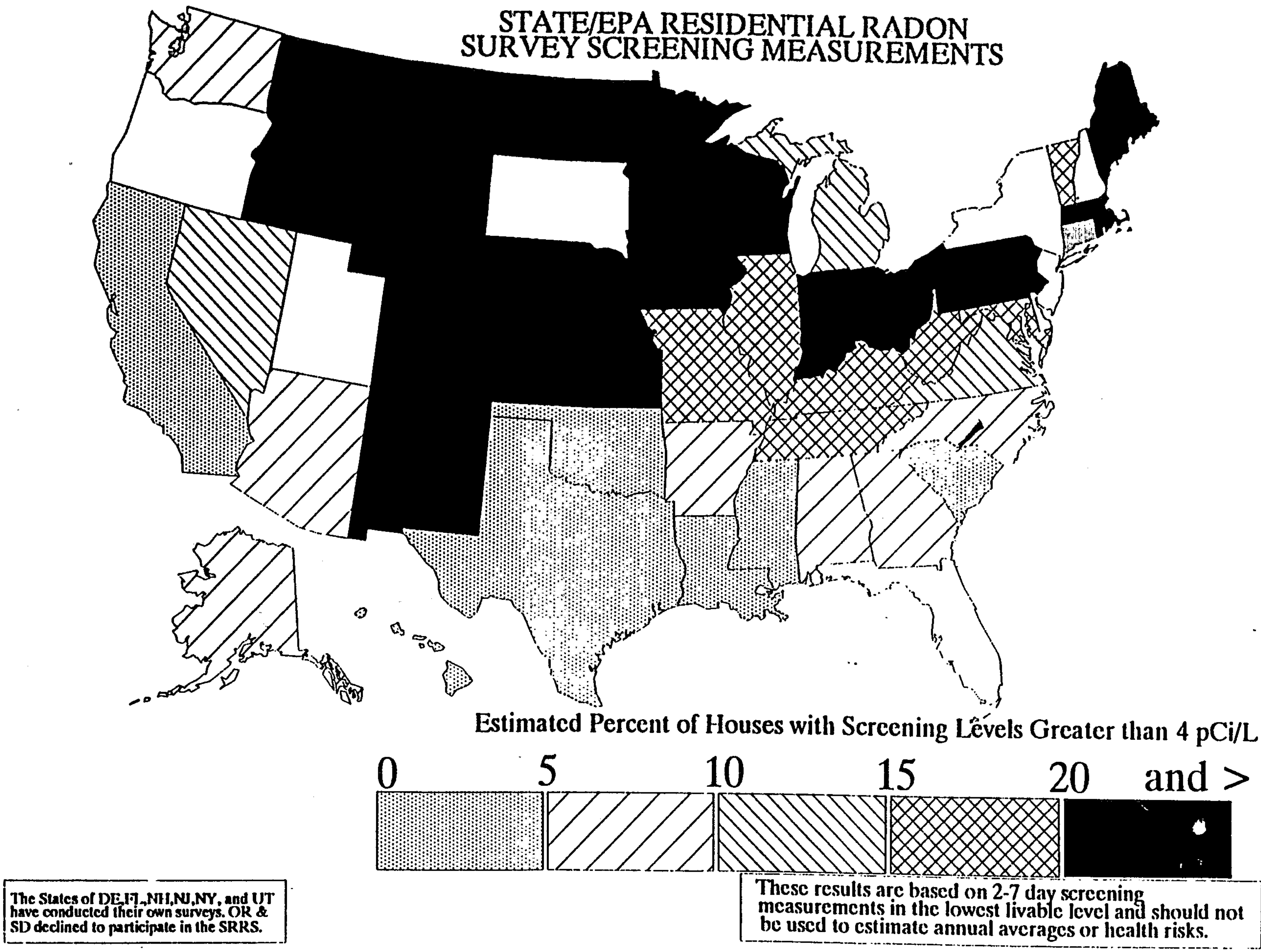

Figure 3. Percent of homes tested in the State/EPA Residential Radon Survey with screening indoor radon levels exceeding 4 pCi/L.

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.

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APPENDIX A
GEOLOGIC TIME SCALE

Subdivisions (and their symbols)						Age estimates of boundaries in mega-annum (Ma)[1]	
Eon or Eonothem	Era or Erathem	Period, System, Subperiod, Subsystem		Epoch or Series			
Phanerozoic[2]	Cenozoic[2] (Cz)	Quaternary[2] (Q)		Holocene		0.010	
				Pleistocene		1.6	(1.6–1.9)
		Tertiary (T)	Neogene[2] Subperiod or Subsystem (N)	Pliocene		5	(4.9–5.3)
				Miocene		24	(23–26)
			Paleogene[2] Subperiod or Subsystem (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 (TR)		Late	Upper		
				Middle	Middle		
				Early	Lower	~240	
	Paleozoic[2] (Pz)	Permian (P)		Late	Upper		
				Early	Lower	290	(290–305)
		Carboniferous Systems (C)	Pennsylvanian (IP)	Late	Upper		
				Middle	Middle		
				Early	Lower	~330	
			Mississippian (M)	Late	Upper		
				Early	Lower	360	(360–365)
		Devonian (D)		Late	Upper		
				Middle	Middle		
				Early	Lower	410	(405–415)
		Silurian (S)		Late	Upper		
				Middle	Middle		
				Early	Lower	435	(435–440)
		Ordovician (O)		Late	Upper		
				Middle	Middle		
				Early	Lower	500	(495–510)
		Cambrian (Є)		Late	Upper		
				Middle	Middle		
				Early	Lower	~570[3]	
Proterozoic (P)	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/m^3 (Becquerels per cubic meter)- a metric unit of radioactivity used to describe radon concentrations in a volume of air. One becquerel is equal to one radioactive disintegration per second. One pCi/L is equal to 37 Bq/m^3.

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

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

Geologic terms and terms related to the study of radon

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

eolian Pertaining to sediments deposited by the wind.

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

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

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

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

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

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

formation A mappable body of rock having similar characteristics.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

placer deposit See heavy minerals

residual Formed by weathering of a material in place.

residuum Deposit of residual material.

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

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

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

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

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

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

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

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

shrink-swell clay See clay mineral.

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

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

slope An inclined part of the earth's surface.

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

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

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

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

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

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

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

uraniferous Containing uranium, usually more than 2 ppm.

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

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

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

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

APPENDIX C
EPA REGIONAL OFFICES

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EPA Region 4
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EPA Region 5 (5AR26)
77 West Jackson Blvd.
Chicago, IL 60604-3507
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EPA Region 6 (6T-AS)
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San Francisco, CA 94105
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Seattle, WA 98101
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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

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EPA REGION 5 GEOLOGIC RADON POTENTIAL SUMMARY

by
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EPA Region 5 comprises the states of Illinois, Indiana, Michigan, Minnesota, Ohio, and Wisconsin. 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 chapter. More detailed information on the geology and radon potential of each state in Region 5 is given in the individual state chapters. The individual chapters describing the geology and radon potential of the six states in EPA Region 5, though much more detailed than this summary, still are generalized assessments and there is no substitute for having a home tested. Radon levels, both high and low, can be quite localized, and within any radon potential area homes with indoor radon levels both above and below the predicted average will likely be found.

Radon potential in EPA Region 5 is controlled by three primary factors. Bedrock geology provides the source material for the overlying glacial deposits, and in areas with no glacial cover, directly provides the parent material for the soils. Glacial geology (fig. 1) is an important factor because glaciers redistributed the bedrock and glacially-derived soils have different soil characteristics from soils developed on bedrock. Climate, particularly precipitation and temperature, in concert with the soil's parent material, controls soil moisture, the extent of soil development and weathering, and the types of weathering products that form in the soils. The following is a brief, generalized discussion of the bedrock and glacial geology of EPA Region 5 as they pertain to indoor radon. More detailed discussions may be found in the individual state geologic radon potential chapters.

Western and southern Minnesota are underlain by deposits of the Des Moines and Red River glacial lobes. Des Moines lobe tills are silty clays and clays derived from Upper Cretaceous sandstones and shales, which have relatively high concentrations of uranium and high radon emanating power. Deposits of the Red River lobe are similar to those of the Des Moines lobe, but also contain silt and clay deposits of glacial Lake Agassiz, a large glacial lake that occupied the Red River Valley along the Minnesota-North Dakota border. The Upper Cretaceous Pierre Shale provides good radon source material because, as a whole, it contains higher-than-average amounts of uranium (average crustal abundance of uranium is about 2.5 parts per million). Glacial deposits of the Red River and Des Moines lobes generate high (> 4 pCi/L) average indoor radon concentrations (fig. 2) and have high geologic radon potential (fig. 3). Northern Wisconsin, the western part of the Upper Peninsula of Michigan, and part of northern Minnesota are underlain by glacial deposits of the Lake Superior lobe. Parts of northern Minnesota are also underlain by deposits of the Rainy and Wadena lobes (fig. 1). The underlying source rocks for these tills are Precambrian volcanic rocks, metasedimentary and metavolcanic rocks, and granitic plutonic rocks of the Canadian Shield. The volcanic, metasedimentary, and metavolcanic rocks have relatively low uranium contents, and the granitic rocks have variable, mostly moderate to high, uranium contents. The sandy tills derived from the

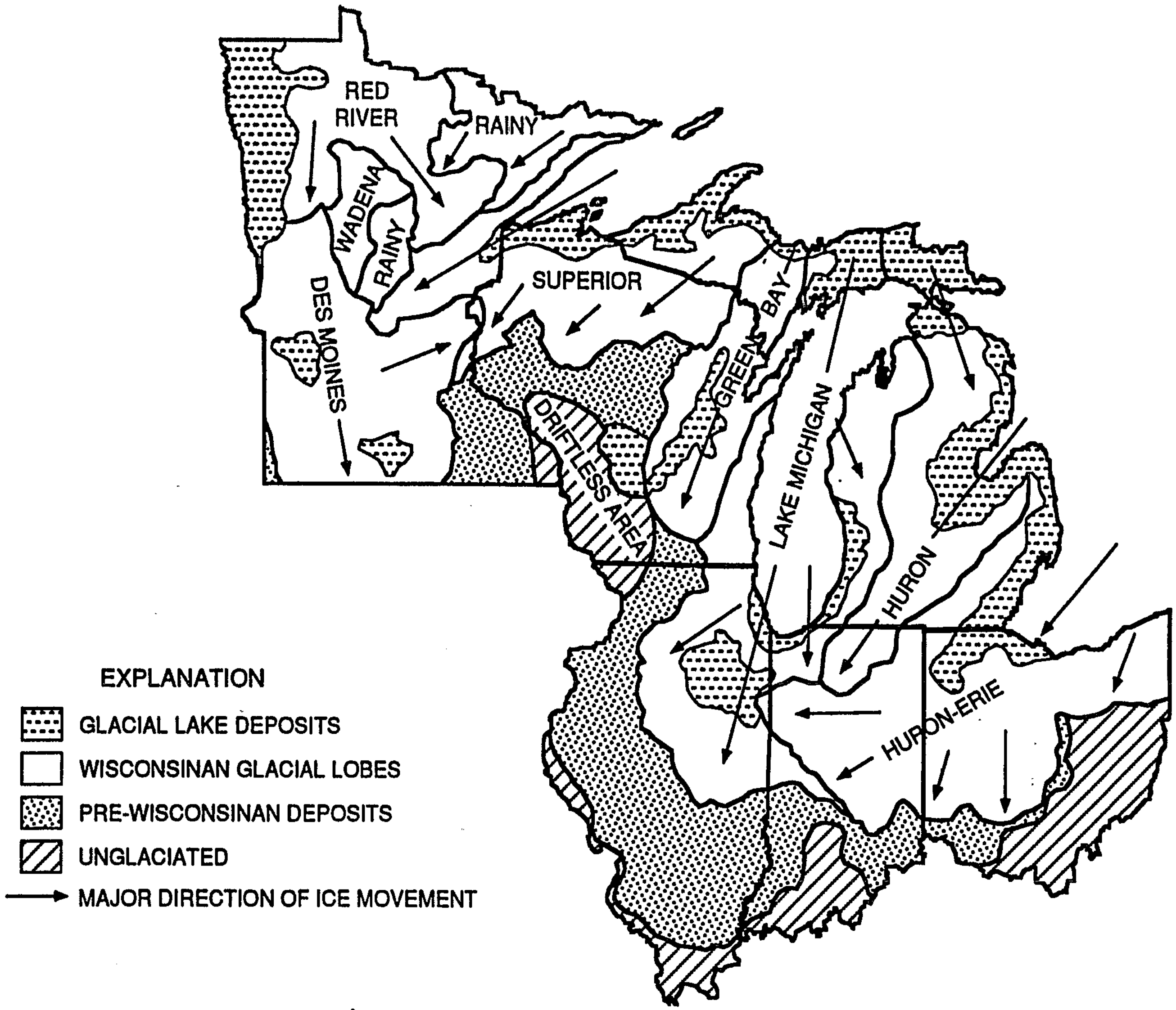

Figure 1. Generalized glacial geologic map of EPA Region 5 showing names of major Wisconsin-age glacial lobes.

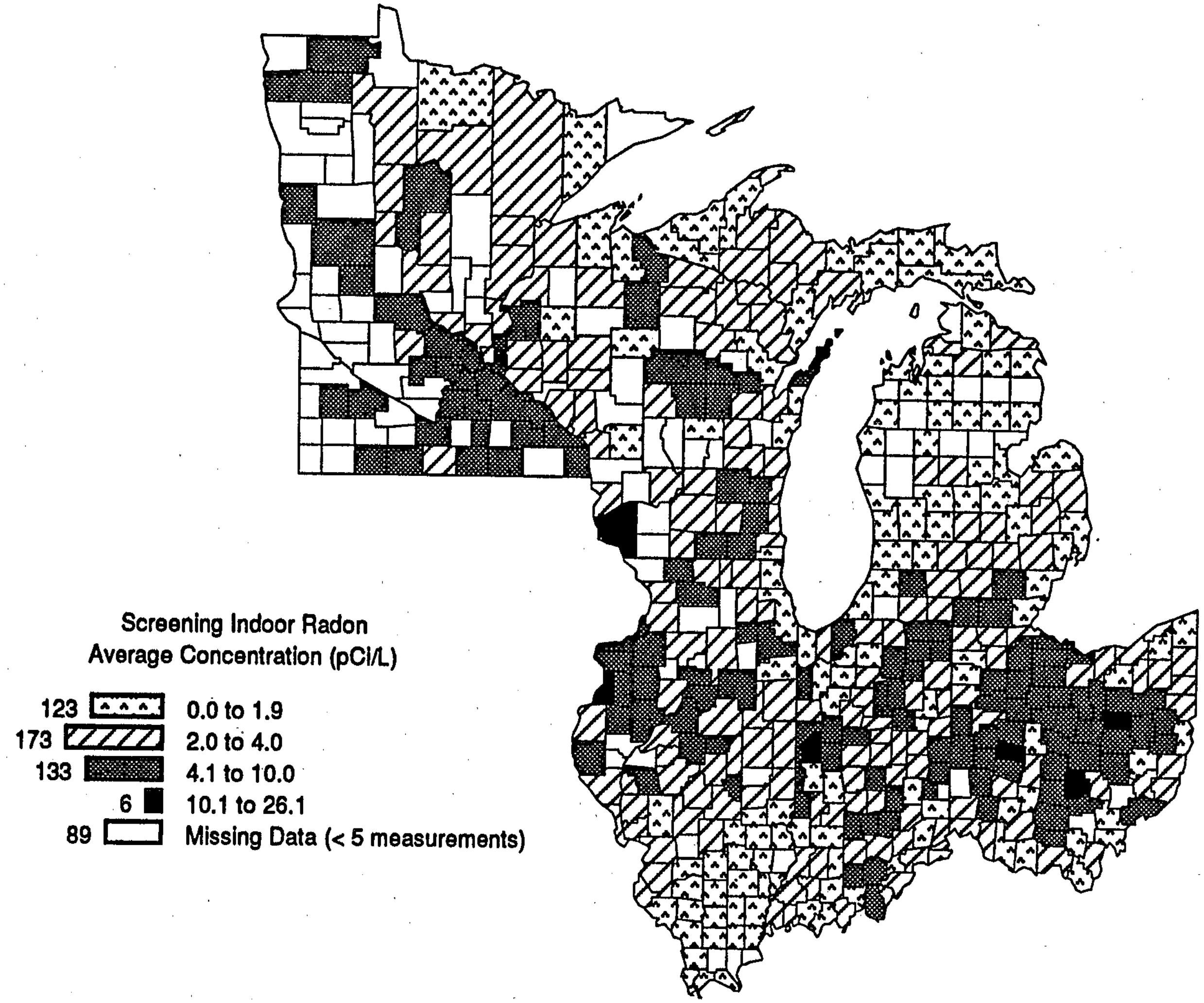

Figure 2. Screening indoor radon data for counties with 5 or more measurements in EPA Region 5. Data are from the EPA/State Residential Radon Survey and represent 2-7 day charcoal canister measurements. Histograms in map legends show the number of counties in each category. The number of samples in each county may not be sufficient to statistically characterize the average radon levels in the counties, but they do suggest general trends.

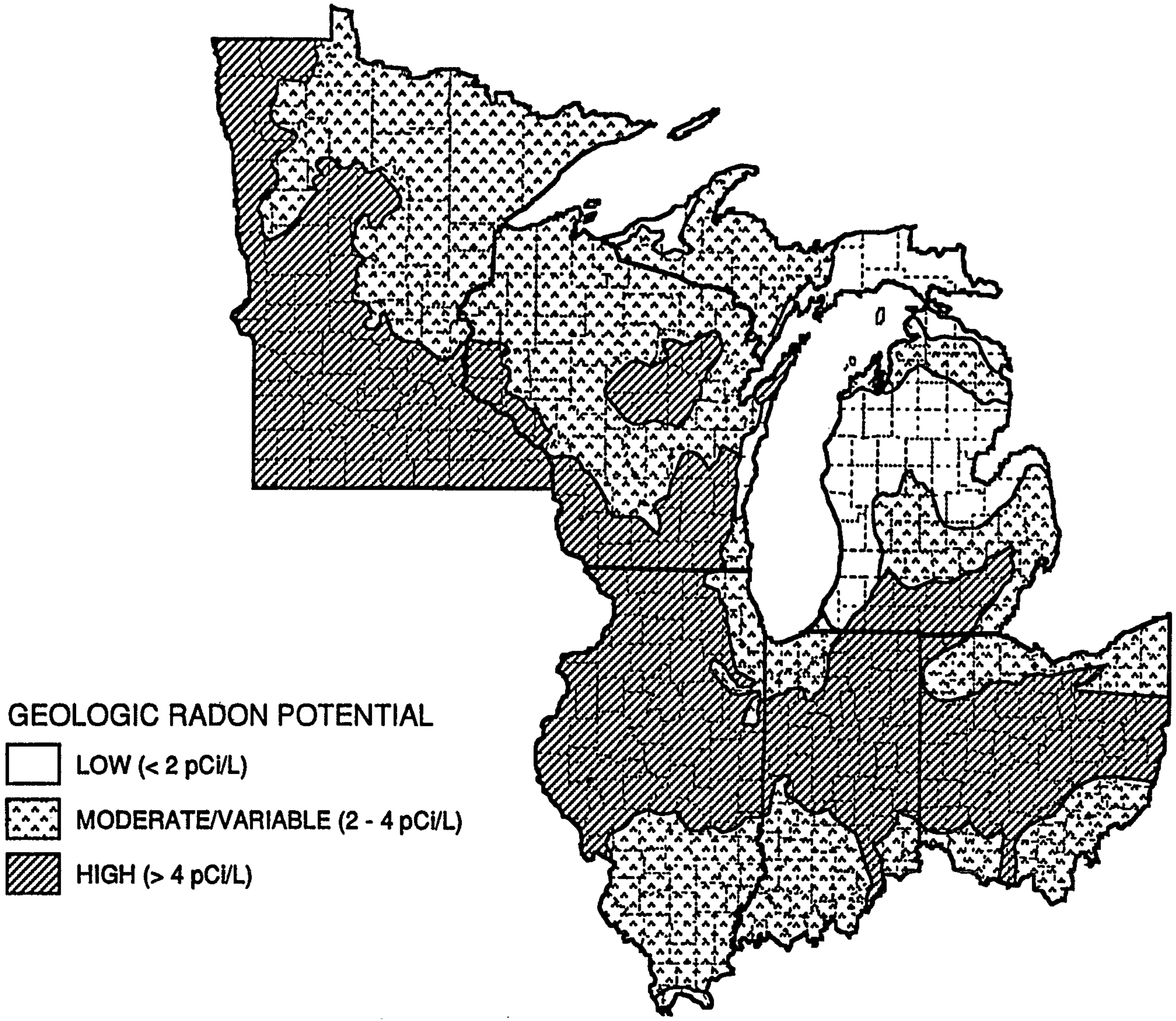

Figure 3. Geologic radon potential areas of EPA Region 5.

volcanic, metasedimentary, and metavolcanic rocks have relatively high permeability, but because of their lower uranium content of and lower emanating power, they have mostly moderate to locally high radon potential (fig. 3). Sandy, granite-rich tills in northern Minnesota generally have high radon potential. Granites and granite gneisses, black slates and graphitic schists, and iron-formation are associated with anomalous uranium concentrations and locally high radon in northern Wisconsin and adjacent northwestern Michigan. In central Wisconsin, uraniferous granites of the Middle Proterozoic Wolf River and Wausau plutons are exposed at the surface or covered by a thin layer of glacial deposits and cause some of the highest indoor radon concentrations in the State. An area in southwestern Wisconsin and adjacent smaller parts of Minnesota, Iowa, and Illinois, is called the "Driftless Area" (fig. 1). It is not covered by glacial deposits but parts of the area were likely overrun by glaciers at least once. The Driftless Area is underlain by Cambrian and Ordovician limestone, dolomite, and sandstone with moderate to high radon potential.

Glacial deposits in southern Wisconsin, northern and central Illinois, and western Indiana are primarily from the Green Bay and Lake Michigan lobes. The Green Bay and Lake Michigan lobes advanced from their source in the Hudson Bay region of Canada and moved southward, terminating in Illinois and Iowa. These tills range from sandy to clayey and are derived primarily from shales, sandstones, and carbonate rocks of southern Wisconsin, the western Michigan Basin, and the northern Illinois Basin. A small part of eastern Illinois and much of western Indiana are covered by deposits of the Huron-Erie lobe, and west-central Illinois is covered by glacial deposits of pre-Wisconsinan, mostly Illinoian, age. The Huron-Erie lobe entered Illinois from the east and moved westward and southwestward into the State. Huron-Erie lobe and pre-Wisconsinan glacial deposits are derived from Paleozoic shale, sandstone, siltstone, carbonate rocks, and coal of the Illinois Basin, and they are commonly calcareous due to the addition of limestones and dolomites of northern Indiana and Ohio and southern Ontario. In contrast, Lake Michigan lobe deposits contain significant amounts of dark gray to black Devonian and Mississippian shales of the Michigan Basin, accounting for the high clay content of Lake Michigan lobe tills. Unglaciated southernmost Illinois is part of the Mississippi Embayment of the Coastal Plain and has low geologic radon potential.

Wisconsin-age glacial deposits in Indiana were deposited by three main glacial lobes—the Lake Michigan lobe, which advanced southward as far as central Indiana; the Huron-Erie lobe; and the Saginaw sublobe of the Huron lobe (labeled Huron lobe on fig. 1), which advanced from the northeast across northern Ohio and southern Michigan, respectively. Michigan lobe deposits are clayey near Lake Michigan, sandy and gravelly in an outwash and morainal area in northwestern Indiana, and clayey to loamy in west-central Indiana. Saginaw sublobe deposits are loamy and calcareous and are derived primarily from carbonate rocks and shale. The Huron-Erie lobe advanced from the northeast and covered much of northern and central Indiana at its maximum extent. Eastern Indiana and western Ohio are underlain by tills of the Huron-Erie lobe that are derived in part from black shales of the Devonian Ohio Shale and Devonian-Mississippian New Albany Shale, but also include Paleozoic limestone, dolomite, sandstone, siltstone, and gray shale. Black shales and carbonates underlie and provide source material for glacial deposits in a roughly north-south pattern through central Ohio, including the Columbus area, and extend south of the glacial limit, where the black shales form a prominant arcuate pattern in northern Kentucky that curves northward into southern Indiana and underlies glacial deposits in east-central Indiana. The overall radon potential of this area is high. Eastern Ohio is underlain by Devonian to Permian shales and limestones with moderate to high radon potential.

The Michigan Basin covers all of the Southern Peninsula and the eastern half of the Northern Peninsula of Michigan, as well as parts of eastern Wisconsin and northeastern Illinois, northern Indiana, and northwestern Ohio. Glacial deposits include silty and clayey tills of the Lake Michigan, Huron, and Huron-Erie lobes (fig. 1). Huron lobe tills are sandy to gravelly and calcareous, containing pebbles and cobbles of limestone, dolomite, and some sandstone and shale, with boulders of igneous and metamorphic rocks and quartzite. Tills of the Huron-Erie and Lake Michigan lobes are derived from similar source rocks but are more silty and clayey in texture. Source rocks for these tills are sandstones, gray shales, and carbonate rocks of the Michigan Basin, which are generally poor radon sources. In the Southern Peninsula, the Devonian Bell, Antrim, and Ellsworth Shales, and Mississippian Sunbury Shale locally contain organic-rich black shale layers with higher-than-average amounts of uranium, except for the Antrim Shale, which is organic rich throughout. These shales underlie and constitute source rock for glacial deposits in the northern, southeastern, and southwestern parts of the Southern Peninsula, and are locally exposed at the surface in the northern part of the Southern Peninsula. Because of generally moist soils, soils developed on tills derived from black shales in Michigan generate moderate to locally high radon, with higher values more common in the southern part of the State (fig. 2).

Glaciated areas present special problems for radon-potential assessment because bedrock material in the central United States was commonly transported hundreds of km from its source. Glaciers are quite effective in redistributing uranium-rich rocks; for example, in Ohio, uranium-bearing black shales have been disseminated over much of western Ohio and eastern Indiana, now covering a much larger area than their original outcrop pattern, and display a prominent radiometric high. The physical, chemical, and drainage characteristics of soils formed from glacial deposits vary according to source bedrock type and the glacial features on which they are formed. For example, soils formed from ground moraine deposits tend to be more poorly drained and contain more fine-grained material than soils formed on kames, moraines, or eskers, which are generally coarser and well-drained. In general, soils developed from coarser-grained tills are poorly structured, poorly sorted, and poorly developed, but are generally more highly permeable than the bedrock from which they are derived.

Clayey tills, such as those underlying parts of western and southern Minnesota, have relatively high emanation coefficients and usually have low to moderate permeability, depending on the degree to which the clays are mixed with coarser sediments. Tills consisting of mostly coarse material tend to emanate less radon because larger grains have lower surface area-to-volume ratios, but because these soils have generally high permeabilities, radon transport distances are generally longer. Structures built in these materials are thus able to draw soil air from a larger source volume, so moderately to highly elevated indoor radon concentrations may be achieved from comparatively lower-radioactivity soils. In till soils with extremely high permeability, atmospheric dilution may become significant, and if the soils have low to moderate radium contents, elevated indoor radon levels would be less likely to occur. Soil moisture has a significant effect on radon generation and transport and high levels of soil moisture generally lower the radon potential of an area. The main effect of soil moisture is its tendency to occlude soil pores and thus inhibit soil-gas transport. Soils in wetter climates from northern Minnesota to northern Michigan generally have lower radon potential than soils derived from similar tills in the southern parts of those states or in Indiana and Illinois, in part because of higher soil moisture conditions to the north.

PRELIMINARY GEOLOGIC RADON POTENTIAL ASSESSMENT OF OHIO

by
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INTRODUCTION

Ohio is one of the Great Lakes States and is located south of Lake Erie. Ohio is highly industrialized, but also has significant agricultural activity. The State is subdivided into 88 counties (fig. 1). The population distribution by county is shown on figure 2. All 88 counties in Ohio have more than 10,000 residents, 20 counties have between 100,000 and 500,000 residents, and 5 counties have more than 500,000 residents.

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

GEOGRAPHIC SETTING OF OHIO

Approximately the eastern third of Ohio is part of the Allegheny Plateau. The remainder of the State is part of the Interior Lowlands physiographic province (fig. 3). The Allegheny Plateau, which is drained by the Ohio River, is much more dissected than the Interior Lowlands. The Allegheny Plateau is subdivided into two physiographic sections, the unglaciated plateau and the glaciated plateau (fig. 4). Valleys in the unglaciated section tend to be deeper and steeper sided than in the glaciated section. The Interior Lowlands are subdivided into three physiographic sections–the Till Plains, the Lake Plains, and the Lexington Plain (fig. 4). The Till Plains formed during the glaciation of the Pleistocene Epoch and are either flat or gently undulating. The undulations are due either to variations in the underlying bedrock or to other glacial deposits such as moraines, kames, and eskers. Water trapped between the retreating ice of the last continental ice sheet and the glacial deposits of west-central Ohio produced lakes. The Lake Plains resulted when these lakes drained, exposing the flat lake bottoms. The Lexington Plain is unglaciated and was formed by stream erosion of limestone bedrock. The areas between stream dissections in the Lexington Plain are flat-topped and also contain a large number of sinkholes.

Fig. 1. Counties

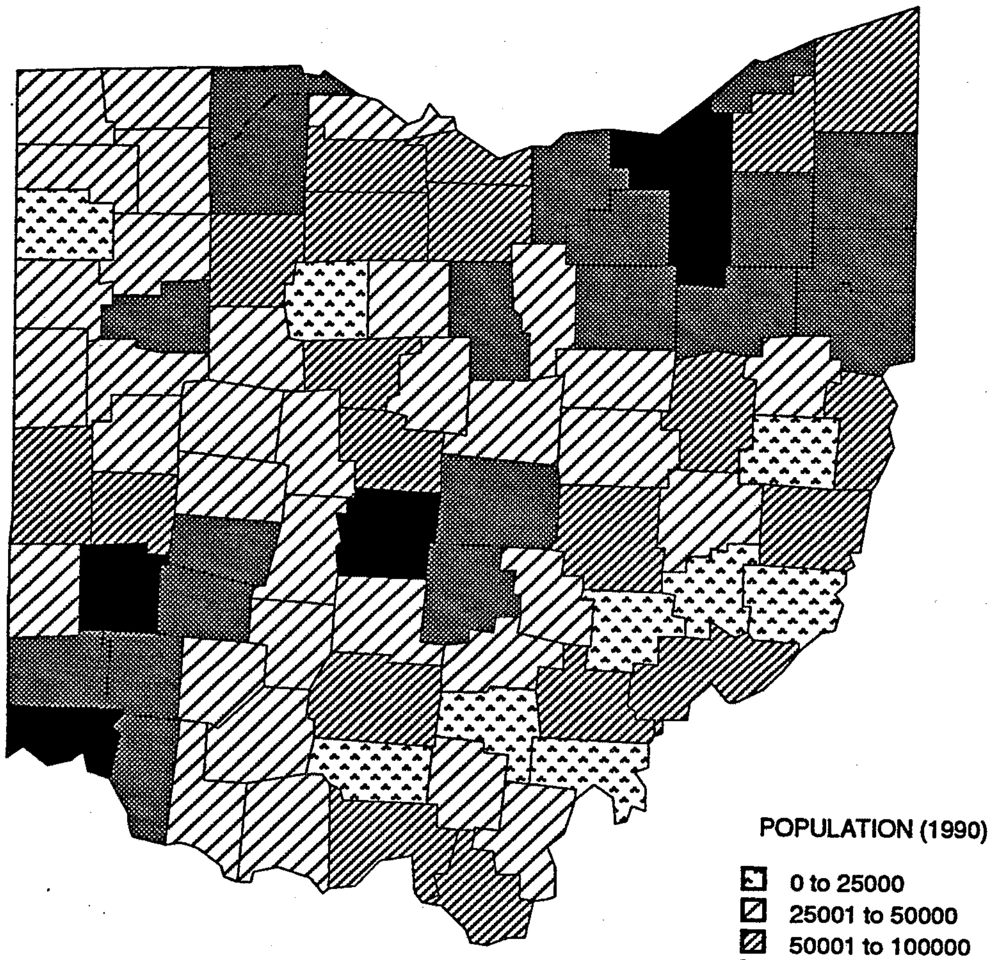
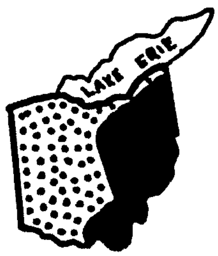


Figure 2. Population of counties in Ohio (1990 U.S. Census data).

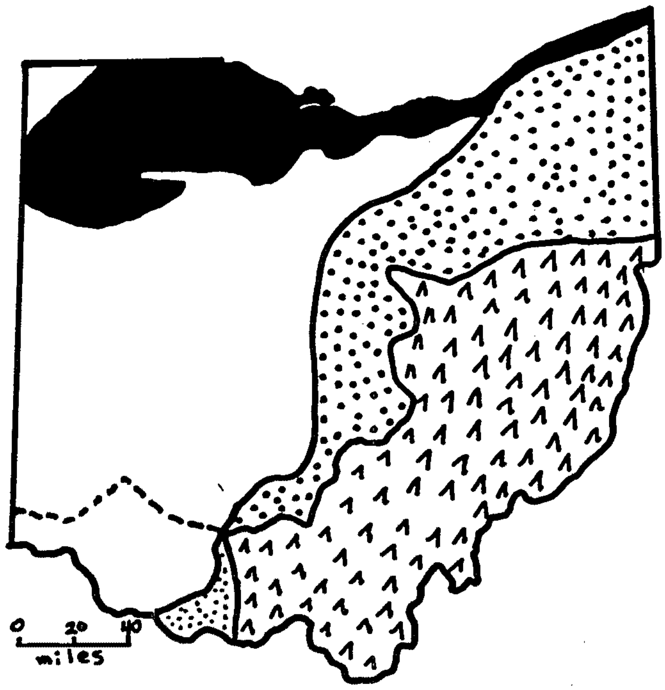


Interior Lowlands

Allegheny Plateau

(modified from Wright, 1953)

Fig. 3. Physical Setting



(modified from Noble and Korsok, 1975)

Till Plains (Southern limit of Wisconsinan glaciation)

Lake Plains

Glaciated Plateau

Lexington Plain

Unglaciated Plateau

Fig. 4. Physiographic Sections

GEOLOGIC SETTING OF OHIO

The bedrock in Ohio ranges in age from Ordovician to Permian. (Note--a Geologic Time Scale is presented in the appendix to the introduction.) Only rocks of sedimentary origin crop out in Ohio; however, igneous and metamorphic material is present in the deposits left behind by the continental glaciers. In general, rocks become younger from west to east in Ohio (fig. 5). A generalized section of rocks of Ohio, listing formation names, member names, and other geologic information for each of the geologic time periods can be found in Stout (1947). The stratigraphy of western Ohio is dominated by carbonate rocks, and numerous thin limestones are present in eastern Ohio along with shales, sandstones, and coals (fig. 6). The abundance of carbonates is also reflected in the soils. Devonian shales crop out in a north-south band in the center of the State and along Lake Erie (fig. 5).

About two-thirds of Ohio was glaciated during the Pleistocene Epoch. Deposits left behind by three of the four major glacial advances have been identified in Ohio. The oldest, pre-Illinoian (formerly called Kansan), is of limited extent and is only found in the southwest corner of the State. The next oldest, Illinoian, is exposed in a band just below the furthest advance of the youngest glacial deposits, the Wisconsinan (fig. 7). Wisconsinan lake deposits, kames and eskers, ground moraine, and end moraines are shown on figure 7.

SOILS

The soil regions found in Ohio are shown on figure 8 and the drainage characteristics of the soils are shown on figure 9. Drainage characteristics give an indication of the soil permeability, which influences radon migration. Because the amount of moisture available to soils affects both emanation and transport of radon, a map showing annual precipitation has been included (fig. 10).

INDOOR RADON DATA

Figure 11 presents screening indoor radon data from the State/EPA Residential Radon Survey graphically, and Table 1 presents the data from which figure 11 was derived, including data from those counties with less than 5 measurements (which are not shown on figure 11). Figure 1 shows the Ohio counties and can be used in conjunction with the indoor radon maps shown in figure 11. Forty-two of the counties in Ohio had average radon concentrations greater than 4 pCi/L (fig. 11 & Table 1). Five counties had greater than 60 percent of the homes with radon concentrations greater than 4 pCi/L (fig. 11, Table 1). Twenty-five counties had between 40 and 60 percent of the homes with radon concentrations greater than 4 pCi/L (fig. 11, Table 1).

In general, counties with average radon concentrations greater than 4 pCi/L seem to be associated with the north-south trending Ohio Shale outcrop band that has been redistributed by glaciers, with limestone glacial soils, and with some residual limestone soils (figs. 5, 7, 8, 11). In a study of Franklin County (located over the N-S outcrop band of Ohio Shale), Grafton (1990) found that 92 percent of the homes in a random survey using screening indoor radon measurements had indoor radon concentrations greater than 4 pCi/L. The counties around the precipitation high in the northeastern corner of the State (fig. 10) in general have a low percentage of homes with radon concentrations exceeding 4 pCi/L. This may partially be due to inhibited radon transport caused by the precipitation.

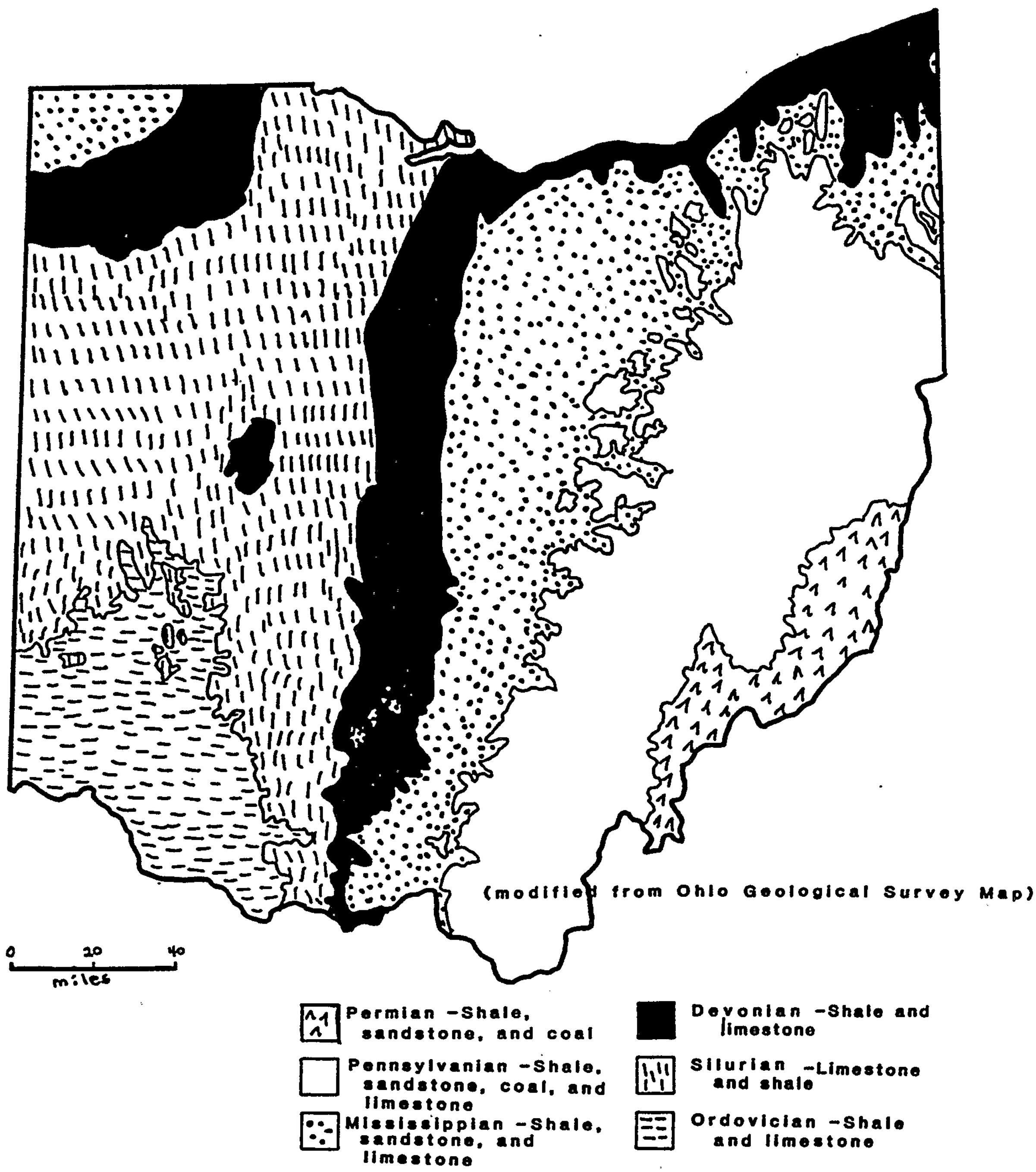
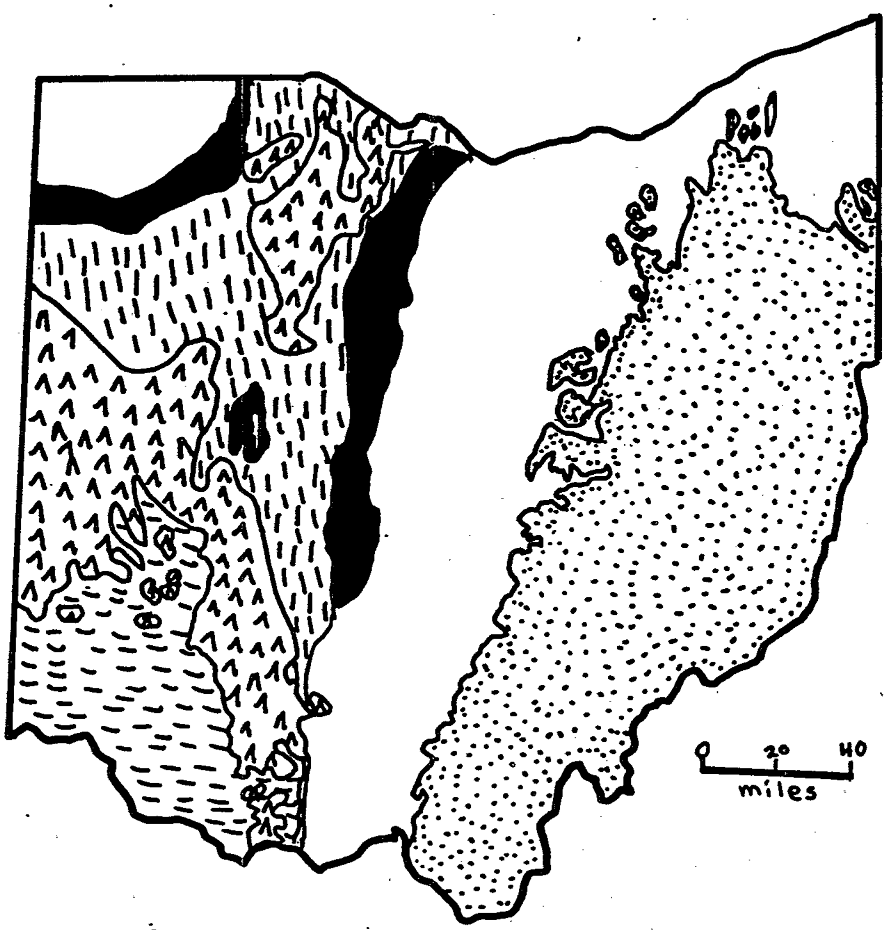


Fig. 5. Geologic Map



(modified from Wright, 1953)

Numerous thin undifferentiated limestones

Deleware and Columbus Limestones

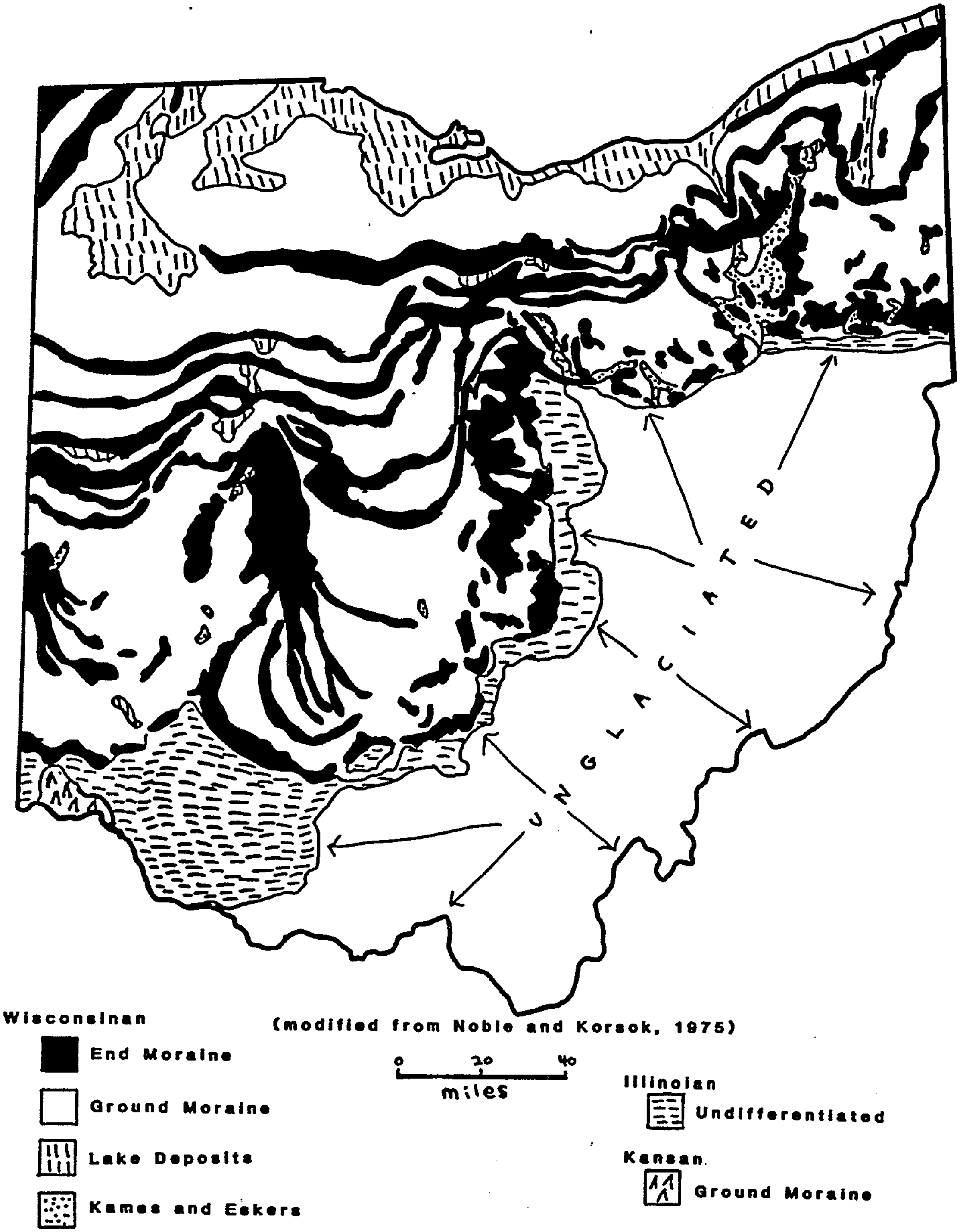
Bass Island and Detroit River Groups (dolomites)

Niagra Group (dolomite)

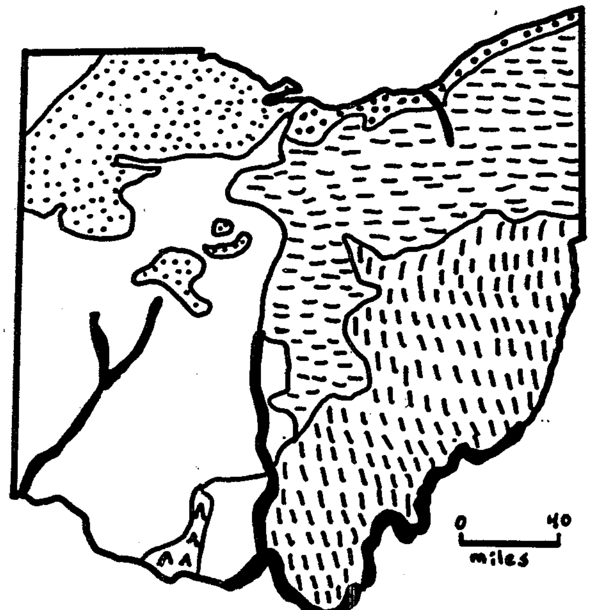
Richmond, Maysville and Eden Groups (limestones and shales)

Fig. 6. Limestone and Dolomite Resources

Fig. 7. Glacial Deposits



(modified from Noble and Korsok, 1975)



Bottom, terrace, and outwash soils

Glacial limestone soils

Glacial and lacustrine soils over limestone

Glacial sandstone and shale soils

Lacustrine sandstone and shale soils

Residual limestone soils

Residual sandstone and shale soils

(modified from Noble and Korsok, 1975)

Fig. 8. Soils

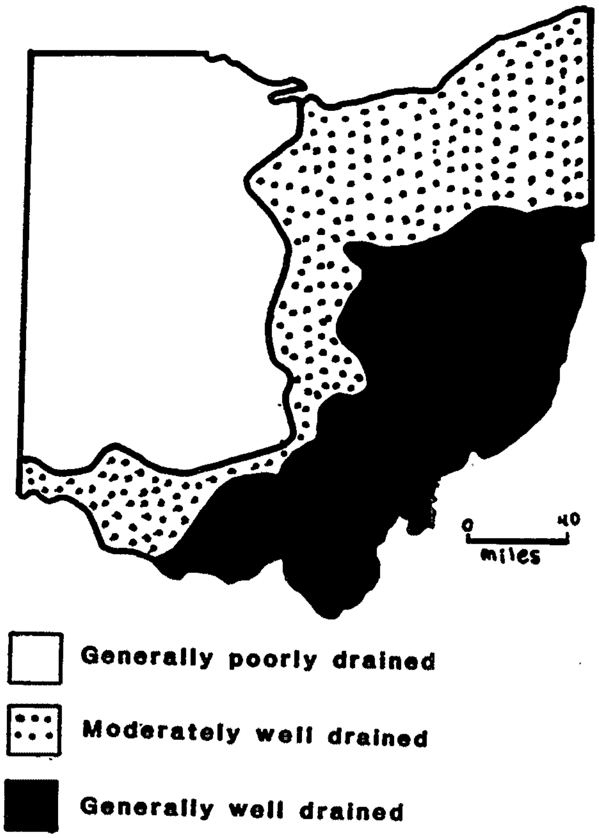


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Fig. 9. Soil Drainage Characteristics

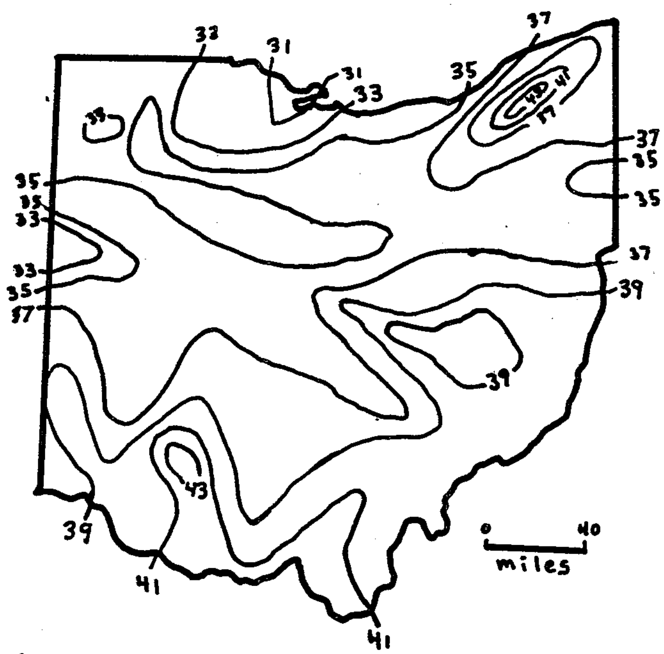

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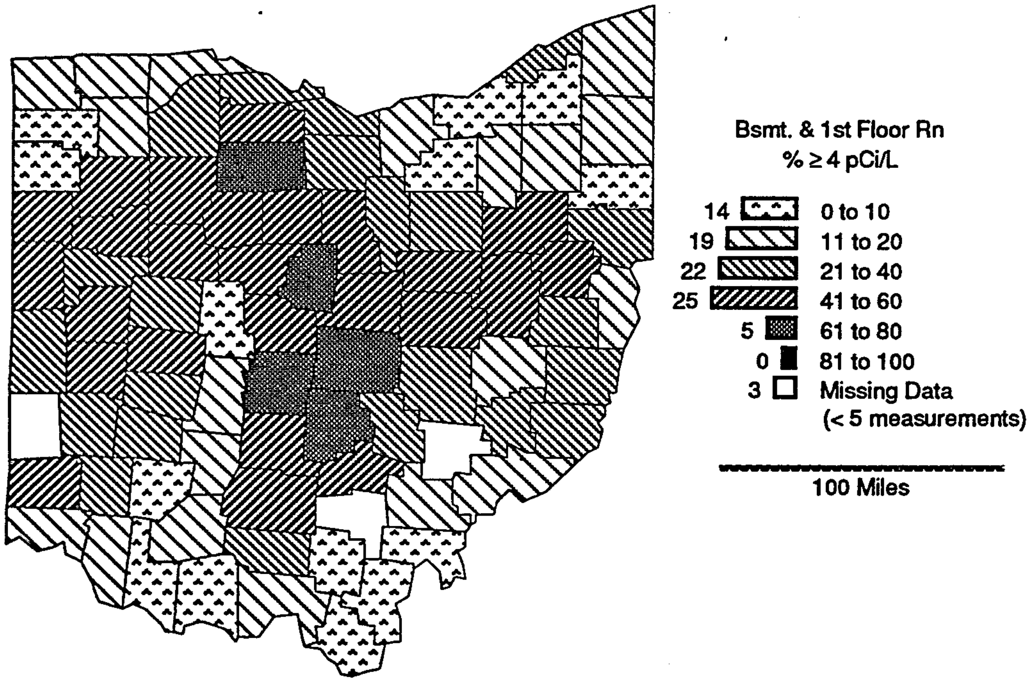
Fig. 10. Mean Annual Precipitation (inches)



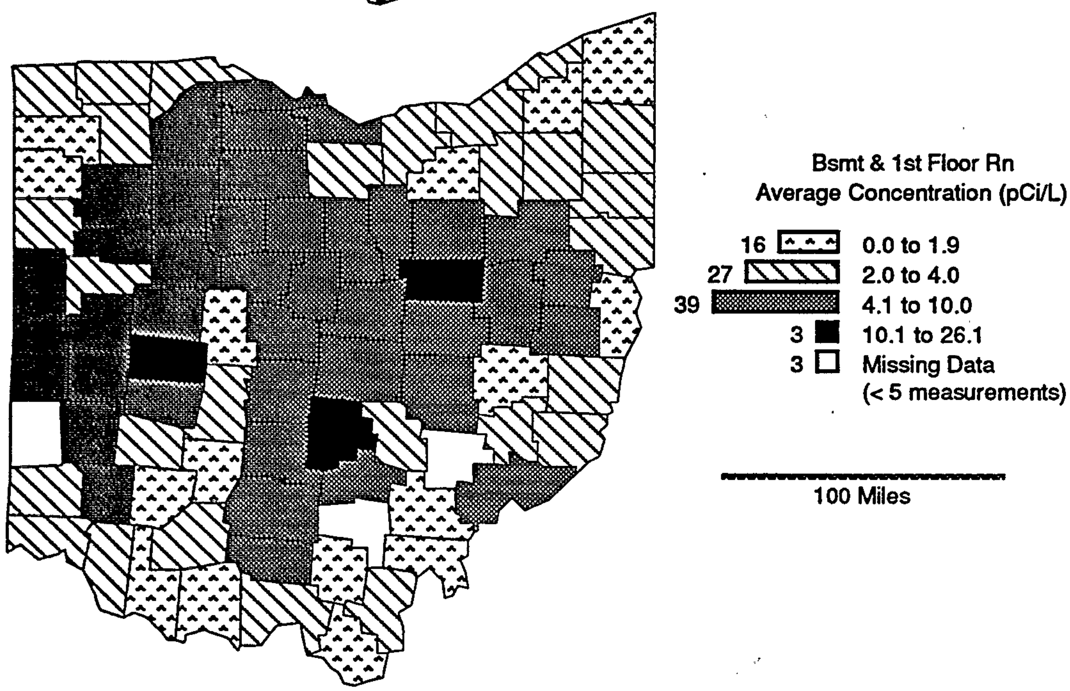


Figure 11. Screening indoor radon data from the EPA/State Residential Radon Survey of Ohio, 1988-89, for counties with 5 or more measurements. Data are from 2-7 day charcoal canister tests. Histograms in map legends show the number of counties in each category. The number of samples in each county (see Table 1) may not be sufficient to statistically characterize the radon levels of the counties, but they do suggest general trends. Unequal category intervals were chosen to provide reference to decision and action levels.

TABLE 1. Screening indoor radon data from the EPA/State Residential Radon Survey of Ohio conducted during 1988-89. Data represent 2-7 day charcoal canister measurements from the lowest level of each home tested.

COUNTY	NO. OF MEAS.	MEAN	GEOM. MEAN	MEDIAN	STD. DEV.	MAXIMUM	%>4 pCi/L	%>20 pCi/L
ADAMS	10	1.9	1.1	2.1	1.5	4.8	10	0
ALLEN	28	7.2	3.6	3.9	12.9	62.6	50	7
ASHLAND	20	6.0	3.4	2.7	8.8	36.6	30	10
ASHTABULA	15	1.9	1.2	0.9	2.2	7.5	13	0
ATHENS	14	1.9	1.0	1.2	2.0	6.4	14	0
AUGLAIZE	10	2.8	1.5	1.6	2.6	7.9	30	0
BELMONT	12	3.3	2.3	2.2	2.9	10.1	33	0
BROWN	5	1.2	0.9	1.1	0.8	2.1	0	0
BUTLER	33	4.0	2.6	3.0	3.6	14.9	42	0
CARROLL	7	8.6	4.7	3.5	10.2	27.7	43	14
CHAMPAIGN	12	26.1	3.2	4.3	75.4	265.2	50	8
CLARK	15	7.8	3.3	2.0	10.6	33.7	40	13
CLERMONT	12	2.6	1.2	1.5	3.1	10.7	17	0
CLINTON	9	1.6	1.1	2.1	1.2	3.4	0	0
COLUMBIANA	13	2.7	1.7	1.9	2.3	7.8	23	0
COSHOCTON	18	9.7	4.3	3.4	14.0	56.9	50	11
CRAWFORD	14	5.3	4.0	5.3	3.1	11.6	57	0
CUYAHOGA	120	2.0	1.0	1.1	6.8	74.5	4	1
DARKE	15	5.1	2.6	2.9	4.6	13.0	40	0
DEFIANCE	8	1.9	1.6	1.9	1.0	3.9	0	0
DELAWARE	20	6.2	4.1	5.6	5.5	21.7	55	5
ERIE	19	4.5	2.8	2.5	4.9	21.1	37	5
FAIRFIELD	31	19.9	6.1	8.1	45.0	238.5	61	26
FAYETTE	6	1.7	1.0	1.3	1.6	4.5	17	0
FRANKLIN	170	7.4	5.3	5.4	6.9	46.0	64	5
FULTON	6	2.5	1.9	2.3	1.6	4.8	17	0
GALLIA	11	2.2	1.4	1.2	2.5	9.2	9	0
GEAUGA	6	1.1	0.8	1.2	0.8	2.4	0	0
GREENE	25	4.0	2.5	2.7	3.5	11.1	40	0
GUERNSEY	13	1.8	1.2	1.4	1.6	4.9	15	0
HAMILTON	90	2.1	1.4	1.4	2.2	16.2	14	0
HANCOCK	15	5.6	3.6	3.0	5.4	16.1	47	0
HARDIN	17	6.0	3.2	3.7	6.7	26.2	41	6
HARRISON	7	4.5	3.5	2.7	3.8	10.1	29	0
HENRY	16	2.5	1.5	2.2	1.9	6.1	13	0
HIGHLAND	8	2.4	1.7	1.7	2.2	7.3	13	0
HOCKING	9	4.7	3.6	5.4	2.9	8.2	56	0
HOLMES	9	10.4	4.4	4.4	15.7	50.5	56	11
HURON	14	3.7	2.2	3.4	3.3	11.8	36	0
JACKSON	15	1.3	1.0	1.1	0.9	3.4	0	0
JEFFERSON	7	1.9	1.2	1.5	2.1	6.4	14	0

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

COUNTY	NO. OF MEAS.	MEAN	GEOM. MEAN	MEDIAN	STD. DEV.	MAXIMUM	%>4 pCi/L	%>20 pCi/L
KNOX	14	7.2	4.5	5.2	7.4	28.8	57	7
LAKE	28	3.9	1.6	1.5	6.7	31.2	21	4
LAWRENCE	9	1.0	0.9	0.8	0.5	1.7	0	0
LICKING	29	8.0	5.1	5.3	6.8	28.9	72	7
LOGAN	19	5.4	2.5	2.4	6.8	24.1	37	5
LORAIN	21	2.7	1.4	1.4	4.0	17.1	19	0
LUCAS	71	2.6	1.8	1.8	2.9	15.8	17	0
MADISON	10	2.4	1.7	1.6	1.9	5.9	20	0
MAHONING	20	2.1	1.6	1.9	1.4	5.1	10	0
MARION	17	4.9	3.1	2.9	5.2	20.8	41	6
MEDINA	9	1.4	1.1	1.3	1.0	3.3	0	0
MEIGS	9	1.1	0.9	1.0	0.9	3.2	0	0
MERCER	12	5.6	2.4	3.0	9.9	36.5	42	8
MIAMI	22	8.3	4.9	5.4	10.3	46.8	55	9
MONROE	6	3.5	2.6	2.8	2.7	8.2	33	0
MONTGOMERY	67	4.3	2.5	2.5	6.8	46.8	28	3
MORGAN	2	9.2	1.0	9.2	12.9	18.3	50	0
MORROW	8	6.3	5.3	5.9	3.8	12.7	63	0
MUSKINGUM	24	4.6	3.1	2.9	4.6	19.4	38	0
NOBLE	6	3.2	3.0	2.9	1.3	4.8	33	0
OTTAWA	9	5.4	0.9	1.0	7.9	19.5	33	0
PAULDING	8	1.3	0.9	0.8	1.3	3.5	0	0
PERRY	12	3.8	1.9	1.8	5.3	18.8	25	0
PICKAWAY	7	4.5	3.3	4.6	3.2	8.2	57	0
PIKE	8	8.5	2.6	2.7	9.9	22.8	38	25
PORTAGE	6	4.1	2.0	1.8	6.3	16.8	17	0
PREBLE	4	4.1	3.1	2.7	3.6	9.3	25	0
PUTNAM	18	5.7	4.1	4.1	4.9	20.2	50	6
RICHLAND	29	5.4	3.5	2.7	6.6	32.7	41	3
ROSS	10	6.9	3.5	4.0	7.7	26.7	50	10
SANDUSKY	11	5.7	4.4	4.0	4.5	17.0	45	0
SCIOTO	13	2.5	1.7	1.5	2.5	9.5	15	0
SENECA	21	6.0	3.9	5.4	4.4	15.3	62	0
SHELBY	9	8.3	4.6	3.8	8.4	21.7	44	11
STARK	50	5.5	3.5	3.8	5.5	25.0	46	4
SUMMIT	60	3.2	2.0	2.1	4.0	22.7	20	3
TRUMBULL	34	2.2	1.5	1.6	2.0	7.9	12	0
TUSCARAWAS	13	6.5	3.4	3.5	7.5	26.2	46	8
UNION	6	1.5	0.9	1.6	1.1	2.9	0	0
VAN WERT	18	3.8	2.8	3.8	2.8	9.6	44	0
VINTON	2	2.2	2.1	2.2	0.4	2.4	0	0
WARREN	15	4.5	3.3	3.6	3.7	14.8	40	0
WASHINGTON	16	7.6	2.3	2.1	21.4	87.6	19	6

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

COUNTY	NO. OF MEAS.	MEAN	GEOM. MEAN	MEDIAN	STD. DEV.	MAXIMUM	%>4 pCi/L	%>20 pCi/L
WAYNE	12	4.2	2.0	2.2	6.3	22.8	25	8
WILLIAMS	8	3.5	1.8	2.2	5.3	16.4	13	0
WOOD	18	4.9	2.8	2.5	6.5	27.3	28	6
WYANDOT	10	7.0	4.8	4.8	7.6	27.4	50	10

The American Lung Association of Ohio (address in Bibliography) tested a total of 1,148 homes in the State, of which 48.9 percent had less than 4 pCi/L, 27.4 percent had 4 to 10 pCi/L, 12.7 percent had 10 to 20 pCi/L, 5.4 percent had 20 to 100 pCi/L, and 5.7 percent had greater than 100 pCi/L indoor radon. Their data appears to compare reasonably well with the State/EPA data.

GEOLOGIC RADON POTENTIAL

The first rock units to be investigated as potential source rocks of radon in Ohio were the organic-rich marine shales of the Devonian. The Upper Devonian Ohio Shale averages 30 ppm uranium and is the largest source of uranium in Ohio (Belisto and others, 1988). Stout (1947) divides the Ohio Shale into three members, in ascending order: the Huron, the Chagrin, and the Cleveland. Ghahremani (1981) found higher soil-gas radon concentrations associated with thicker portions of the Cleveland and Huron Members in northeast Ohio. Hume and others (1989) found radon levels as high as 3,000 pCi/L in ground water associated with the Huron Member in Erie, Huron, and Seneca counties. In northeastern Ohio, Ghahremani (1988) found a good correlation among the bedrock type (Cleveland or Huron Members of Ohio Shale), the amount of fracturing in the rock, and the migration of soil-gas radon to the surface and into structures.

Harrell and others (1991) found a strong positive correlation among uranium, indoor radon, and organic carbon content in the Ohio Shale. They discovered that radon escaping from the shale varies in direct proportion to the uranium content; the uranium content increases with the organic content, and because the organic carbon content of the shale increases from east to west, so does the radon emanating from the Ohio Shale. They predicted that high indoor radon values will be found along the north-south Ohio Shale outcrop. They further state that a thick layer of glacial material would serve to retard or act as a barrier to radon migration provided that the glacial material does not contain clasts of Ohio Shale. They also believe that large-scale advective transport is occurring because of the abundant vertical fractures in the Ohio Shale.

Limestones and dolomites generally do not contain much uranium (i.e. they are below the crustal average of 2.5 ppm [Carmichael, 1989]) unless they are rich in phosphate. However, Harrell and others (1991) found higher radon in basements over the phosphate-poor limestones and dolomites of the Columbus and Delaware Limestones (Middle Devonian) and the "Monroe Formation" [A name replaced by the Bass Islands (Upper Silurian) and Detroit River (Lower Devonian) Groups, fig. 6.] than they did in basements over the Ohio Shale in the same area. When carbonate rocks weather, the uranium and other metals that were widely dispersed in the rock can be concentrated in the iron-rich soils that form as a result of the weathering. This phenomenon may explain the higher radon values observed by Harrell and others (1991). Much of Ohio is underlain by limestones and dolomites (fig. 6) and approximately 2/3 of the soils present in Ohio are described as glacial limestone soils or as residual limestone soils (fig. 8). Because uranium may have been concentrated in these soils formed from carbonate rocks, they represent a potential radon source material.

Approximately two-thirds of Ohio is covered by glacial material (fig. 7). Smith and Mapes (1989) found that the permeability of the glacial sediment appears to be the most important physical attribute controlling surface radon concentrations, regardless of sediment thickness (see fig. 9 for estimates of soil permeabilities). They found that the influence of bedrock is twofold: (1) the rocks may be producing radon themselves, and (2) they may contribute radon-producing materials to glacial sediments derived from them. Smith and Mapes (1989) also found that, as a general rule, areas underlain by end moraines had the lowest indoor radon measurements and that areas

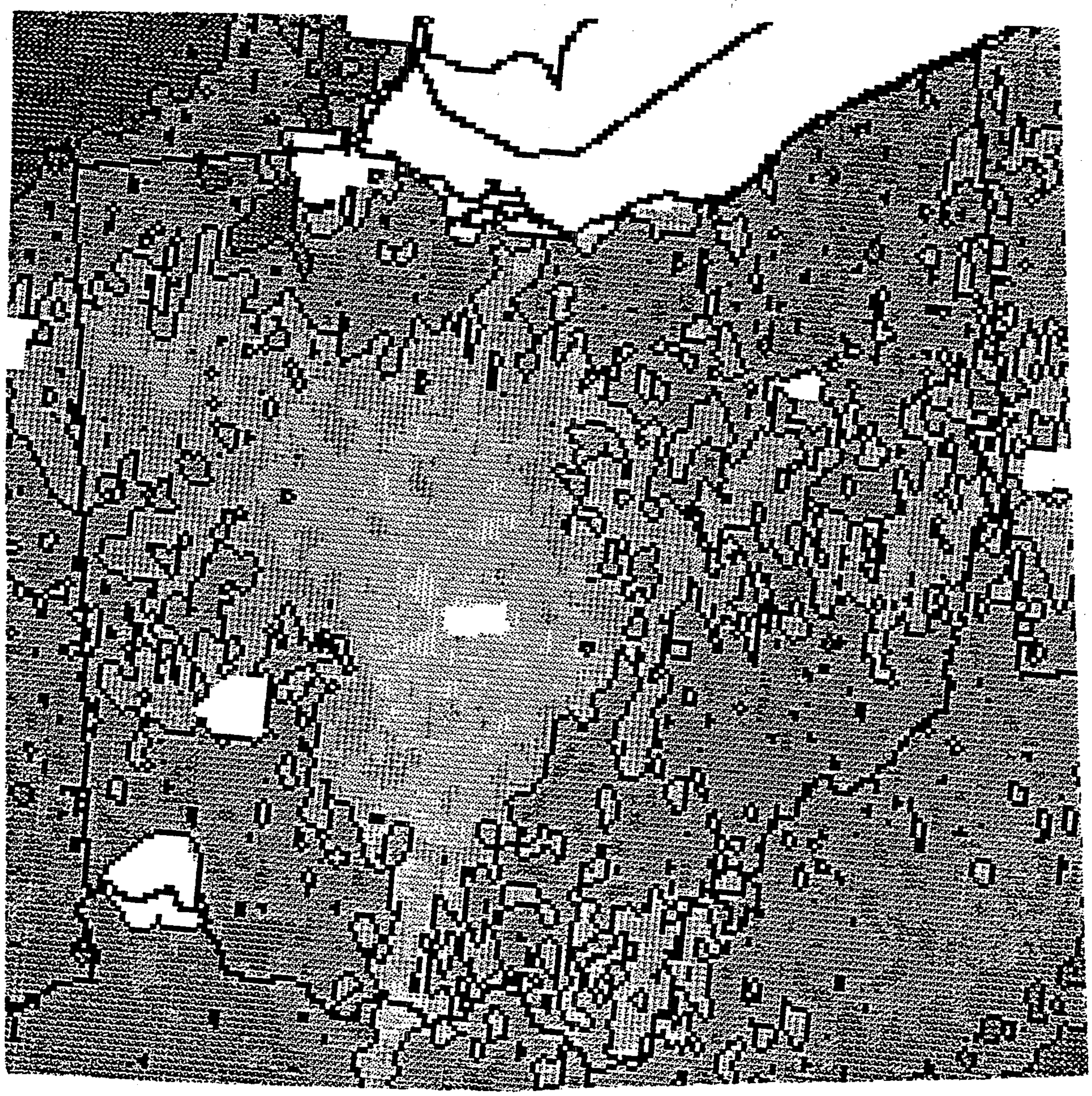


Figure 12. Aerial radiometric map of Ohio (after Duval and others, 1989). Contour lines at 1.5 and 2.5 ppm equivalent uranium (eU). Pixels shaded from 0 to 6.0 ppm eU at 0.5 ppm eU increments; darker pixels have lower eU values; white indicates no data.

underlain by glacial outwash and alluvium had the highest radon measurements (probably a permeability influence).

Figure 12 is an aerial radiometric map of Ohio produced from the NURE data (Duval and others, 1989). The north-south-trending Ohio Shale belt and several of the terminal moraines can be distinguished by their equivalent uranium (eU) signature on the map (see figs. 5, 7, and 12). A series of 1:500,000 aerial radiometric contour maps showing eU, eTh, and percent K are available for Ohio (Duval, 1985). A series of color aerial radiometric maps (scale of 1:1,000,000) are also available for Ohio (Duval, 1987). Overall, the radiometric map corresponds well with the geology.

SUMMARY

Ohio has a moderate to high radon potential in general. Its radon potential has been summarized using the Radon Index (RI) Matrix and the Confidence Index (CI) Matrix, which are discussed and described in the introduction to this volume. Table 2 presents the Radon Index and Confidence Index scores for the generalized radon potential areas shown on figure 13.

Area 1 has a moderate radon potential (RI=11) and comprises those parts of both the glaciated and unglaciated plateau that in general have less than 2.5 ppm eU (fig. 12). The rocks in Area 1 are dominantly Mississippian through Permian in age and have a diversity of lithologies (i.e. shale, sandstone, coal, and limestone). Area 2 has a high radon potential (RI=12) and comprises those parts of the glaciated and unglaciated plateau that in general have more than 2.5 ppm eU (fig. 12). Area 3, the Till Plains of Wisconsinan age, has a high radon potential (RI=14). The bedrock in Area 3 is dominantly Ordovician through Devonian in age, with the exception of the northwestern corner of the State, where it is Mississippian. The lithology of these rocks is dominantly limestone and shale. Area 3 was given 2 GFE points for the known high radon potential of the Devonian shales and glacial limestone soils (Harrell and others, 1991). Area 4, the Lake Plains, has a moderate radon potential (RI=10) and has generally poorly drained clayey soils. Area 5, the Lexington Plain, has a high radon potential (RI=13). Area 5 has generally well-drained limestone and shale soil soils developed on Ordovician and Silurian-age bedrock. Area 6, the Pre-Wisconsinan Till Plains (i.e. Till Plains south of the southern limit of Wisconsinan glaciation on figure 4), has a moderate radon potential (RI=11). Area 6 in general has a lower eU than the Wisconsinan Till Plains to the north.

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 that 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 (RI) and Confidence Index (CI) scores for generalized radon potential areas of Ohio shown on figure 13.

AREA

FACTOR	1 RI	1 CI	2 RI	2 CI	3 RI	3 CI
INDOOR RADON	2	3	2	3	2	3
RADIOACTIVITY	2	2	3	2	3	2
GEOLOGY	2	2	2	2	3	2
SOIL PERM.	2	2	2	2	1	2
ARCHITECTURE	3	--	3	--	3	--
GFE POINTS	0	--	0	--	+2	--
TOTAL	11	9	12	9	14	9
RANKING	MOD	MOD	HIGH	MOD	HIGH	MOD

FACTOR	4 RI	4 CI	5 RI	5 CI	6 RI	6 CI
INDOOR RADON	2	3	2	3	2	3
RADIOACTIVITY	2	2	3	2	2	2
GEOLOGY	2	2	3	2	2	2
SOIL PERM.	1	2	3	2	2	2
ARCHITECTURE	3	--	3	--	3	--
GFE POINTS	0	--	0	--	0	--
TOTAL	10	9	14	9	11	9
RANKING	MOD	MOD	HIGH	MOD	MOD	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

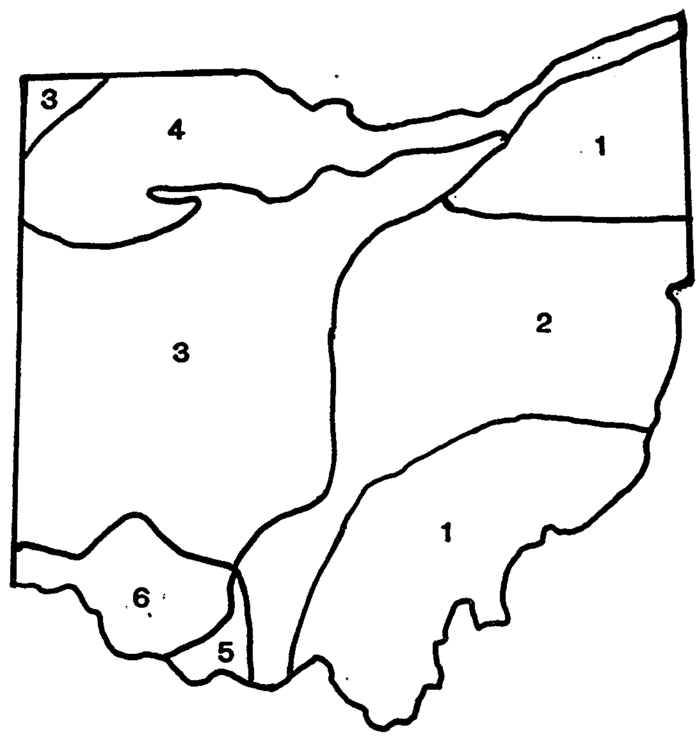


Fig. 13. Generalized Radon Potential Areas

(Described in Table 2)

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EPA's Map of Radon Zones

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

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

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

OHIO MAP OF RADON ZONES

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

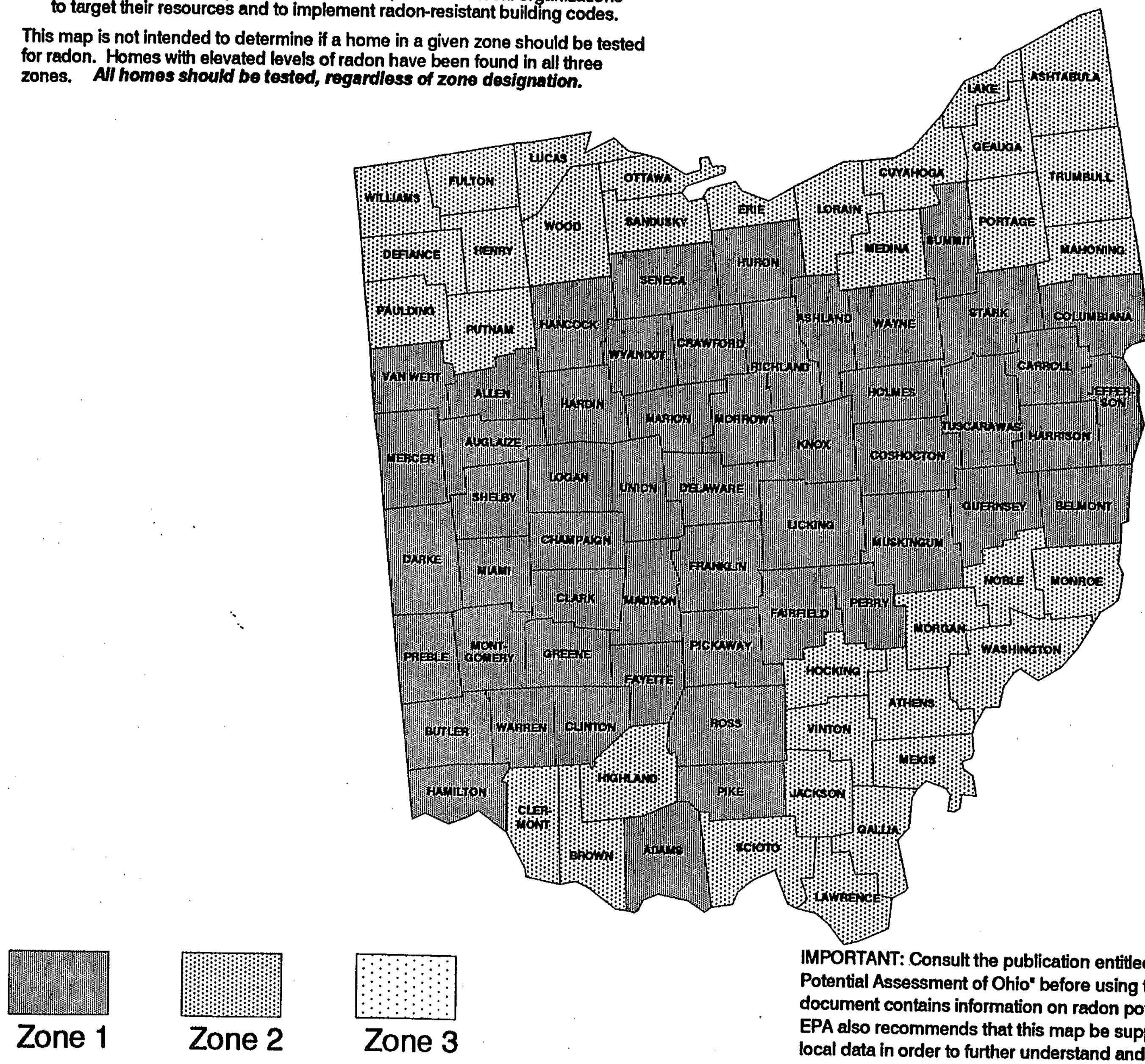
Two counties do not strictly follow the methodology for adapting the geologic provinces to zones. EPA and the Ohio Department of Health have designated Hamilton and Summit counties as Zone 1. Although these counties demonstrate moderate radon potential overall, they are prone to have locally high radon potential areas. This determination has been made based on the geology of these counties and on indoor radon data that was submitted by the Ohio Department of Health.

Although the information provided in Part IV of this report -- the State chapter entitled "Preliminary Geologic Radon Potential Assessment of Ohio" -- 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 5 EPA office or the Ohio radon program for information on testing and fixing homes. Telephone numbers and addresses can be found in Part II of this report.

OHIO - 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 Ohio" 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.