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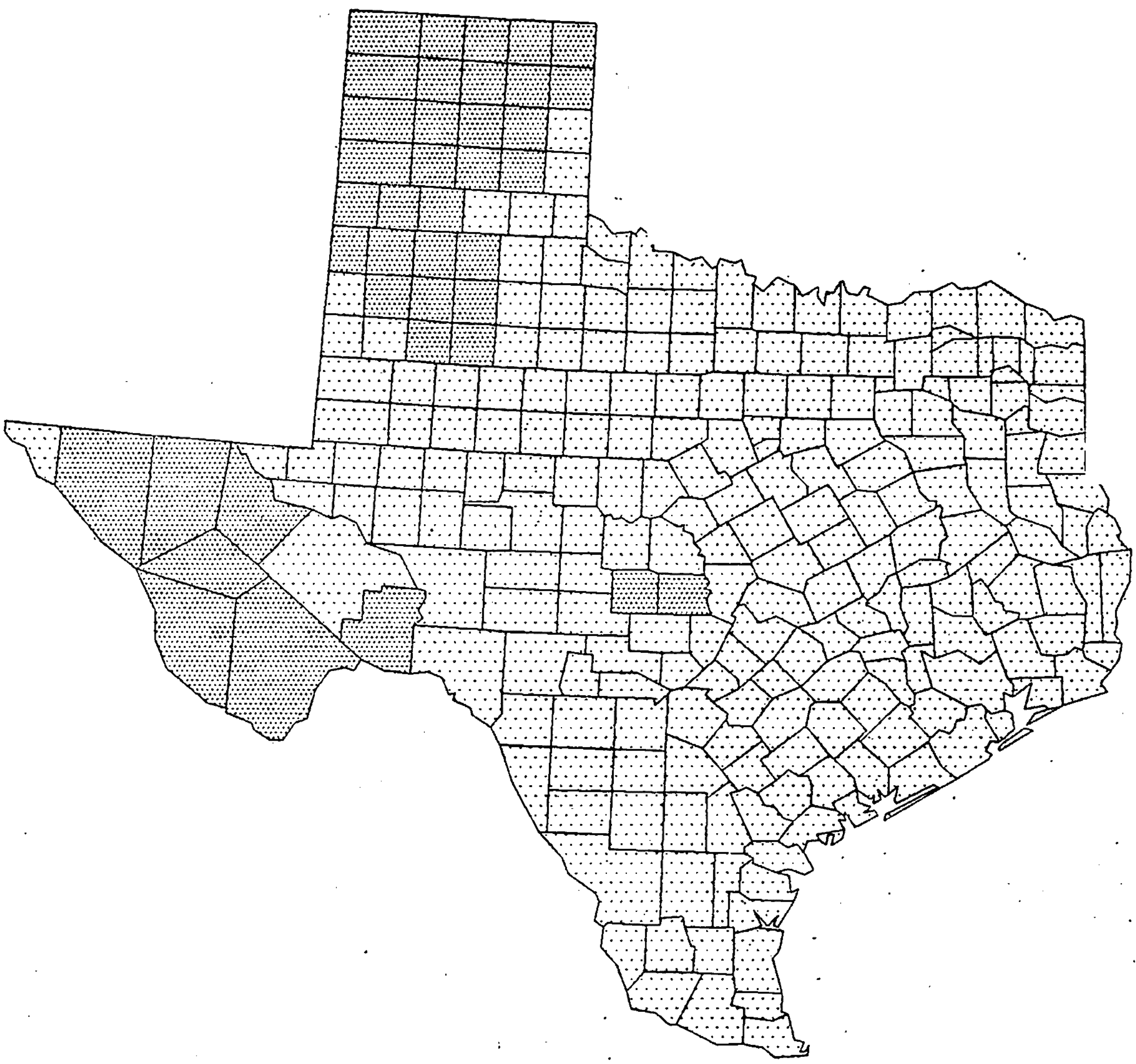
EPA's Map of Radon Zones

TEXAS



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TEXAS

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.

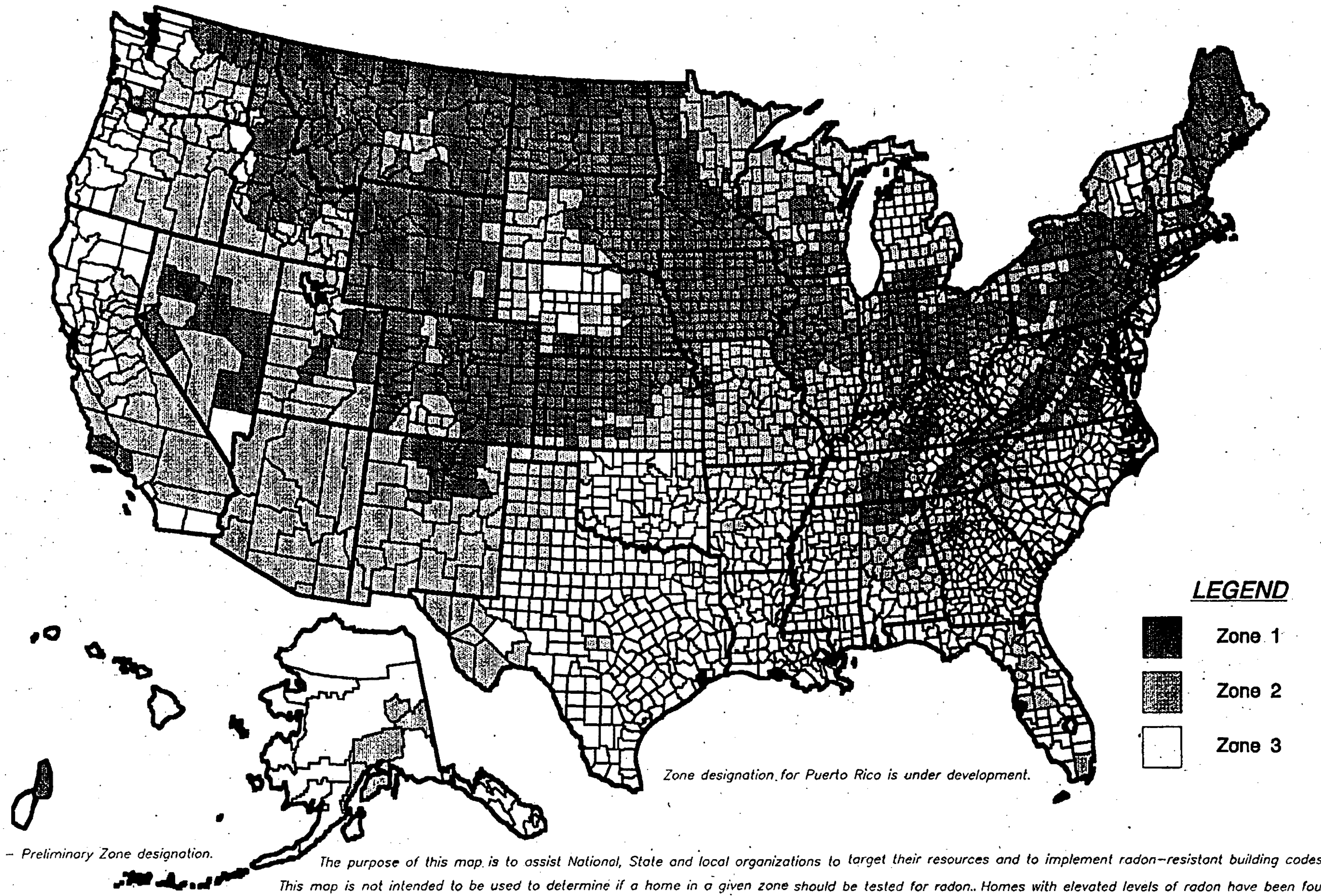
The Map of Radon Zones and its supporting documentation establish no regulatory requirements. Use of this map by State or local radon programs and building code officials is voluntary. The information presented on the Map of Radon Zones and in the supporting documentation is not applicable to radon in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

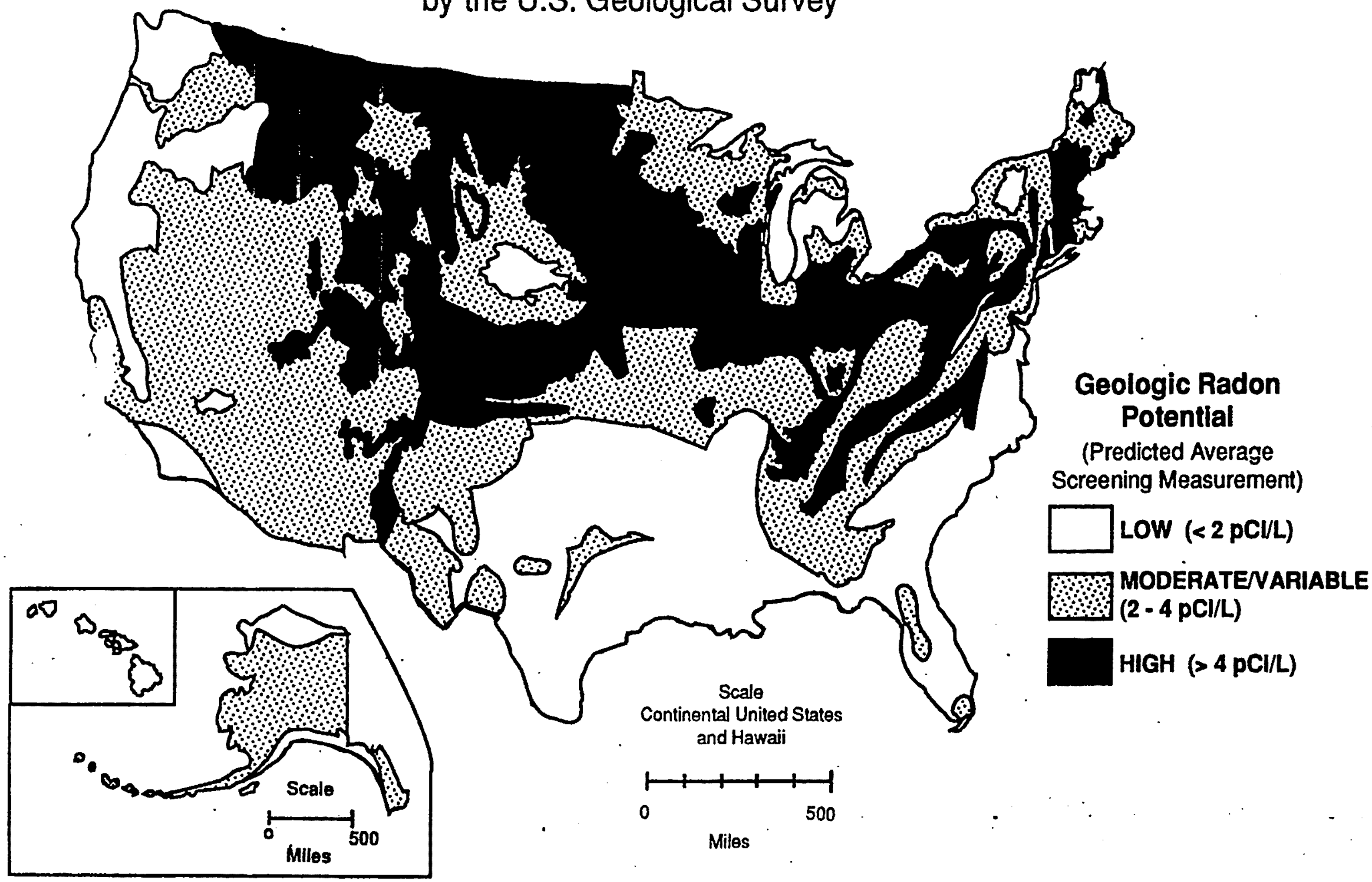
This map is not intended to be used to determine if a home in a given zone should be tested for radon.. Homes with elevated levels of radon have been found in all three zones. ***All homes should be tested, regardless of geographic location.***

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

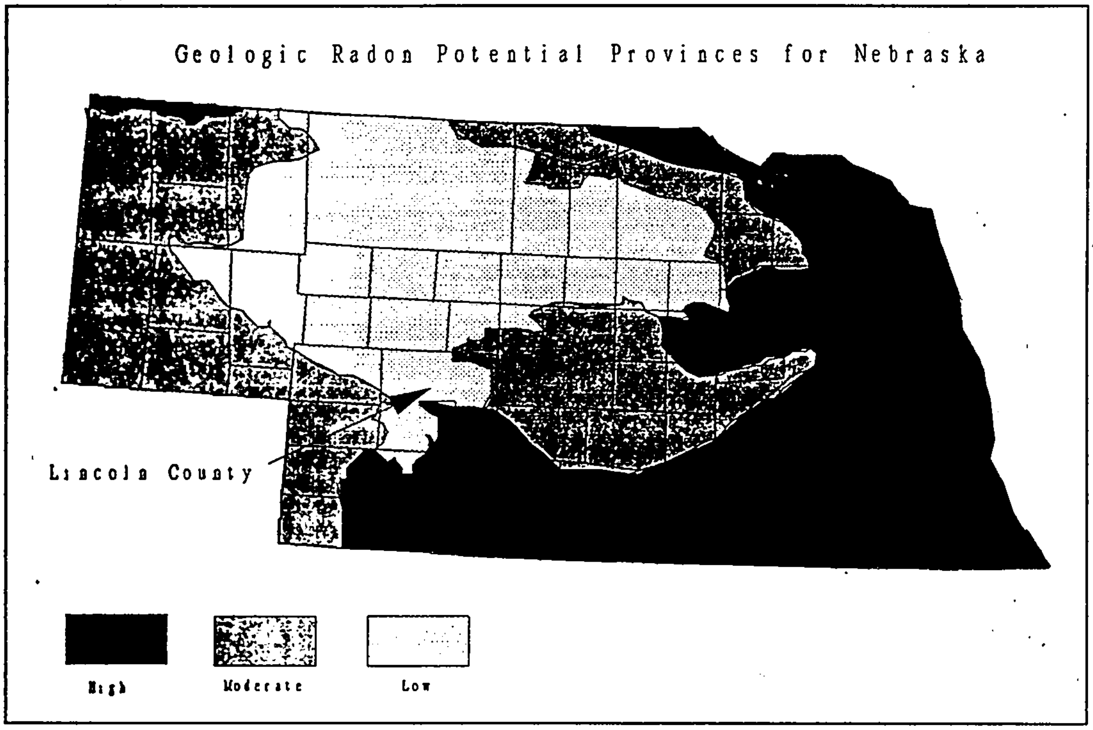
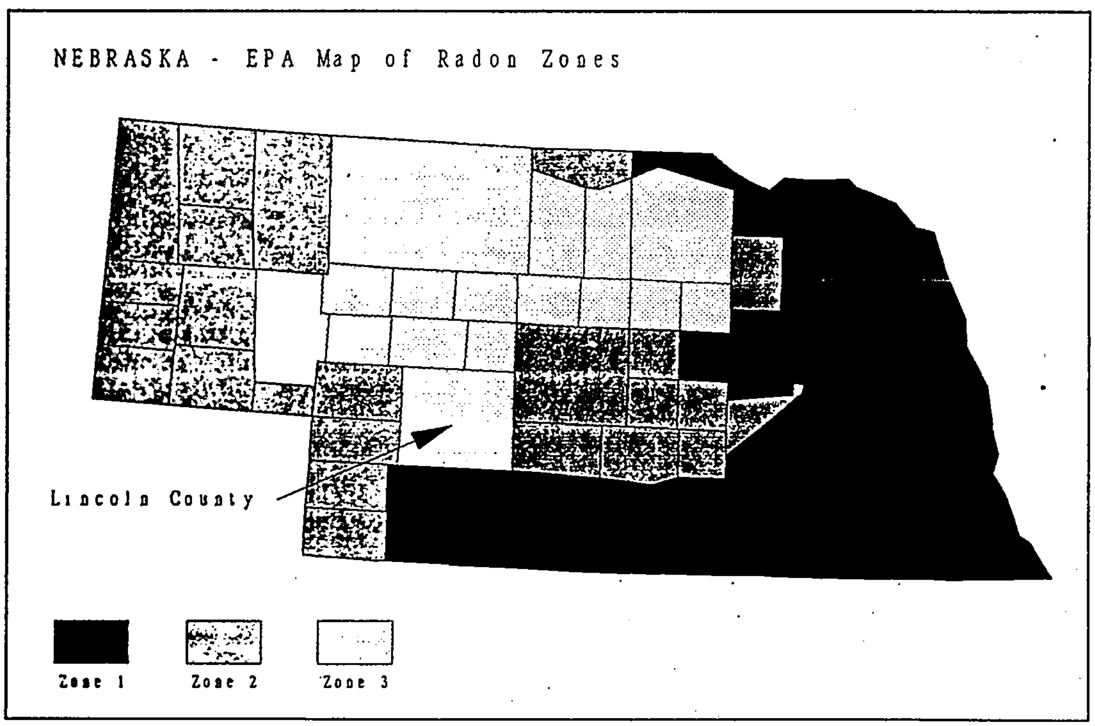


Figure 4



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

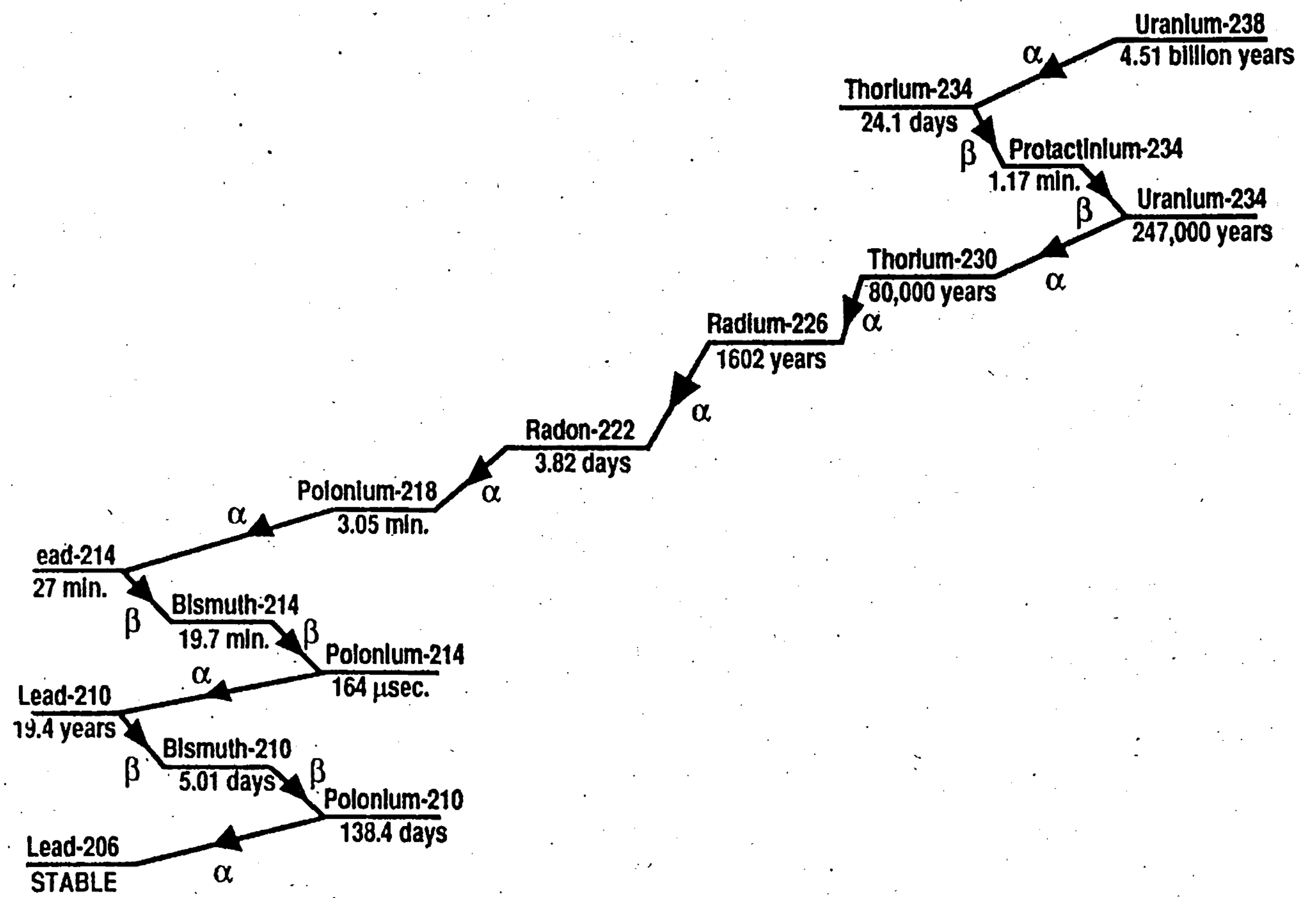

Figure 1. The uranium-238 decay series, showing the half-lives of elements and their modes of decay (after Wanty and Schoen, 1991). α denotes alpha decay, β denotes beta decay.

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).

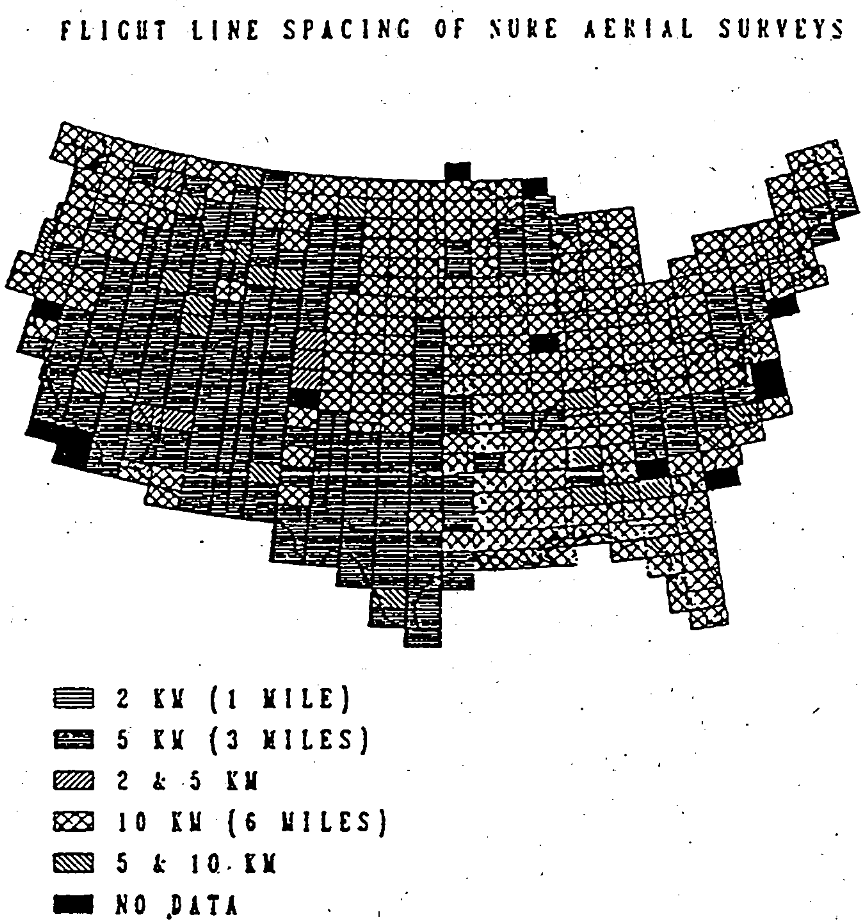

Figure 2. Nominal flightline spacings for NURE aerial gamma-ray surveys covering the contiguous United States (from Duval and others, 1990). Rectangles represent 1°x2° quadrangles.

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.

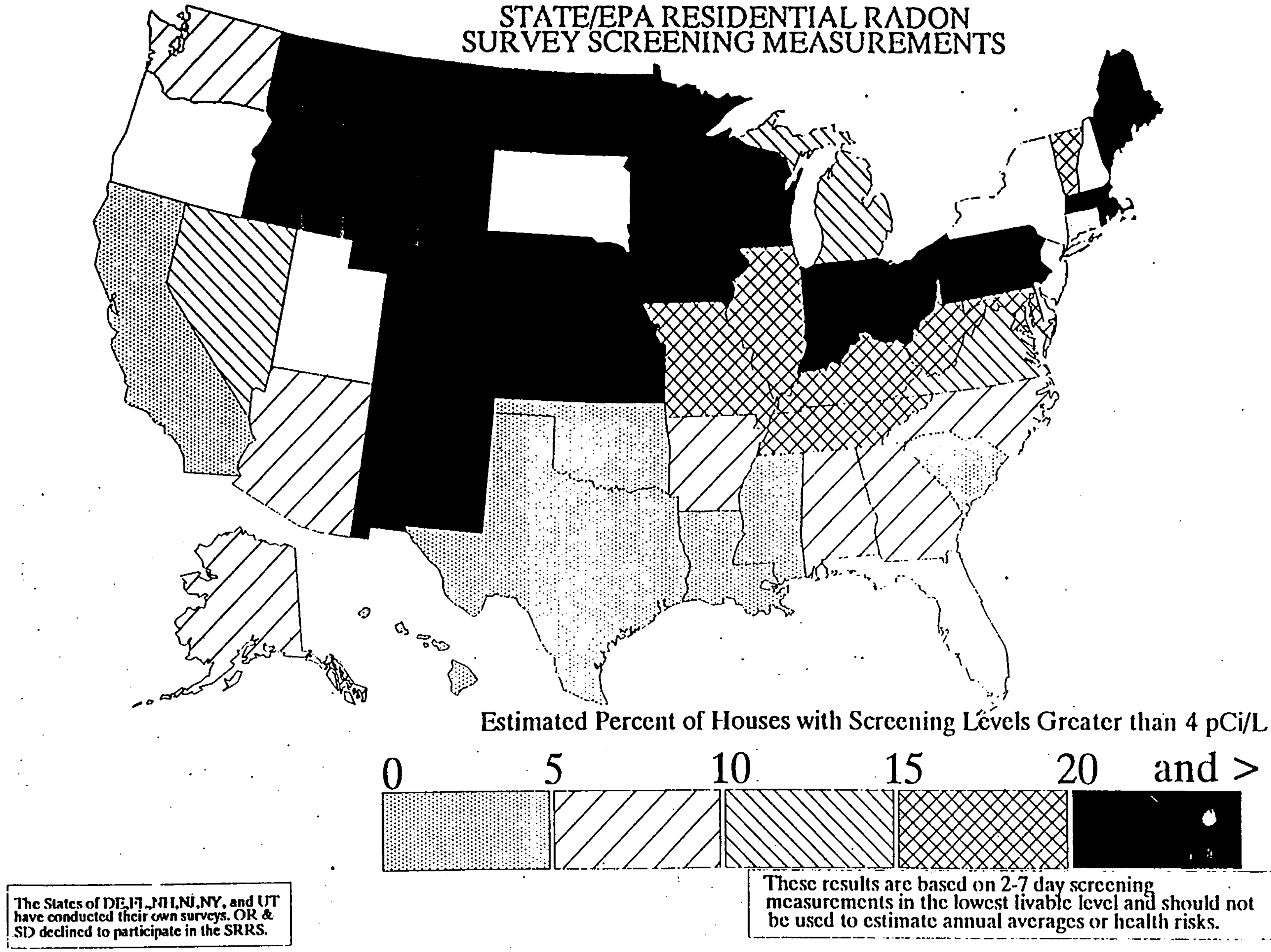

Figure 3. Percent of homes tested in the State/EPA Residential Radon Survey with screening indoor radon levels exceeding 4 pCi/L.

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

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

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

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

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

[4] Informal time term without specific rank.

APPENDIX B
GLOSSARY OF TERMS

Units of measure

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

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

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

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

Geologic terms and terms related to the study of radon

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

eolian Pertaining to sediments deposited by the wind.

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

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

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

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

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

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

formation A mappable body of rock having similar characteristics.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

placer deposit See heavy minerals

residual Formed by weathering of a material in place.

residuum Deposit of residual material.

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

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

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

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

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

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

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

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

shrink-swell clay See clay mineral.

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

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

slope An inclined part of the earth's surface.

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

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

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

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

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

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

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

uraniferous Containing uranium, usually more than 2 ppm.

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

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

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

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

APPENDIX C
EPA REGIONAL OFFICES

EPA Regional Offices

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Region 3 (3AH14)
841 Chestnut Street
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EPA Region 4
345 Courtland Street, N.E.
Atlanta, GA 30365
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EPA Region 5 (5AR26)
77 West Jackson Blvd.
Chicago, IL 60604-3507
(312) 886-6175

EPA Region 6 (6T-AS)
1445 Ross Avenue
Dallas, TX 75202-2733
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EPA Region 7
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Kansas City, KS 66101
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San Francisco, CA 94105
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1200 Sixth Avenue
Seattle, WA 98101
(202) 442-7660

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

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May, 1993

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EPA REGION 6 GEOLOGIC RADON POTENTIAL SUMMARY

by
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EPA Region 6 includes the states Arkansas, Louisiana, New Mexico, Oklahoma, and Texas. For each state, geologic radon potential areas were delineated and ranked on the basis of geology, soils, housing construction, indoor radon, and other factors. Areas in which the *average screening indoor radon level of all homes within the area* is estimated to be greater than 4 pCi/L were ranked high. Areas in which the average screening indoor radon level of all homes within the area is estimated to be between 2 and 4 pCi/L were ranked moderate/variable, and areas in which the average screening indoor radon level of all homes within the area is estimated to be less than 2 pCi/L were ranked low. Information on the data used and on the radon potential ranking scheme is given in the introduction to this volume. More detailed information on the geology and radon potential of each state in Region 6 is given in the individual state chapters. The individual chapters describing the geology and radon potential of the states in Region 6, though much more detailed than this summary, still are generalized assessments and there is no substitute for having a home tested. Within any radon potential area homes with indoor radon levels both above and below the predicted average likely will be found.

Figure 1 shows a generalized map of the physiographic/geologic provinces in Region 6. The following summary of radon potential in Region 6 is based on these provinces. Figure 2 shows average screening indoor radon levels by county calculated from the State/EPA Residential Radon Survey. Figure 3 shows the geologic radon potential areas in Region 6, combined and summarized from the individual state chapters.

ARKANSAS

The geologic radon potential of Arkansas is generally low to moderate. Paleozoic marine limestones, dolomites, and uraniferous black shales appear to be associated with most of the indoor radon levels greater than 4 pCi/L in the State.

Ordovician through Mississippian-age sedimentary rocks, including limestone, dolomite, shale, and sandstone, underlie most of the Springfield and Salem Plateaus. Black shales and residual soils developed from carbonate rocks in the Springfield and Salem Plateaus are moderate to locally high in geologic radon potential. The Ordovician limestones, dolomites, black shales, and sandstones have moderate (1.5-2.5 ppm) to high (>2.5 ppm) equivalent uranium (eU, from aeroradioactivity surveys) and some of the highest indoor radon in the State is associated with them. The Mississippian limestones and shales, however, have low (<1.5 ppm) equivalent uranium with very localized areas of high eU, but also have moderate to high levels of indoor radon associated with them. Black shales and carbonaceous sandstones within the Mississippian, Devonian, and Ordovician units of the plateaus are the likely cause of the local areas of high eU. The Chattanooga Shale and shale units within the Mississippian limestones may be responsible for some of the high indoor radon levels found in Benton County. Limestones are usually low in radionuclide elements but residual soils developed from limestones may be elevated in uranium and radium. Karst and cave features are also thought to accumulate radon.

The Boston Mountains, Arkansas Valley, Fourche Mountains, and Athens Plateau are underlain predominantly by Mississippian and Pennsylvanian sandstones and shales with low to

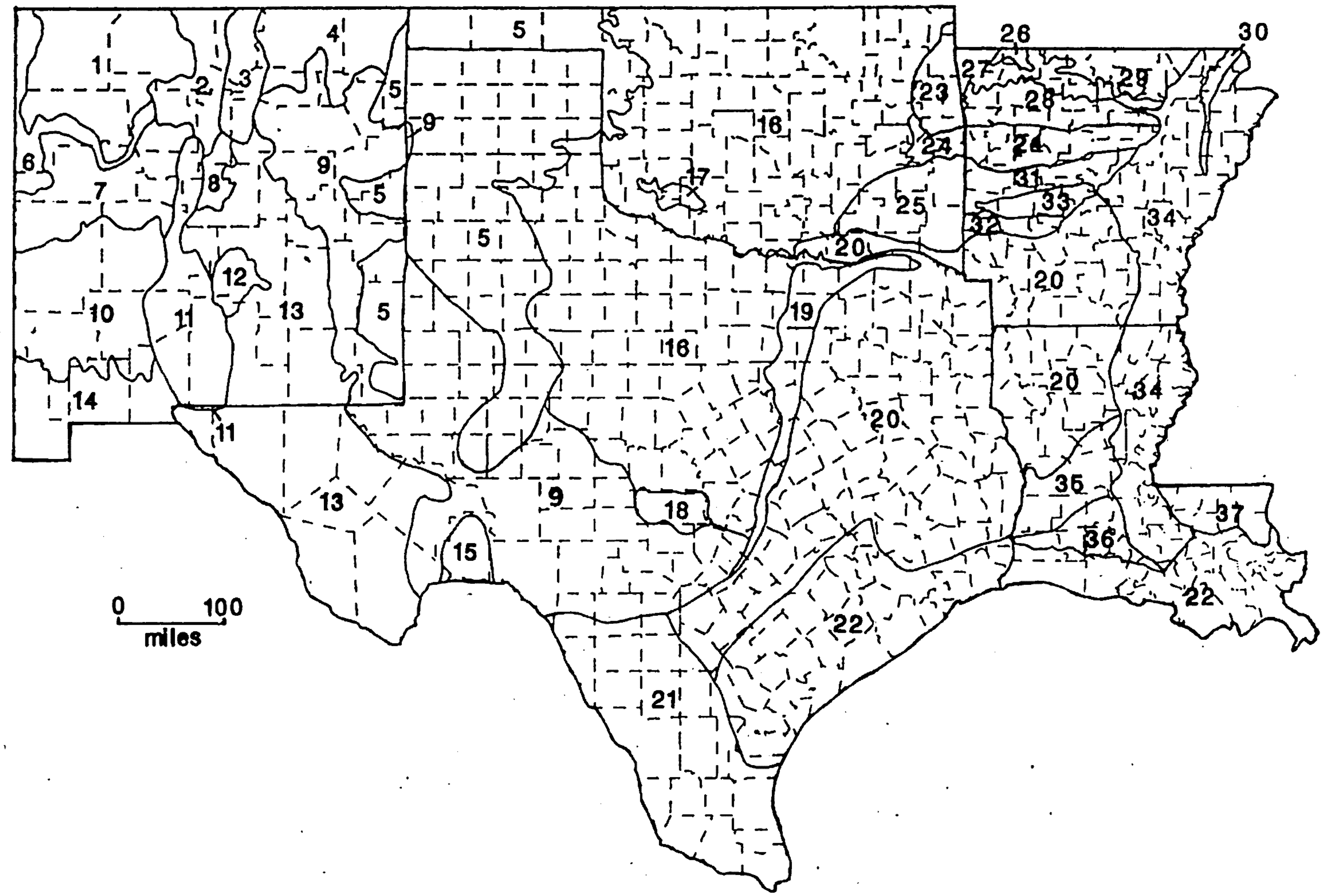

Figure 1. Geologic radon potential areas of EPA Region 6. 1, 4, 7–Cretaceous marine rocks; 2–Jemez Mountains; 3, 11–Southern Rocky Mountains; 5, 15–Tertiary Ogallala Formation (High Plains); 6–Grants uranium belt; 8, 9–Plains and Plateaus (Triassic, Cretaceous and Quaternary deposits; 10–Datil-Mogollon volcanic field; 12–Tertiary volcanic and Cretaceous sedimentary rocks; 13–Late Paleozoic marine limestones; 14–Eastward extension of the Basin and Range Province; 16–Central Oklahoma and Texas (Paleozoic marine sediments); 17–Wichita Mountains; 18, 19–Cretaceous Central Texas and Llano Uplift; 20–Northern Coastal Plains (Old Uplands (LA)); 21–Southern Texas Plain; 22–Coastal Plain (TX)/Old Uplands (LA); 23–Ozark Plateau; 24–Lower Arkansas River Valley; 25–Ouachita Mountains; 26, 29–Salem Plateau; 27–Springfield Plateau; 28–Boston Mountains; 30–Crowley's Ridge; 31–Fourche Mountains; 32–Athens Plateau; 33–Central Ouchita Mountains; 34–Mississippi Alluvial Plain; 35, 37–Terraces; 36–Prairies.

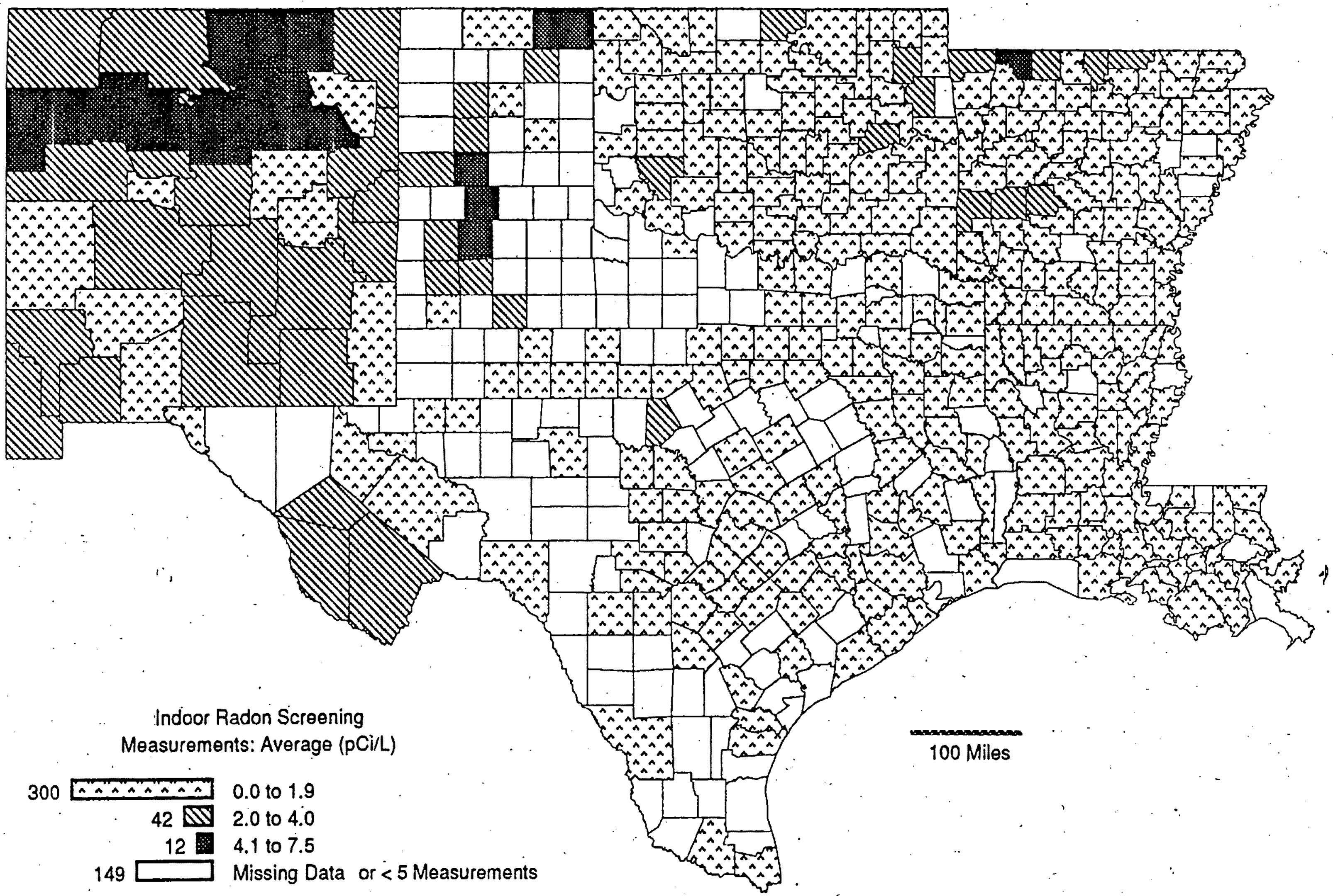

Figure 2. Screening indoor radon average for counties with 5 or more measurements in EPA Region 6. Data are from 2-7 day charcoal canister tests. Data for all states are from the EPA/State Residential Radon Survey. Histograms in map legends show the number of counties in each category.

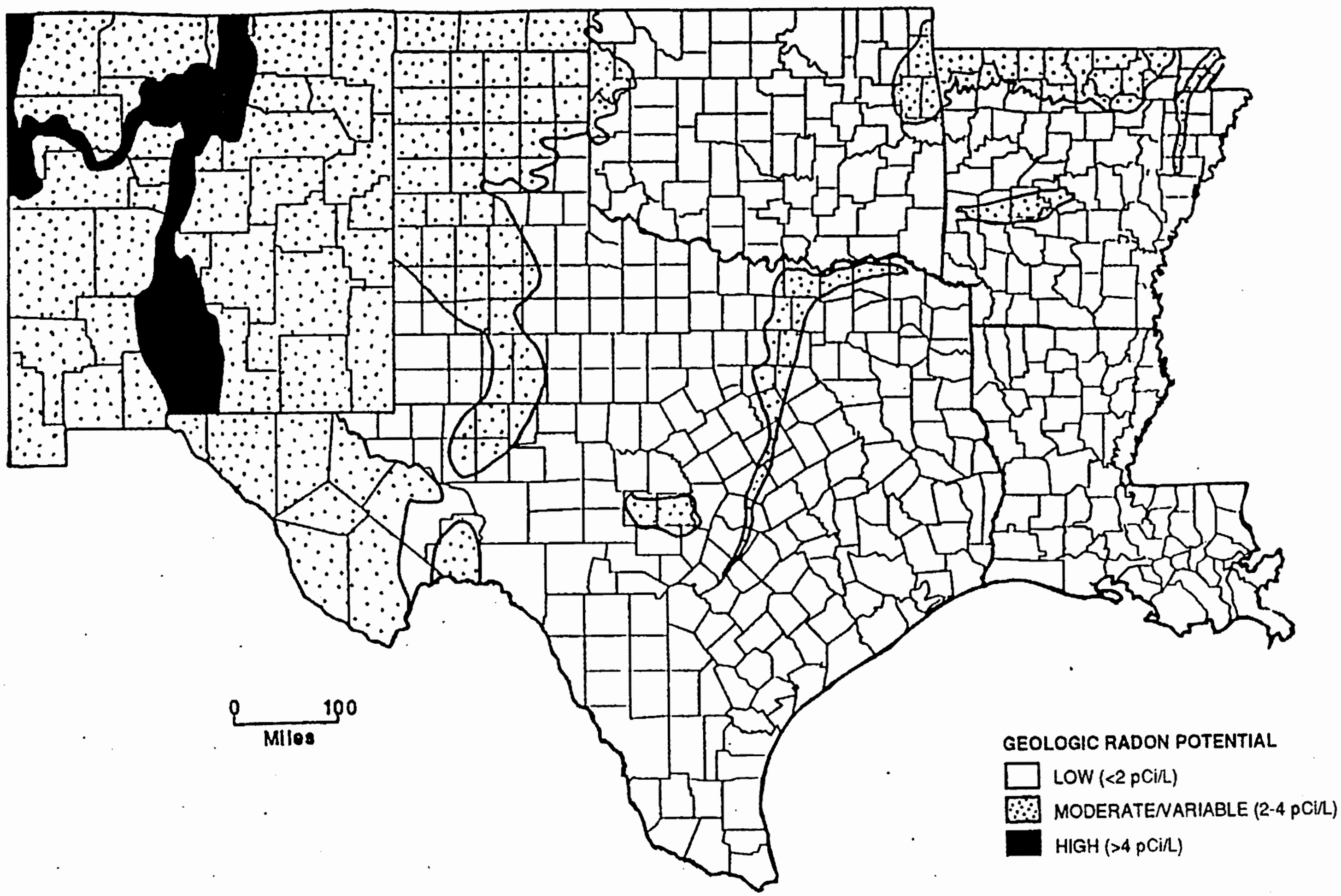

Figure 3. Geologic radon potential areas of EPA Region 6. For more detail, refer to individual state radon potential chapters.

moderate radon potential. Although the indoor radon average for these provinces is low, there are a number of counties in these provinces with screening indoor radon averages slightly higher than 1 pCi/L and maximum readings greater than 4 pCi/L. The marine black shales are probably uranium-bearing. Further, carbonaceous sandstones of the Upper Atoka Formation and Savanna Formation have high (>2.5 ppm) eU associated with them. Uranium also occurs in the Jackfork Sandstone in Montgomery County and in the Atoka Formation in Crawford County. These rocks are the most likely sources for the indoor radon levels. Radon from a hydrocarbon source in these rocks should not be ruled out. The presence of radon and uranium in some natural gas, petroleum, and asphaltite is well known and could contribute radon to indoor air in some locations.

The Central Ouachita Mountains are underlain by intensely-deformed Ordovician and Silurian shales and sandstones with minor chert and limestone. These rocks generally have low to moderate radon potential. Aeroradiometric signatures of 2.5 ppm eU or more are associated with the Ordovician black shales and possibly with some syenite intrusions. Indoor radon in the Central Ouachita Mountains is low to moderate and permeability of the soils is low to moderate.

The West Gulf Coastal Plain is generally low in radon potential. Some of the Cretaceous and Tertiary sediments have moderate eU (1.5-2.5 ppm). Recent studies in the Coastal Plain of Texas, Alabama, and New Jersey show that glauconite and phosphate in sandstones, chalks, marls, and limestones, as well as black organic clays, shales, and muds, are often associated with high concentrations of uranium and radon in the sediments, and could be sources for elevated indoor radon levels. Several formations within the Gulf Coastal Plain of Arkansas contain these types of sediments, especially parts of the upper Cretaceous and lower Tertiary section, but average indoor radon levels in this area are not elevated. The Quaternary sediments of the Coastal Plain have low eU and the indoor radon average is low for the Gulf Coastal Plain overall.

The Mississippi Alluvial Plain and Crowley's Ridge have low to locally moderate radon potential. The southern half of the Mississippi Alluvial Plain is made up predominantly of quartzose sediments, has generally low eU, and has low indoor radon. The northern half of the alluvial plain, however, includes the loess of Crowley's Ridge, which appears to have high equivalent uranium associated with it, and possibly a high loess content in the surrounding sediments in general. The northeastern corner of Arkansas appears to be crossed by the large belt of loess that continues into Kentucky and Tennessee and shows as a distinct area of high eU on the aeroradiometric map of the United States. Some areas of high eU may also be due to uranium in phosphate-rich fertilizers used in agricultural areas. Several of the counties in the northern part of the alluvial plain have maximum indoor radon values greater than 4 pCi/L and indoor radon averages between 1 and 2 pCi/L, which are generally higher than those in surrounding counties.

LOUISIANA

The geology of Louisiana is dominated by ancient marine sediments of the Gulf Coastal Plain and modern river deposits from the Mississippi River and its tributaries. Louisiana is generally an area of low geologic radon potential. The climate, soil, and lifestyle of the inhabitants of Louisiana have influenced building construction styles and building ventilation which, in general, do not allow high concentrations of radon to accumulate. Many homes in Louisiana are built on piers or are slab-on-grade. Overall indoor radon is low; however, several parishes had individual homes with radon levels greater than 4 pCi/L. Parishes with indoor radon levels greater than 4 pCi/L are found in different parts of the State, in parishes underlain by coastal plain sediments, terrace deposits, and loess.

In the Coastal Plain of Louisiana the glauconitic, carbonaceous, and phosphatic sediments have some geologic potential to produce radon, particularly the Cretaceous and lower Tertiary-age geologic units located in the northern portion (Old Uplands) of the State.. Soils from clays, shales, and marls in the Coastal Plain commonly have low permeability, so even though these sediments may be a possible source of radon, low permeability probably inhibits radon availability. Some of the glauconitic sands and silts with moderate permeability may be the source of locally high indoor radon. Moderate levels of radioactivity (1.5-2.5 ppm eU) are associated with areas underlain by the Eocene through lower Oligocene-age Coastal Plain sediments, but do not follow formation boundaries or strike belts in a systematic manner. The pattern of moderate radioactivity in this area does appear to follow river drainages and the aeroradioactivity pattern may be associated with northwest- and northeast-trending joints and or faults which, in turn, may control drainage patterns. Part of the pattern of low aeroradioactivity in the Coastal Plain may be influenced by ground saturation with water. This area receives high precipitation and contains an extensive system of bayous and rivers. Besides damping gamma radioactivity, ground saturation can also inhibit radon movement.

The youngest Coastal Plain sediments, particularly Oligocene and younger, have decreasing amounts of glauconite and phosphate and become increasingly siliceous (silica-rich), and thus, are less likely to be significant sources of radon. However, the possibility of roll-front uranium deposits in sedimentary rocks and sediments of Oligocene-Miocene age, analogous to the roll-front uranium deposits in Texas, has been proposed. Anomalous gamma-ray activity has been measured in the lower Catahoula sandstone, but no uranium deposits have yet been identified.

The fluvial and deltaic sediments in the Mississippi Alluvial Plain are low in geologic radon potential. They are not likely to have elevated amounts of uranium and the saturated to seasonally wet conditions of the soils, as well as the high water tables, do not facilitate radon availability. Coarse gravels in the terraces of the Mississippi Alluvial Plain have locally very high permeability and may be a source of radon.

Loess units in the northern portion of the Mississippi floodplain can easily be identified by their radiometric signature on the aeroradioactivity map of Louisiana. Loess is associated with high radiometric anomalies throughout the United States. Radiometric anomalies also seem to be associated with exposures of loess in Iberia, Lafayette, eastern Acadia, and northern Vermilion Parishes, in the southeastern part of the Prairies. Loess tends to have low permeability, so even though these sediments may be a possible source of high radon, the lack of permeability, particularly in wet soils, may inhibit radon availability.

NEW MEXICO

An overriding factor in the geologic evaluation of New Mexico is the abundance and widespread outcrops in local areas of known uranium-producing and uranium-bearing rocks in the State. Rocks known to contain significant uranium deposits, occurrences, or reserves, and rocks such as marine shales or phosphatic limestones that are known to contain low but uniform concentrations of uranium, all have the potential to contribute to elevated levels of indoor radon. In New Mexico, these rocks include Precambrian granites, pegmatites, and small hydrothermal veins; the Pennsylvanian and Permian Cutler Formation, Sangre de Cristo Formation, and San Andres Limestone; the Triassic Chinle Formation; the Jurassic Morrison Formation and Todilto Limestone Member (Wanakah Formation); the Cretaceous Dakota Sandstone, Kirtland Shale, Fruitland Formation, and Crevasse Canyon Formation; the Cretaceous and Tertiary Ojo Alamo Sandstone;

Tertiary Ogallala Formation and Popotosa Formation (Santa Fe Group); Tertiary alkalic intrusive rocks and rhyolitic and andesitic volcanic rocks such as the Alum Mountain andesite; and the Quaternary Bandelier Tuff and Valles Rhyolite.

Several areas in New Mexico contain outcrops of one or more of these rock units that may contribute to elevated radon levels. The southern an... .tern rims of the San Juan Basin expose a Paleozoic to Tertiary sedimentary section that contains the Jurassic, Cretaceous, and Tertiary sedimentary rocks having a high radiometric signature and that are known to host uranium deposits in the Grants uranium district, as well as in the Chuska and Carrizo Mountains. In north-central New Mexico, the Jemez Mountains are formed in part by volcanic rocks that include the Bandelier Tuff and the Valles Rhyolite; this area also has an associated high radiometric signature. In northeastern New Mexico, Precambrian crystalline rocks and Paleozoic sedimentary rocks of the southern Rocky Mountains and Tertiary volcanic rocks and Cretaceous sedimentary rocks are associated with radiometric highs. In southwestern New Mexico, middle Tertiary volcanic rocks of the Datil-Mogollon region are also associated with high radiometric signatures. Remaining areas of the Colorado Plateau, the Basin and Range, and the Great Plains are associated with only moderate to low radiometric signatures on the aeroradiometric map; these areas generally contain Paleozoic to Mesozoic sedimentary rocks, scattered Tertiary and Quaternary volcanic rocks, and locally, Tertiary sedimentary rocks.

The southern extension of the Rocky Mountains and uplifted Paleozoic sedimentary rocks in central New Mexico; Upper Cretaceous marine shales and uranium-bearing Jurassic fluvial sandstones of the Grants uranium belt in the northeastern part of the State; and Tertiary volcanic rocks in the Jemez Mountains, just west of the southern Rocky Mountains, have high radon potential. Average screening indoor radon levels are greater than 4 pCi/L and aeroradioactivity signatures are generally greater than 2.5 ppm eU. Rocks such as Precambrian granites and uplifted Paleozoic strata, Jurassic sandstones and limestones, or Cretaceous to Tertiary shales and volcanic rocks that are known to contain or produce uranium are the most likely sources of elevated indoor radon levels in these areas. The remainder of the State has generally moderate radioactivity, average screening indoor radon levels less than 4 pCi/L, and overall moderate geologic radon potential.

OKLAHOMA

The geology of Oklahoma is dominated by sedimentary rocks and unconsolidated sediments that vary in age from Cambrian to Holocene. Precambrian and Cambrian igneous rocks are exposed in the core of the Arbuckle and Wichita Mountains and crop out in about 1 percent of the State. The western, northern, and central part of the State is underlain by very gently west-dipping sedimentary rocks of the northern shelf areas. A series of uplifts and basins flank the central shelf area. The Gulf Coastal Plain forms the southeastern edge of the State.

Most of the rocks that crop out in the central and eastern part of the State are marine in origin; they include limestone, dolomite, shale, sandstone, chert, and coal of Cambrian through Permian age. Nonmarine rocks of Permian and Tertiary age, including shale, sandstone, and conglomerate, are present in the western part of the central Oklahoma Hills and Plains area; sand, clay, gravel, and caliche dominate in the High Plains in the western part of the State. The Gulf Coastal Plain is underlain by Cretaceous nonmarine sand and clay and marine limestone and clay. Some of these units locally are moderately uranium-bearing.

Surface radioactivity across the State varies from less than 0.5 ppm to 5.0 ppm eU. Higher levels of equivalent uranium (>2.5 ppm) are consistently associated with black shales in the southeastern and westernmost Ouachita Mountains, the Arbuckle Mountains, and the Ozark Plateau; with Permian shale in Roger Mills, Custer, Washita, and Beckham Counties; with granites and related rocks in the Wichita Mountains; and with Cretaceous shale and associated limestone in the Coastal Plain. Low eU values (<1.5 ppm) are associated with large areas of dune sand adjacent to rivers in western Oklahoma; with eolian sands in the High Plains in Cimarron and Ellis Counties; and with Mississippian and Pennsylvanian rocks in the Ouachita Mountains, the Ozark Plateau, and the eastern part of the central Oklahoma plains and hills.

Areas of Oklahoma ranked as locally moderate to high are underlain by black, phosphatic shales and associated limestones in the northeastern part of the State and near the Arbuckle Mountains; the Upper Permian Rush Springs Formation in Caddo County; and granites, rhyolites, and related dikes in the Wichita Mountains in the southwestern part of the State. Areas ranked as generally low are underlain by Paleozoic marine sedimentary rocks in central and northwestern Oklahoma and by Tertiary continental sedimentary rocks on the High Plains.

Well-drained alluvial terraces along some rivers (for example, along the Arkansas River west of Tulsa); steep, thin, sandy to gravelly soils developed on sandstone on river bluffs (for example, bluffs in the southeastern suburbs of Tulsa); and clayey loams on uraniferous shales (in the northeastern corner of the State) are responsible for a significant percentage of elevated indoor radon levels in those areas. Thus, in addition to soils derived from rocks with elevated uranium content, soils in selected parts of counties where river terraces and sandstone bluffs occur might also have elevated radon potential.

Soil moisture may have an additional effect on radon potential across the State. Indoor radon values tend to be higher west of Oklahoma City where rainfall is less than 32 inches per year and lowest in the southeastern corner of the State, where rainfall ranges from 32 to 64 inches per year. Indoor radon values in northeastern Oklahoma, where rainfall is also high, include many readings greater than 4 pCi/L, but the effects of uraniferous black shales and weathered limestone soils on indoor radon may increase the levels overall and counter the effects of regional variation in soil moisture. High permeability, dry soils, and moderate uranium content may be responsible for elevated indoor radon readings in Beaver County.

TEXAS

The geologic radon potential of Texas is relatively low to moderate overall. The relatively mild climate throughout much of the State, especially in the most populous areas, and the predominance of slab-on-grade housing seems to have influenced the overall potential. Significant percentages of houses with radon levels exceeding 4 pCi/L are restricted primarily to the High Plains and the Western Mountains and Basins provinces. However, no physiographic province in Texas is completely free from indoor radon levels greater than 4 pCi/L.

Elevated indoor radon can be expected in several geologic settings in Texas. Granites and metamorphic rocks in central Texas, Tertiary silicic volcanic and tuffaceous sedimentary rocks in western Texas, dark marine shales in east-central Texas and the Big Bend area, sand and caliche associated with the Ogallala Formation and overlying units in the High Plains of Texas, sediments of Late Cretaceous age along the eastern edge of central Texas, and residual soils and alluvium derived from these units are likely to have significant percentages of homes over 4 pCi/L. Except for the High Plains and the Western Mountains and Basins Provinces, these rocks generally make up only a relatively small percentage of the surface area of the various physiographic provinces. However, the outcrop belt of Upper Cretaceous sedimentary rocks of the East Texas Province passes near some substantial population centers. Extreme indoor radon levels (greater than 100 pCi/L) may be expected where structures are inadvertently sited on uranium occurrences. This is more likely to occur in more populated areas along the outcrop belt of the Ogallala Formation at the edge of the Llano Estacada in the northern and central parts of the High Plains and Plateaus Province. In this outcrop area, sedimentary rocks with more than 10 ppm uranium are relatively common.

The northern part of the High Plains and Plateau Province has moderate radon potential. Uranium occurrences, uranium-bearing calcrete and silcrete, and uranium-bearing lacustrine rocks along the outcrop belt of the Ogallala Formation and in small upper Tertiary lacustrine basins within the northern High Plains may locally cause very high indoor radon levels. Indoor radon data are elevated in many counties in this area . Equivalent uranium values in this area range from 1.0 to 4.0 ppm. An area of elevated eU along the Rio Grande River is included in this radon potential province. The southern part of the High Plains and Plateaus Province has low radon potential overall as suggested by generally low eU values and low indoor radon. This area is sparsely populated and existing indoor radon measurements may not adequately reflect the geologic radon potential. An area of low eU covered by the sandy facies of the Blackwater Draw Formation in the northeastern corner of the Western Mountains and Basins Province is included in this radon potential area. Some parts of this province that may have locally elevated indoor radon levels include areas of thin soils over limestone and dolomite in the Edwards Plateau of the southern part of this province, and areas of carbonaceous sediments in the southeastern part of this province.

The Western Mountains and Basins Province has moderate indoor radon potential overall. Although average indoor radon levels are mixed (low in El Paso County, but high in three southern counties), areas of elevated eU are widespread. Uranium-bearing Precambrian rocks, silicic volcanic rocks, and alluvium derived from them may locally cause average indoor radon levels in some communities to exceed 4 pCi/L. Some indoor radon levels exceeding 20 pCi/L may also be expected. Exceptionally dry soils in this province may tend to lower radon potential. In very dry soils, the emanating fraction of radon from mineral matter is lowered somewhat.

The Central Texas Province has low radon potential overall; however, areas along the outcrop belt of the Woodbine and Eagle Ford Formations and the Austin Chalk along the east edge of this province, and areas of Precambrian metamorphic and undifferentiated igneous rocks in the Llano Uplift in the southern part of this province have moderate geologic radon potential. Structures sited on uranium occurrences in the Triassic Dockum Group in the western part of this province may locally have very high indoor radon levels.

The East Texas Province has low radon potential overall. Soil moisture levels are typically high; soil permeability is typically low to moderate; and eU levels are low to moderate. A few areas of well-drained soils and elevated eU may be associated with local areas of moderately elevated indoor radon levels.

The South Texas Plain has low radon potential due to generally low eU and low to moderate soil permeability. Some structures sited on soils with slightly elevated uranium contents in this province may locally have elevated indoor radon levels, but such soils are generally also clay rich and this may mitigate radon movement. The Texas Coastal Plain has low radon potential. Low aeroradioactivity, low to moderate soil permeability, and locally high water tables contribute to the low radon potential of the region.

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PRELIMINARY GEOLOGIC RADON POTENTIAL ASSESSMENT OF TEXAS

by

James K. Otton and Linda C.S. Gundersen

U.S. Geological Survey

INTRODUCTION

This assessment of the radon potential of Texas is based upon geologic information derived from publications of the Texas Bureau of Economic Geology, from publications of the U.S. Geological Survey, and from an analysis of indoor radon data gathered by the State of Texas and the US Environmental Protection Agency (EPA) during the winter of 1990-91 Much information on the geographic setting is derived from The National Atlas of the United States of America.

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

PHYSIOGRAPHIC SETTING

Texas is a large state that extends from the Gulf Coast westward to the southern limits of the Rocky Mountains and northward to the continental interior of the United States. For the purposes of this report, six physiographic subdivisions have been defined (fig. 1). The Western Mountains and Basins province is characterized by plains with intervening mountains and hills. In the western part of this province, high mountains with 3000-5000 feet of relief occur. In the eastern part, relief decreases to 500-1000 feet.

The High Plains and Plateaus Province comprises broad, smooth plains with 100-300 feet of relief in the northern portion, and areas of tablelands, high hills, and plains with moderate relief (300-1000 feet) in the southern portion. The Central Texas Province is an extension of the Great Plains. It is characterized by tablelands and plains with hills of low to moderate relief (100-500 feet) in the west and irregular plains and hills (relief 100-500 feet) to the east. The East Texas Province is an area composed mostly of irregular plains (100-300 feet of relief), except for an area of plains with hills (300-500 feet of relief) in the east-central part. The Coastal Plain Province is an area of smooth plains of low relief (0-100 feet). The South Texas Plain Province includes a large area of irregular plains to the northwest (relief 100-300 feet) and an area of flat plains along the coast (0-100 feet of relief).

Annual precipitation (fig. 2) increases eastward across Texas from less than 10 inches per year to 55-60 inches per year in the southeast corner of the State near the Texas-Louisiana border. In hilly to mountainous areas, precipitation increases with altitude.

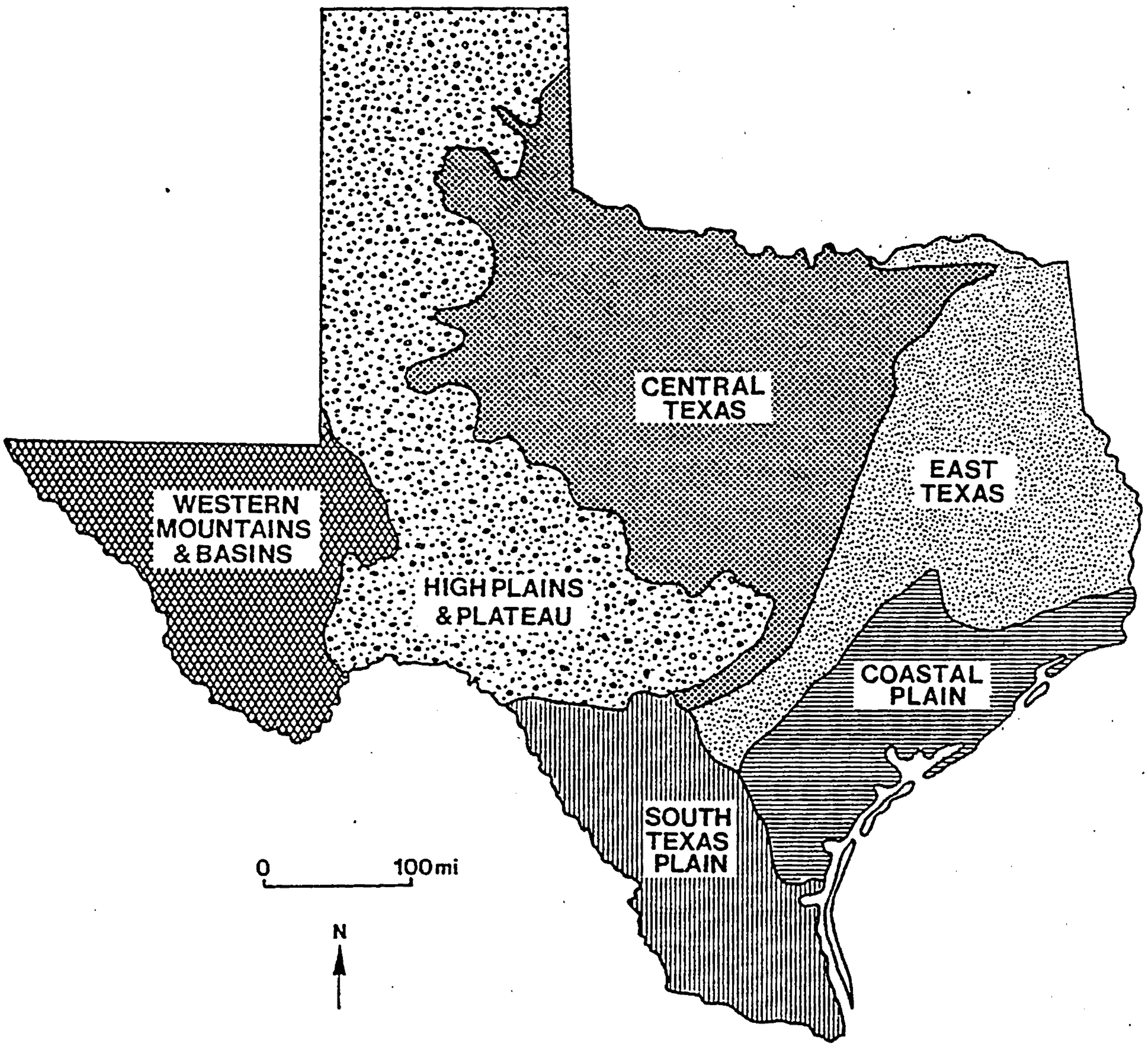

Fig. 1- Map showing physiographic provinces of Texas.
From Facts on File, 1984.

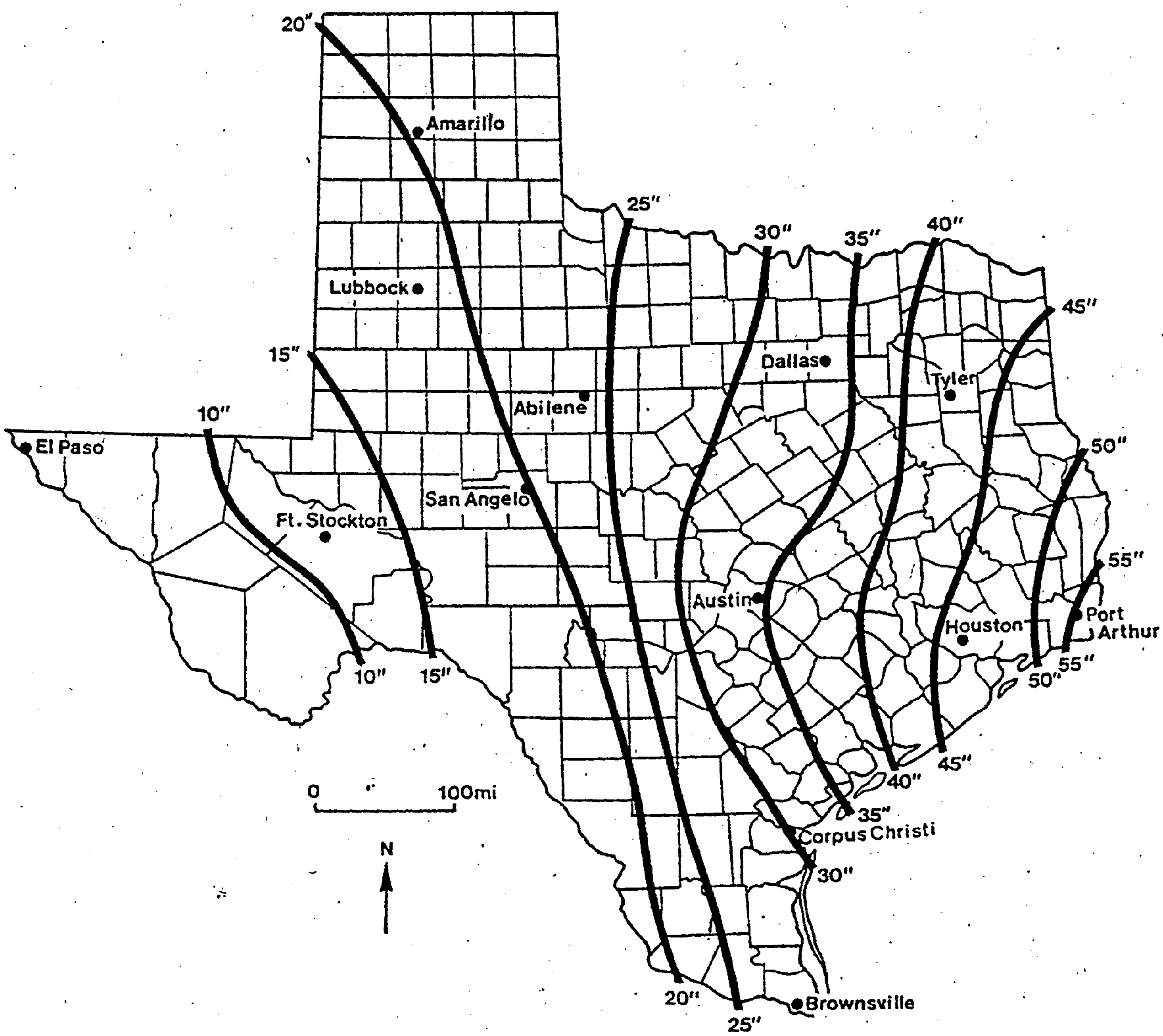

Fig. 2- Map showing annual precipitation in Texas.
From Facts on File, 1984.

About 80 percent of the population of Texas (fig. 3) is concentrated in urban areas of the central and southeast parts of the State. Dallas-Ft. Worth, Houston, and San Antonio are the major urban centers. Rural areas in the Western Mountains and Basins and South Texas Plain Provinces are sparsely populated, whereas rural areas in the East Texas Province and the western part of the Central Texas Province are more heavily populated.

Vegetation and land use vary considerably across the State. Most of the High Plains and Plateaus Province is used principally for dryland and irrigated crops, although in many areas semiarid grasslands are used for grazing. In the southeast part of this province, grazed forest and woodlands predominate. In the Western Mountains and Basins Province, grazed desert shrublands, grasslands, and open woodlands are found. In the Central Texas Province, croplands dominate, with some pasture, woodland, and forest. Grazed grasslands lie at the western edge of this province. The East Texas Province is largely covered by woodland and forest, with lesser cropland and pasture. In the Coastal Plain Province, there is a mixture of cropland, pasture, and grazed forest and woodlands. Extensive marshlands occur along the coast. In the South Texas Plain Province, grazed grassland, open woodland, and desert shrubland occur, plus some areas of dry and irrigated cropland.

GEOLOGIC SETTING

Texas is underlain mostly by sedimentary rocks and unconsolidated sediments that vary in age from Cambrian to Holocene. Precambrian metamorphic and igneous rocks are exposed in the core of the Llano (southern Central Texas Province) and Van Horn uplifts (Western Mountains and Basins Province) (figs. 4 and 5), but they are exposed in less than 1 percent of the State. Tertiary volcanic rocks and related Tertiary volcaniclastic sedimentary rocks occur in volcanic centers and associated small basins in the Western Mountains and Basins Province.

Structurally, the northern, western, and central part of the State is characterized by series of uplifts and basins of pre-Cretaceous age (Figs. 4 and 5). Cretaceous and younger sedimentary rocks of the southeastern 40 percent of the State dip into the Gulf of Mexico basin. Tertiary volcanism and subsequent extension affected the westernmost part of the State, resulting in the formation of extensional basins, intervening mountain ranges, and volcanic centers. During the Miocene, a broad sheet of alluvial fan and related sedimentary rocks (the Ogallalla Formation and overlying units) were deposited on the flank of a broad north-trending uplift in central New Mexico. The erosional remnants of this sheet form the Texas High Plains (the northern part of the High Plains and Plateaus Province).

The sedimentary rocks that crop out in the Western Mountains and Basins, southern High Plains and Plateaus, and most of the East Texas Provinces are marine in origin; they include limestone, dolomite, shale, evaporite deposits, and sandstone of Cambrian through Cretaceous age (fig. 5). Nonmarine rocks of Triassic age, including shale, sandstone, and conglomerate, are present in limited areas in the western part of the Central Texas Province and along the Canadian River valley in the northern part of the High Plains and Plateaus Province. Nonmarine gravel, sand, clay, and caliche (also called calcrete) dominate the northern 60 percent of the High Plains and Plateaus Province. The East Texas, Coastal Plain, South Texas Plain, and the east edge of the Central Texas Provinces are underlain by Cretaceous through Quaternary marine sandstone, shale, chalk, limestone, siltstone, clay, and lignite. Some of the sandstones and shales in this latter area are tuffaceous and some of the shales are carbonaceous.

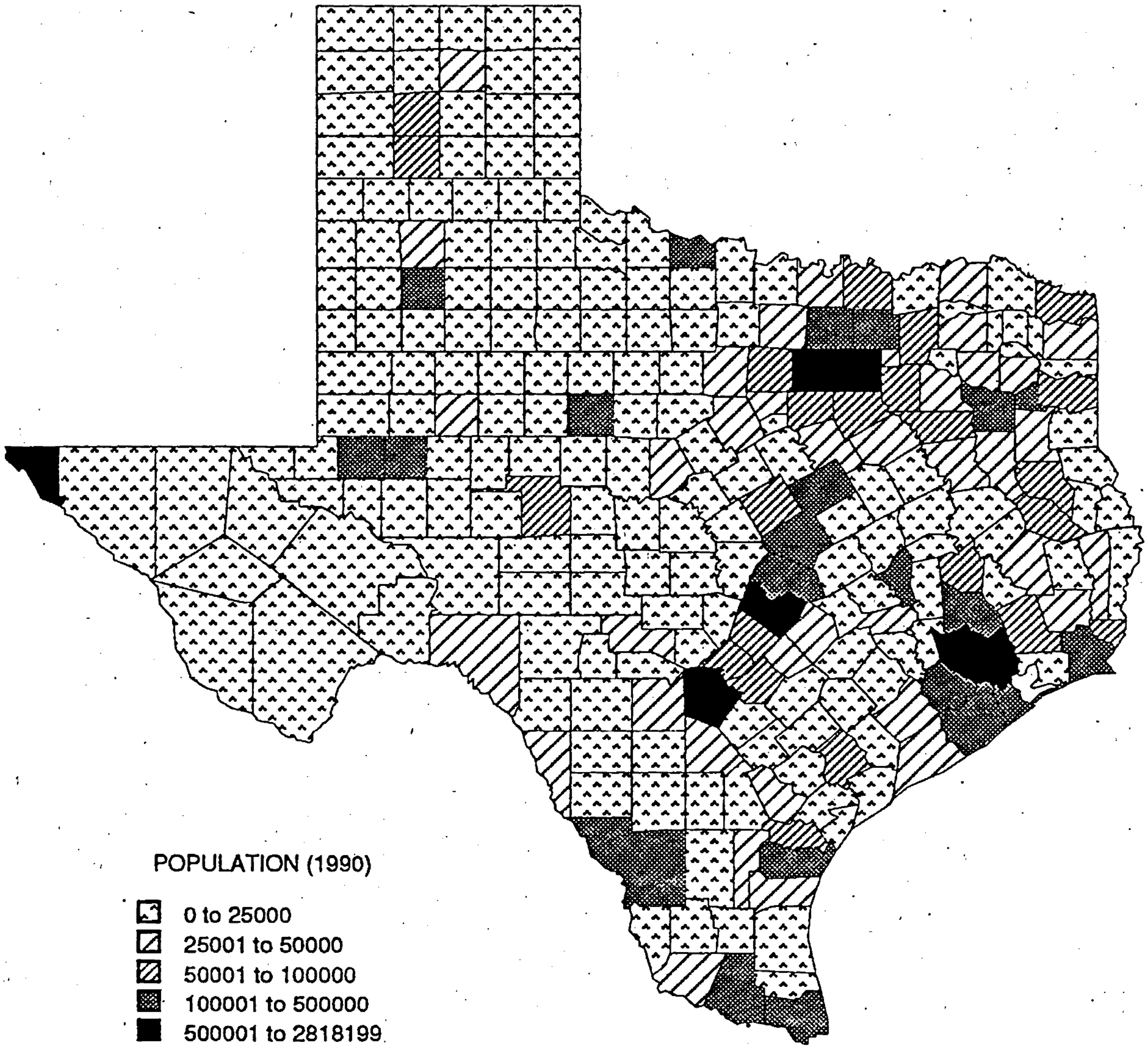

Fig. 3- Population of counties in Texas (1990 U.S. Census data).

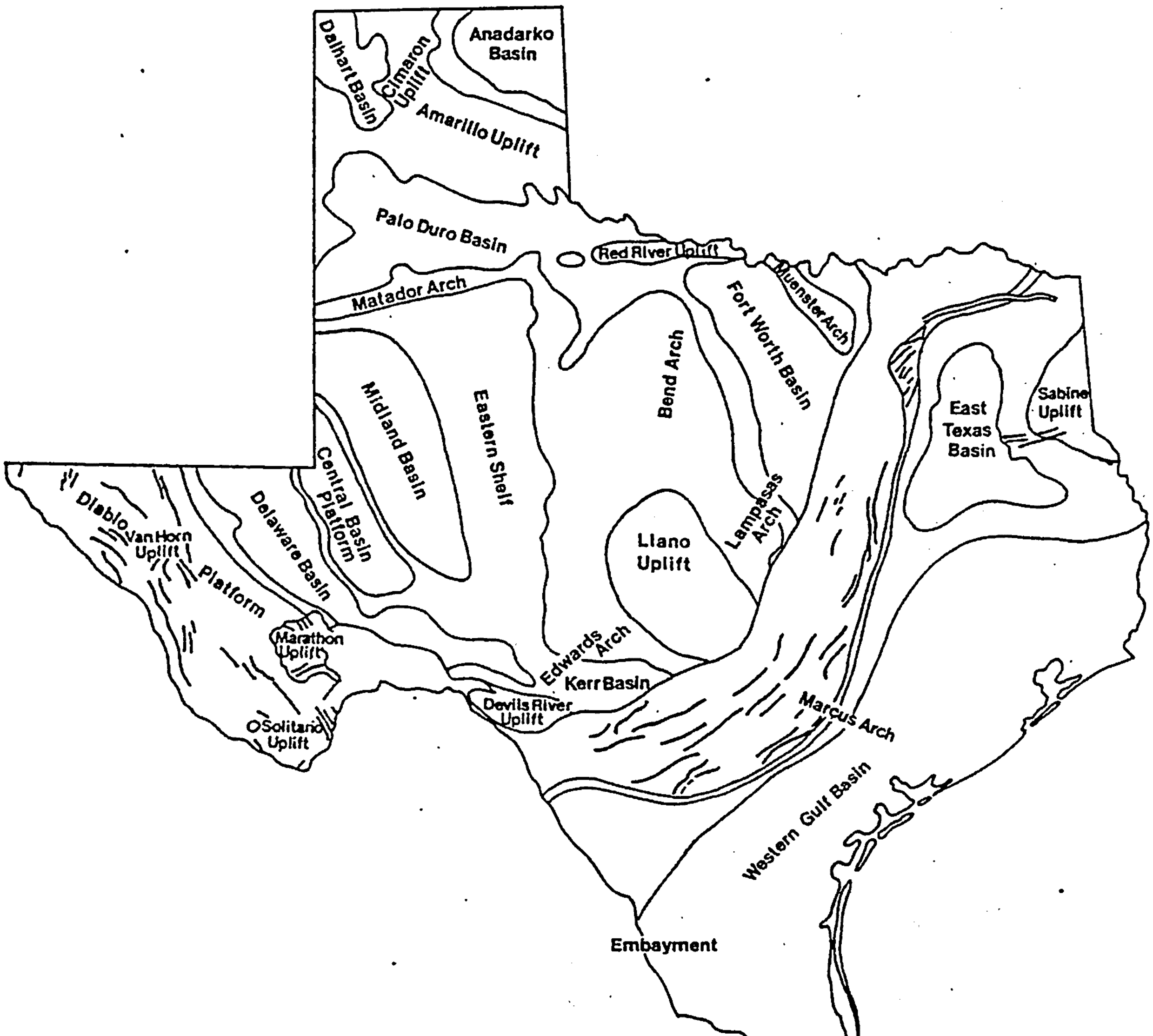

Fig. 4- Major geologic structures in Texas. From Renfro and others, 1973.

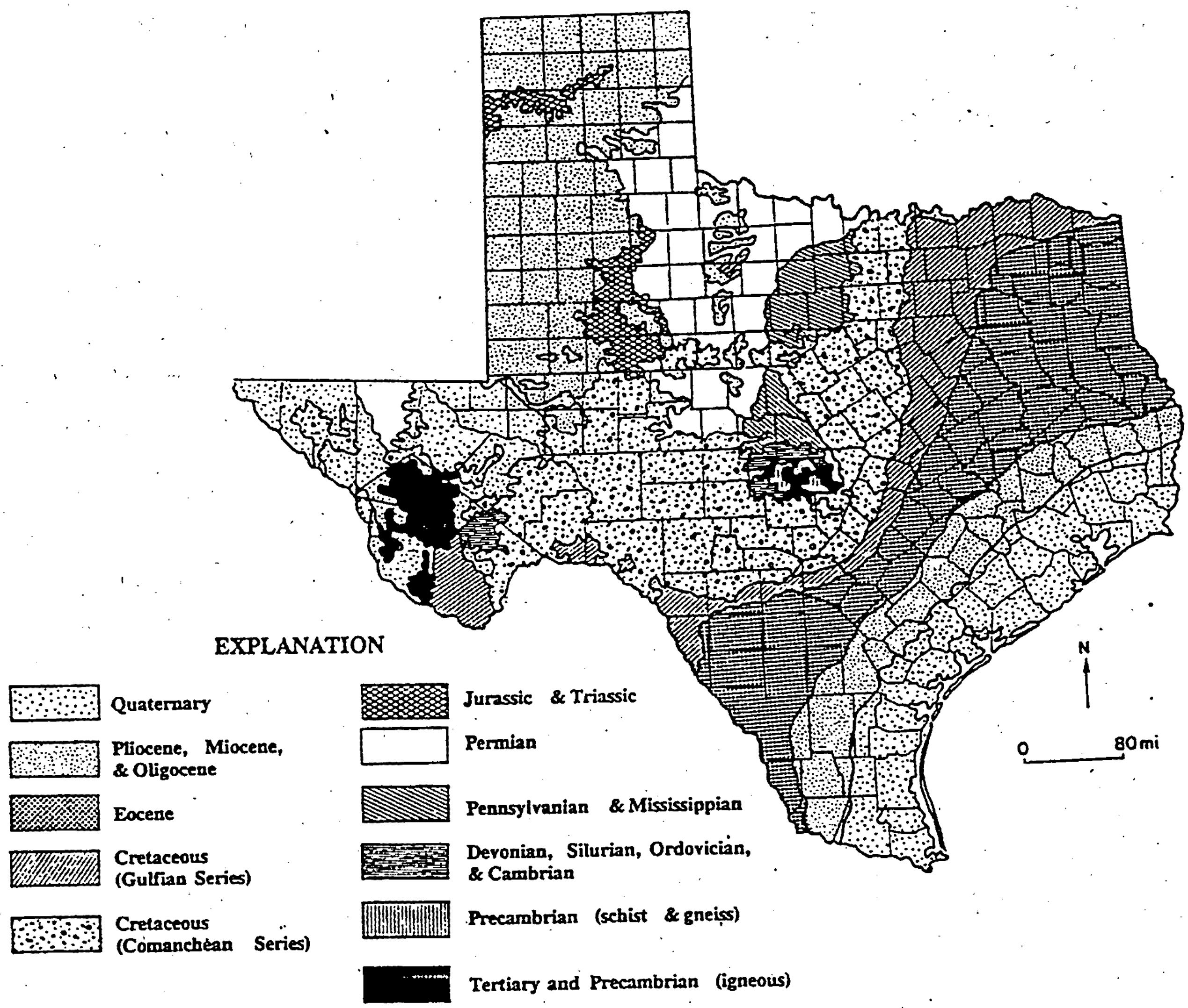

Fig. 5- Generalized geologic map of Texas. From Arbingast (1976).

An aeroradiometric map of Texas (fig. 6) shows that the average equivalent uranium (eU) content of rocks and soils at the surface is about 1.5 ppm. Rocks and soils across the State vary from less than 0.5 ppm to greater than 5.5 ppm eU. Levels of eU less than 1.0 ppm are associated with eolian deposits (especially the sand-rich facies of the Pleistocene Blackwater Draw Formation) of western Texas and with Quaternary marine deposits of the Gulf Coastal area. Higher levels of uranium (>2.5 ppm) are associated with 1) Precambrian metamorphic and igneous rocks in the Llano and Van Horn uplifts, and alluvium derived from them; 2) Tertiary rhyolitic and alkaline volcanic rocks in westernmost Texas; 3) the Miocene Ogallalla Formation and overlying sediments in the Panhandle of Texas (northernmost part of the High Plains and Plateaus Province); 4) Triassic nonmarine sedimentary rocks of the Dockum Group in northwestern Texas; 5) Upper Cretaceous carbonaceous rocks in east-central Texas (the Woodbine and Eagle Ford Formations between the Dallas-Ft. Worth and Austin areas) and in the Big Bend area; and 6) part of the northeast-trending outcrop belt of Tertiary tuffaceous fluvial and marine sedimentary rocks in the northern part of the South Texas Plain and southwest part of the Coastal Plain Provinces. Two small areas of greater than 5.5 ppm eU occur in this latter area; these represent places where the aircraft flew over open-pit uranium mines.

Studies of soil-gas radon and radioactivity along transects crossing Cretaceous and younger rocks from the Central Texas Province to the Coastal Plain Province (Gundersen and others, 1991) show that elevated soil-gas radon (as much as 6500 picocuries per liter, pCi/L) is associated with some Upper Cretaceous sedimentary rocks, principally carbonaceous shale and mudstone of the Woodbine and Eagle Ford Formations and the Austin Chalk, but that most of the Cretaceous, Tertiary and Quaternary units were low to moderate in soil-gas radon and radioactivity.

Uranium occurrences and deposits are found in several areas of Texas. A major uranium mining district is hosted by Tertiary sandstones in South Texas. Small uranium deposits occur in sandstones of the Triassic Dockum Group in the western part of central Texas. Uranium-rich calcrete and silcrete occurs in sandstones and mudstones of the Ogallalla Formation and in overlying Pliocene and Pleistocene sandstones and lacustrine sedimentary rocks in the northern part of the High Plains and Plateaus Province. Uranium occurs in volcanic rocks and volcaniclastic sedimentary rocks near volcanic centers in the Western Mountains and Basins Province.

SOILS

Extensive areas of highly permeable soils (>6 in/hr in a percolation test) are generally not found in Texas, although sandy soils with permeabilities near or locally exceeding this value occur in several areas. In the central part of the High Plains and Plateaus Province, near the southeastern corner of New Mexico, sandy loams and fine sandy loams dominate. These soils may have sufficient permeability to influence indoor radon levels. Substantial areas of sandy soils occur in the central parts of the South Texas Plain Province and the southwestern part of the Coastal Plain Province; however, these often have highly cemented zones of caliche at depth that may hinder the ability of radon to migrate. Alluvial fan deposits in the Western Mountains and Basins Province may also locally be highly permeable, but these are also commonly highly cemented.

Thin soils with bedrock at shallow depths occur over the limestone and dolomite in the southern part of the High Plains and Plateau Province (Edwards Plateau) and thin, sandy soils occur over granitic rocks in the Llano uplift area. Shallow bedrock in these areas typically contains abundant fracture zones that enhance radon migration.

Fig. 6- Aerial radiometric map of Texas (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.

Soil temperature and soil moisture vary widely across Texas, with steady increases in soil temperature from north to south and steady increases in soil moisture from west to east (Rose and others, 1991). Soils of the northern 10 percent of the High Plains and Plateaus Province are mesic ustic and thus are moderately moist in the wintertime (44-56 percent pore saturation in sandy loams, and 58-74 percent in a silty clay loam) and slightly moist in the summertime (24-44 percent pore saturation in sandy loams, and 39-58 percent pore saturation in silty clay loams). The soils of the Western Mountains and Basins Province are thermic aridic–slightly moist in the wintertime (24-44 percent pore saturation in sandy loams, and 39-58 percent pore saturation in silty clay loams) and slightly dry in the summertime (4-24 percent pore saturation in sandy loams and 6-39 percent pore saturation in silty clay loam). Soils of the rest of the High Plains and Plateaus Province and all of the central Texas Province are thermic ustic–moderately moist in the wintertime (44-56 percent saturation in sandy loams, and 58-74 percent in a silty clay loam) and slightly moist in the summertime (24-44 percent pore saturation in sandy loams, and 39-58 percent pore saturation in silty clay loams). The soils of the East Texas Province and the eastern part of the Coastal Plain Province are thermic udic and are very moist in the wintertime (56-96 percent pore saturation in sandy loams, and 74-99 percent saturation in a silty clay loam) and slightly moist in the summertime (24-44 percent pore saturation in sandy loams, and 39-58 percent pore saturation in silty clay loams). The South Texas Plain and the western part of the Coastal Plain range from hyperthermic aridic along the Rio Grande River to hyperthermic ustic elsewhere. Hyperthermic aridic soils are slightly dry all year long and hyperthermic ustic soils are slightly moist all year long.

The low soil moisture levels in the dry soils of western and southern Texas may decrease the radon emanation coefficient somewhat, especially during the drier periods of the year. The wet winter soils in the East Texas Province may slow radon migration because pore spaces are filled with water.

INDOOR RADON DATA

The U.S. Environmental Protection Agency (EPA), in cooperation with the Texas Department of Health, completed a random, stratified (geology and population) survey of indoor radon levels in homes across Texas during the winter of 1990-1991 (Table 1, fig. 7). A map of counties is included for reference (fig. 8). About 5 percent of measurements in the State/EPA Residential Radon Survey dataset are equal to or greater than 4 pCi/L. Average measurements for 3 counties in the northern High Plains and Plateaus Province average greater than 4 pCi/L. Hale County averages 7.5 pCi/L. Average measurements range from 2-4 pCi/L for three counties in the Big Bend area of the Western Mountains and Basins Province, for several counties in the northern and central High Plains and Plateaus Province, and for Brown County in the Central Texas Province (fig. 7). Values exceeding 20 pCi/L are restricted to the High Plains and Plateaus Province and the Western Mountains and Basins Province. Indoor radon levels are low in counties in the uranium mining area in south Texas, however only 50 houses were measured in 12 counties where uranium mining occurs and this sampling may not have been sufficient to identify areas of possible elevated indoor radon levels asssociated with uranium deposits in the subsurface.

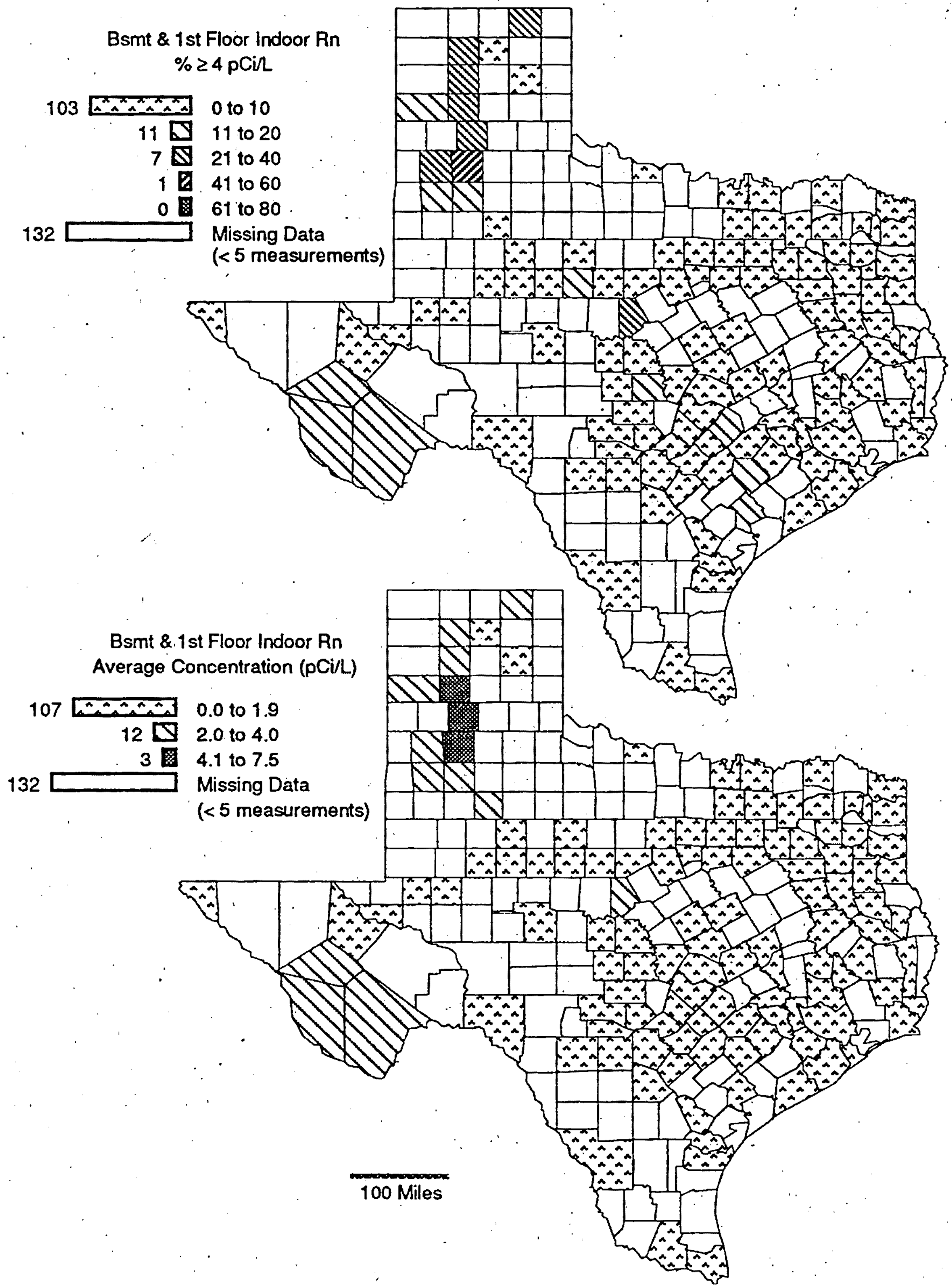

Fig. 7- Screening indoor radon data from the EPA/State Residential Radon Survey of Texas, 1990-91, for counties with 5 or more measurements. Data are from 2-7 day charcoal canister tests. Histograms in map legends show the number of counties in each category. The number of samples in each county (See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

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

COUNTY	NO. OF MEAS.	AVERAGE	MEDIAN	GEOM. MEAN	MAX	%≥4 pCi/L	%≥20 pCi/L
ANDERSON	3	0.0	0.1	0.4	1.4	0	0
ANDREWS	2	1.0	1.0	0.9	1.1	0	0
ANGELINA	12	0.3	0.3	0.3	1.3	0	0
ARANSAS	2	0.0	0.0	0.0	0.0	0	0
ARCHER	2	0.7	0.7	0.5	1.2	0	0
ARMSTRONG	3	2.9	1.5	2.4	5.8	33	0
ATASCOSA	11	0.5	0.5	0.5	1.7	0	0
AUSTIN	8	0.5	0.3	0.4	2.2	0	0
BAILEY	3	3.6	1.6	2.0	8.6	33	0
BANDERA	5	0.6	0.4	0.5	1.0	0	0
BASTROP	9	1.6	0.5	0.9	9.8	11	0
BAYLOR	2	1.0	1.0	0.9	1.4	0	0
BEE	5	0.4	0.3	0.5	0.9	0	0
BELL	18	1.2	1.1	0.9	3.9	0	0
BEXAR	57	1.1	0.8	0.8	6.7	4	0
BLANCO	3	2.0	2.3	1.9	2.7	0	0
BORDEN	2	0.7	0.7	0.6	1.0	0	0
BOSQUE	4	1.2	1.4	1.2	1.5	0	0
BOWIE	22	0.5	0.4	0.5	1.8	0	0
BRAZORIA	25	0.3	0.2	0.4	1.2	0	0
BRAZOS	19	0.8	0.5	0.5	4.2	5	0
BREWSTER	57	2.5	2.3	2.0	8.4	18	0
BRISCOE	2	3.3	3.3	2.8	5.0	50	0
BROWN	6	2.6	0.9	1.3	7.8	33	0
BURNET	97	1.3	1.0	0.9	13.9	5	0
CALDWELL	7	0.2	0.2	0.4	2.2	0	0
CALHOUN	1	1.2	1.2	1.2	1.2	0	0
CALLAHAN	5	0.6	0.6	0.7	1.4	0	0
CAMERON	9	0.5	0.4	0.4	1.4	0	0
CAMP	2	0.8	0.8	0.7	1.0	0	0
CARSON	4	8.8	2.0	3.3	30.1	25	25
CASS	9	0.6	0.8	0.6	1.1	0	0
CASTRO	3	1.6	1.3	1.4	2.7	0	0
CHEROKEE	7	1.0	0.9	0.9	1.6	0	0
CLAY	2	1.4	1.4	1.3	1.4	0	0
COCHRAN	1	1.5	1.5	1.5	1.5	0	0
COKE	1	0.0	0.0	0.0	0.0	0	0
COLEMAN	2	0.6	0.6	0.5	0.9	0	0
COLLIN	36	1.0	0.8	0.8	5.2	3	0
COLORADO	6	0.3	0.4	0.3	0.4	0	0
COMAL	18	1.1	0.8	0.8	3.7	0	0
COMANCHE	4	0.7	0.6	0.6	1.0	0	0
CONCHO	2	0.2	0.2	0.3	0.3	0	0

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

COUNTY	NO. OF MEAS.	AVERAGE	MEDIAN	GEOM. MEAN	MAX	%≥4 pCi/L	%≥20 pCi/L
COOKE	7	1.0	0.9	1.0	1.8	0	0
CORYELL	6	0.9	0.8	0.6	2.2	0	0
CRANE	1	0.1	0.1	0.1	0.1	0	0
CROCKETT	2	1.1	1.1	1.1	1.2	0	0
CROSBY	3	1.2	1.2	1.1	1.8	0	0
DALLAM	1	0.1	0.1	0.1	0.1	0	0
DALLAS	85	1.2	1.0	0.9	6.8	4	0
DAWSON	3	1.8	1.5	1.6	2.7	0	0
DEAF SMITH	6	3.2	3.2	2.3	7.7	17	0
DELTA	1	0.6	0.6	0.6	0.6	0	0
DENTON	30	1.0	0.9	0.8	3.0	0	0
DE WITT	4	0.4	0.4	0.4	0.7	0	0
DICKENS	1	3.1	3.1	3.1	3.1	0	0
DIMMIT	2	0.5	0.5	0.5	0.5	0	0
DONLEY	1	3.2	3.2	3.2	3.2	0	0
DUVAL	3	0.7	0.4	0.9	2.1	0	0
EASTLAND	5	0.6	0.6	0.6	1.2	0	0
ECTOR	39	0.9	0.8	0.7	7.3	3	0
ELLIS	13	0.8	0.7	0.6	2.3	0	0
EL PASO	96	1.0	0.6	0.6	21.6	2	1
ERATH	6	0.4	0.4	0.4	0.7	0	0
FALLS	2	0.4	0.4	0.3	0.7	0	0
FANNIN	2	1.0	1.0	0.4	1.8	0	0
FAYETTE	13	1.1	0.9	0.8	3.2	0	0
FISHER	1	0.0	0.0	0.0	0.0	0	0
FLOYD	2	0.5	0.5	0.4	0.5	0	0
FORT BEND	23	0.3	0.2	0.3	2.2	0	0
FRANKLIN	2	0.2	0.2	0.5	0.5	0	0
FREESTONE	3	0.2	0.2	0.2	0.4	0	0
FRIO	3	0.7	1.0	0.6	1.0	0	0
GAINES	2	0.8	0.8	0.8	1.0	0	0
GALVESTON	35	0.2	0.1	0.3	0.9	0	0
GARZA	20	2.1	1.9	1.7	6.9	10	0
GILLESPIE	12	1.3	0.9	0.8	4.7	8	0
GLASSCOCK	2	1.3	1.3	1.2	1.4	0	0
GOLIAD	4	0.4	0.4	0.3	0.7	0	0
GONZALES	5	1.3	0.6	0.8	3.4	0	0
GRAY	9	1.7	1.7	1.6	2.6	0	0
GRAYSON	14	1.2	0.7	0.7	5.3	7	0
GREGG	21	0.9	0.5	0.6	7.1	5	0
GRIMES	3	0.5	0.1	0.4	1.4	0	0
GUADALUPE	15	1.0	0.9	0.8	3.1	0	0
HALE	15	7.5	3.0	4.2	41.3	47	13
HALL	1	0.4	0.4	0.4	0.4	0	0

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

COUNTY	NO. OF MEAS.	AVERAGE	MEDIAN	GEOM. MEAN	MAX	%≥4 pCi/L	%≥20 pCi/L
HAMILTON	1	0.4	0.4	0.4	0.4	0	0
HANSFORD	3	3.7	3.7	2.5	6.8	33	0
HARDIN	5	0.7	0.8	0.7	1.2	0	0
HARRIS	116	0.4	0.3	0.3	3.8	0	0
HARRISON	21	0.5	0.5	0.5	1.2	0	0
HARTLEY	1	0.6	0.6	0.6	0.6	0	0
HASKELL	1	0.8	0.8	0.8	0.8	0	0
HAYS	15	1.1	0.9	0.9	2.6	0	0
HEMPHILL	1	1.6	1.6	1.6	1.6	0	0
HENDERSON	14	0.7	0.3	0.4	5.1	7	0
HIDALGO	20	0.5	0.4	0.4	1.9	0	0
HILL	2	0.5	0.5	0.5	0.7	0	0
HOCKLEY	7	2.8	1.0	1.8	13.5	14	0
HOOD	7	1.2	1.0	1.0	3.0	0	0
HOPKINS	6	0.3	0.3	0.4	0.6	0	0
HOUSTON	7	0.4	0.2	0.4	1.3	0	0
HOWARD	114	1.7	0.9	0.9	65.9	4	1
HUDSPETH	2	0.6	0.6	0.6	0.8	0	0
HUNT	9	0.6	0.4	0.5	1.8	0	0
HUTCHINSON	14	1.5	1.2	1.3	6.3	7	0
JACK	1	0.3	0.3	0.3	0.3	0	0
JASPER	11	0.5	0.2	0.3	3.1	0	0
JEFF DAVIS	16	3.7	1.7	1.9	13.6	19	0
JEFFERSON	25	0.3	0.2	0.3	0.9	0	0
JIM HOGG	1	1.1	1.1	1.1	1.1	0	0
JOHNSON	7	0.7	0.7	0.7	2.1	0	0
JONES	5	1.0	0.7	0.9	2.8	0	0
KARNES	3	1.7	0.7	0.7	4.4	33	0
KAUFMAN	5	1.1	1.5	0.8	1.6	0	0
KENDALL	5	1.0	1.0	0.9	1.9	0	0
KERR	20	1.4	1.4	1.0	6.0	5	0
KINNEY	3	0.1	0.1	0.2	0.3	0	0
KLEBERG	1	0.5	0.5	0.5	0.5	0	0
KNOX	1	0.9	0.9	0.9	0.9	0	0
LAMAR	5	0.2	0.3	0.4	0.5	0	0
LAMB	10	2.9	2.1	2.2	6.9	30	0
LAMPASAS	2	1.9	1.9	0.8	3.5	0	0
LA SALLE	1	0.1	0.1	0.1	0.1	0	0
LAVACA	10	1.2	0.4	0.7	7.5	10	0
LEE	3	1.2	0.6	0.7	2.9	0	0
LEON	3	0.2	0.2	0.3	0.4	0	0
LIBERTY	2	0.0	0.0	0.0	0.0	0	0
LIMESTONE	4	0.0	0.0	0.2	0.3	0	0
LIPSCOMB	2	1.6	1.6	1.5	1.9	0	0

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

COUNTY	NO. OF MEAS.	AVERAGE	MEDIAN	GEOM. MEAN	MAX	%≥4 pCi/L	%≥20 pCi/L
LIVE OAK	4	0.8	0.4	0.7	2.5	0	0
LLANO	47	1.7	1.3	1.3	5.4	15	0
LUBBOCK	68	2.8	1.9	1.9	23.9	18	1
LYNN	1	1.5	1.5	1.5	1.5	0	0
MCCULLOCH	26	1.2	0.8	0.7	12.5	4	0
MCLENNAN	29	1.2	0.8	0.7	5.9	3	0
MCMULLEN	1	1.5	1.5	1.5	1.5	0	0
MADISON	2	0.4	0.4	0.7	0.7	0	0
MARION	3	0.8	1.0	1.1	1.3	0	0
MARTIN	3	1.8	1.2	1.3	3.8	0	0
MASON	21	1.3	0.9	0.9	7.0	10	0
MATAGORDA	8	0.7	0.5	0.7	2.9	0	0
MAVERICK	3	1.5	1.5	1.4	2.2	0	0
MEDINA	9	0.5	0.4	0.4	1.1	0	0
MENARD	3	1.0	1.1	1.0	1.4	0	0
MIDLAND	48	1.1	1.0	0.9	3.4	0	0
MILAM	7	0.6	0.5	0.7	1.7	0	0
MITCHELL	34	1.4	0.9	0.9	14.0	6	0
MONTAGUE	3	0.7	0.5	0.6	1.3	0	0
MONTGOMERY	27	0.3	0.2	0.4	2.1	0	0
MOORE	6	3.4	3.1	3.3	5.2	33	0
MORRIS	7	0.7	0.9	0.8	1.1	0	0
NACOGDOCHES	9	0.6	0.3	0.5	1.4	0	0
NAVARRO	3	0.1	0.0	0.5	0.5	0	0
NEWTON	2	0.1	0.1	0.3	0.3	0	0
NOLAN	5	0.9	1.1	0.9	1.8	0	0
NUECES	17	0.7	0.5	0.7	2.1	0	0
OCHILTREE	5	3.6	3.1	3.4	5.5	40	0
ORANGE	13	0.5	0.4	0.4	1.2	0	0
PALO PINTO	6	0.7	0.6	0.6	1.9	0	0
PANOLA	9	0.3	0.2	0.3	0.7	0	0
PARKER	5	0.3	0.1	0.3	0.8	0	0
PARMER	4	3.2	3.1	2.1	6.2	50	0
PECOS	6	0.4	0.4	0.3	0.8	0	0
POLK	7	0.5	0.4	0.7	1.3	0	0
POTTER	29	3.4	3.3	2.6	11.1	34	0
PRESIDIO	43	2.6	2.3	2.0	7.2	19	0
RAINS	3	0.3	0.3	0.3	0.3	0	0
RANDALL	20	5.6	3.4	3.3	33.1	35	5
REAL	2	0.2	0.2	0.4	0.4	0	0
RED RIVER	1	0.0	0.0	0.0	0.0	0	0
REEVES	9	1.2	1.2	0.8	2.8	0	0
REFUGIO	1	0.2	0.2	0.2	0.2	0	0
ROBERTSON	5	0.6	0.5	0.4	1.1	0	0

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

COUNTY	NO. OF MEAS.	AVERAGE	MEDIAN	GEOM. MEAN	MAX	%≥4 pCi/L	%≥20 pCi/L
ROCKWALL	3	0.3	0.4	0.4	0.5	0	0
RUNNELS	4	0.8	0.7	0.8	1.1	0	0
RUSK	10	0.2	0.3	0.3	0.7	0	0
SABINE	3	0.5	0.5	0.5	0.8	0	0
SAN AUGUSTINE	5	0.7	0.4	0.7	1.5	0	0
SAN JACINTO	5	0.3	0.3	0.4	0.5	0	0
SAN PATRICIO	7	0.6	0.2	0.3	3.1	0	0
SAN SABA	30	1.2	0.7	0.8	9.6	3	0
SCHLEICHER	1	0.3	0.3	0.3	0.3	0	0
SCURRY	75	1.4	1.1	1.0	7.6	3	0
SHACKELFORD	2	0.4	0.4	0.3	0.4	0	0
SHELBY	3	0.0	0.0	0.4	0.4	0	0
SHERMAN	3	11.7	15.3	10.1	15.6	67	0
SMITH	46	0.5	0.4	0.4	3.7	0	0
STARR	1	0.8	0.8	0.8	0.8	0	0
STEPHENS	3	2.3	2.1	2.2	3.4	0	0
STERLING	1	3.6	3.6	3.6	3.6	0	0
STONEWALL	1	0.7	0.7	0.7	0.7	0	0
SUTTON	1	0.4	0.4	0.4	0.4	0	0
SWISHER	5	6.3	1.9	2.8	15.4	40	0
TARRANT	84	1.1	0.7	0.8	7.4	4	0
TAYLOR	26	1.4	0.9	1.0	5.7	12	0
TERRY	5	1.6	1.5	1.1	3.3	0	0
THROCKMORTON	1	2.0	2.0	2.0	2.0	0	0
TITUS	7	0.4	0.4	0.5	1.0	0	0
TOM GREEN	15	0.9	0.7	0.7	3.3	0	0
TRAVIS	53	1.4	0.8	0.9	7.0	8	0
TRINITY	1	0.6	0.6	0.6	0.6	0	0
TYLER	4	0.5	0.6	0.7	1.0	0	0
UPSHUR	9	0.4	0.1	0.4	1.1	0	0
UPTON	1	2.0	2.0	2.0	2.0	0	0
UVALDE	6	0.8	0.6	0.8	1.9	0	0
VAL VERDE	8	0.5	0.4	0.4	1.0	0	0
VAN ZANDT	8	0.3	0.3	0.3	0.7	0	0
VICTORIA	9	1.4	0.4	0.7	9.5	11	0
WALKER	12	0.6	0.2	0.5	2.8	0	0
WALLER	6	0.2	0.3	0.4	0.6	0	0
WARD	6	0.5	0.7	0.7	1.0	0	0
WASHINGTON	5	0.4	0.3	0.5	1.1	0	0
WEBB	19	0.4	0.4	0.4	1.5	0	0
WHARTON	3	0.6	0.0	1.9	1.9	0	0
WHEELER	4	1.8	2.0	1.2	3.2	0	0
WICHITA	13	1.5	1.3	1.2	4.3	8	0
WILLACY	2	0.5	0.5	0.5	0.6	0	0

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

COUNTY	NO. OF MEAS.	AVERAGE	MEDIAN	GEOM. MEAN	MAX	%≥4 pCi/L	%≥20 pCi/L
WILLIAMSON	38	1.4	1.1	1.0	6.4	3	0
WILSON	6	0.2	0.1	0.3	1.0	0	0
WINKLER	3	0.2	0.0	1.0	1.0	0	0
WISE	3	0.6	0.6	0.9	1.5	0	0
WOOD	16	0.3	0.3	0.3	0.8	0	0
YOAKUM	4	3.2	2.7	1.8	7.3	25	0
YOUNG	2	0.9	0.9	0.9	1.1	0	0
ZAVALA	4	0.6	0.6	0.6	1.1	0	0

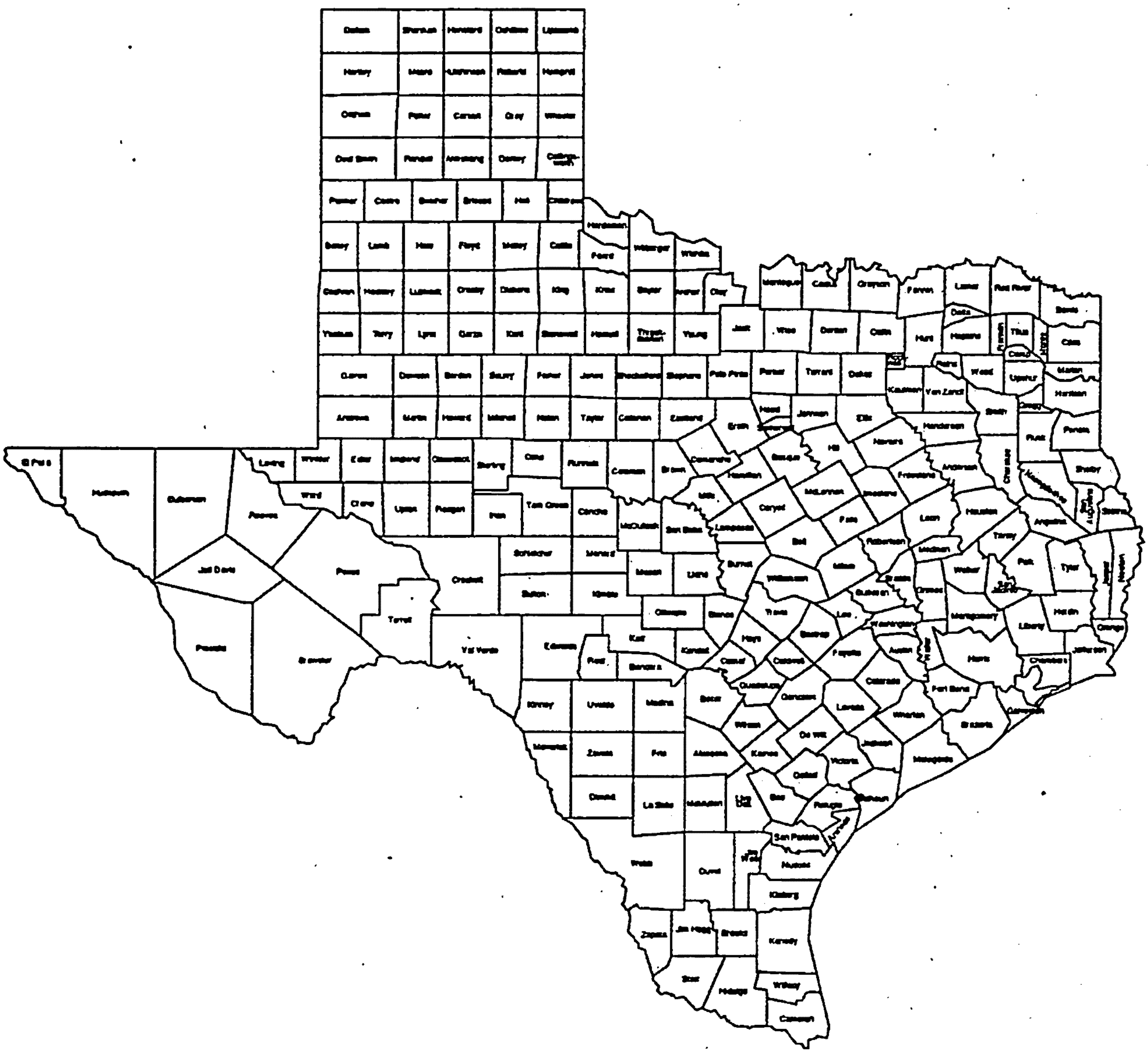

Fig. 8- Map showing counties and county names in Texas.

GEOLOGIC RADON POTENTIAL

The geologic radon potential of Texas is generally low overall. The relatively mild climate throughout much of the State, especially in the most populous areas, and the predominance of slab-on-grade housing seems to have influenced the overall potential. Significant percentages of houses with indoor radon levels exceeding 4 pCi/L are restricted to the High Plains and the Western Mountains and Basins Provinces. However, no physiographic province in Texas is completely free from indoor radon levels above 4 pCi/L.

Elevated indoor radon can be expected in several geologic settings in Texas. Uranium-rich (>2.5 ppm for the purposes of this report) granites and metamorphic rocks in central Texas, uranium-rich Tertiary silicic volcanic and tuffaceous sedimentary rocks in western Texas, uranium-rich dark marine shales in east-central Texas and the Big Bend area, uranium-rich sand and caliche associated with the Ogallalla Formation and overlying units in the High Plains of Texas, uranium-rich sediments of Late Cretaceous age along the eastern edge of central Texas, and residual soils and alluvium derived from these units are likely to have significant percentages of homes with indoor radon levels exceeding 4 pCi/L. Except for the High Plains and the Western Mountains and Basins Provinces, these rocks generally make up only a small percentage of the surface area of the various physiographic provinces. However, the outcrop belt of Upper Cretaceous sedimentary rocks of the East Texas Province passes near substantial population centers. The most likely areas for elevated indoor radon levels to occur are those in which elevated eU values occur in the aeroradiometric data (fig. 6). An exception may be the uranium mining district in south Texas. There, the uranium deposits occur at depth, often below the water table, and the influence of such deposits on the near surface soil-gas radon levels may be subdued.

Extreme indoor radon levels (greater than 100 pCi/L) may be expected where structures are inadvertently sited on uranium occurrences. This is more likely to occur in more populated areas along the outcrop belt of the Ogallalla Formation at the edge of the Llano Estacada in the northern and central parts of the High Plains and Plateaus Province. In this outcrop area, sedimentary rocks with more than 10 ppm uranium are common.

SUMMARY

Eight areas of Texas for which geologic radon potential may be evaluated were delineated (fig. 9). These areas generally follow the physiographic provinces of figure 1 with some modifications based on internal differences in geology, soils, and aeroradiometric signature. A relative index of radon potential (RI) and an index of the level of confidence in the available data (CI) have been established (see discussion in the introductory section of this volume) . The areas are evaluated in Table 2.

The northern part of the High Plains and Plateau Province (N, fig. 9) has moderate radon potential. Uranium occurrences, anomalously uranium-rich calcrete and silcrete, and uranium-rich lacustrine rocks along the outcrop belt of the Ogallalla Formation and in small upper Tertiary lacustrine basins within the northern High Plains may locally cause very high indoor radon levels. Indoor radon data are elevated in many counties in this area . Equivalent uranium values in this area range from 1.0-4.0 ppm. An area of elevated eU along the Rio Grande River (also labeled "N" in fig. 9) is included in this radon potential province.

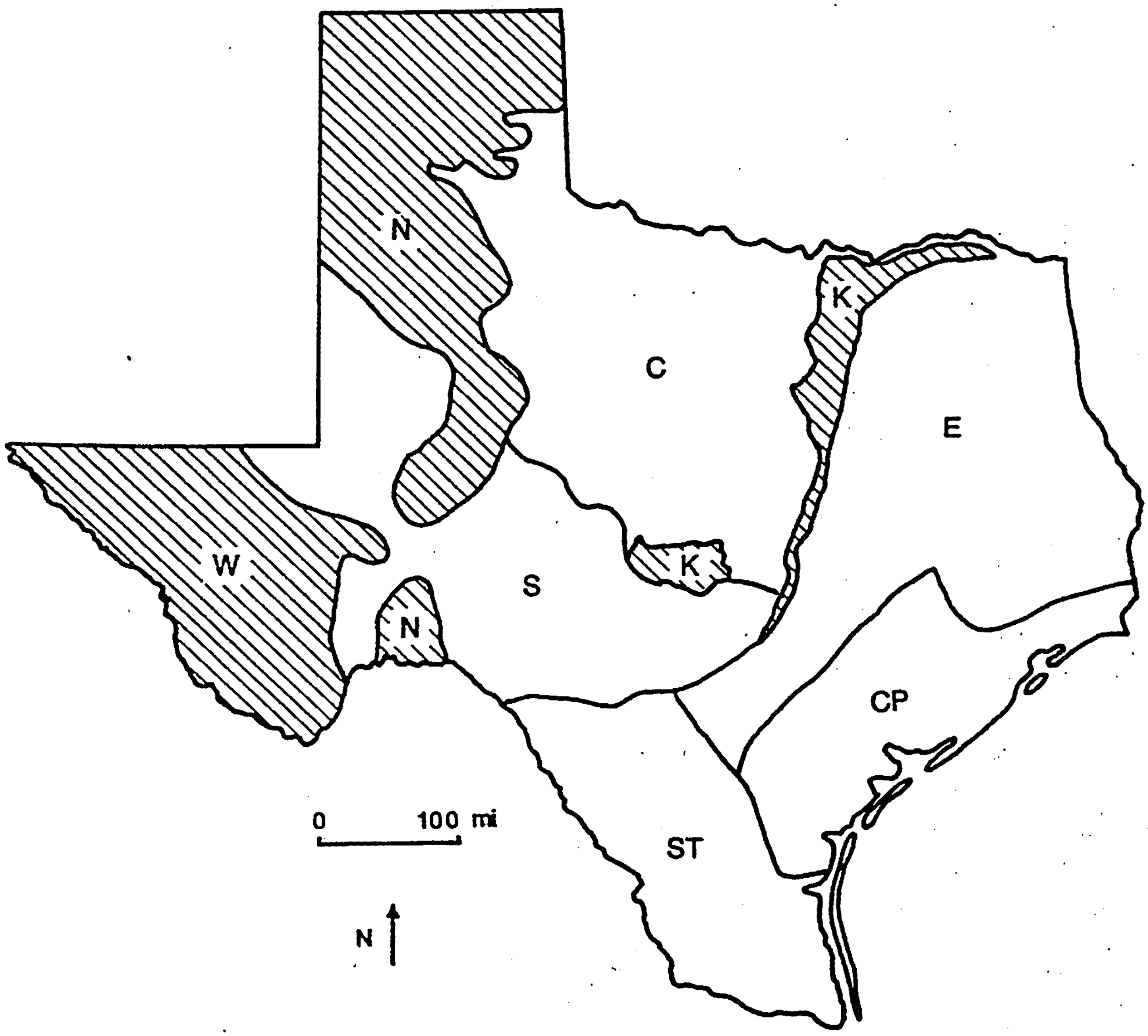

Fig. 9- Map showing radon potential areas of Texas. W- Western mountains and basins; N- Northern High Plains and Plateaus; S- Southern High Plains and Plateaus; C- Central Texas; K- Cretaceous Central Texas and Llano Uplift;; E- East Texas; ST- Southern Texas Plain; CP- Coastal Plain. Cross-hatched areas have moderate potential. The other areas are low.

The southern part of the High Plains and Plateaus Province has low radon potential overall as suggested by generally low eU values and low indoor radon. This area is sparsely populated and indoor radon measurements may not adequately reflect the geologic radon potential. An area of low eU covered by the sandy facies of the Blackwater Draw Formation in the northeast corner of the Western Mountains and Basins Province is included in this radon potential province. Some local areas within this province with potentially high indoor radon levels include areas covered by thin soils over limestone and dolomite in the Edwards Plateau of the southern part of this province and areas underlain by carbonaceous sediments in the southeastern part of this province.

The Western Mountains and Basins Province has moderate indoor radon potential overall. Although average indoor radon levels are mixed (low in El Paso County, but high in three southern counties), areas of elevated eU are widespread (fig. 6). Uranium-rich Precambrian rocks and uranium-rich silicic volcanic rocks and alluvium derived from them may locally cause average indoor radon levels in some communities to exceed 4 pCi/L. Values exceeding 20 pCi/L may also be expected locally. Exceptionally dry soils in this province may tend to lower radon potential. In very dry soils, the emanating fraction of radon from mineral matter is lowered.

The Central Texas Province has low radon potential overall; however, areas along the outcrop belt of the Woodbine and Eagle Ford Formations and the Austin Chalk (part of the Upper Cretaceous Gulfian Series, fig. 5) along the eastern edge of this province and areas of Precambrian metamorphic and undifferentiated igneous rocks in the Llano Uplift (fig. 5) in the southern part of this province have moderate geologic radon potential and are separated out as a distinctive radon potential area. Structures sited on uranium occurrences in the Triassic Dockum Group in the western part of this province may locally have very high indoor radon levels.

The East Texas Province has low radon potential overall. Soil moistures are typically high; soil permeability is typically low to moderate; and eU levels are low to moderate. A few areas of well-drained soils and elevated eU (fig. 6) may be localized areas of moderate radon potential.

The Texas Coastal Plain has low geologic radon potential. Low aeroradioactivity, low to moderate soil permeability, and locally high water tables contribute to low radon potential.

The South Texas Plain has low radon potential due to generally low eU and low to moderate soil permeability. Some structures sited on the more uranium-rich soils in this province (fig. 6) may locally have elevated indoor radon levels, but such soils are generally also clay-rich and this may mitigate against radon movement.

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 geologic radon potential areas of Texas. See figure 9 for locations of areas.

FACTOR	Northern High P/P RI	Northern High P/P CI	Southern High P/P RI	Southern High P/P CI	Western Mtns/Basins RI	Western Mtns/Basins CI	Central Texas RI	Central Texas CI
INDOOR RADON	2	2	1?	1	2?	1	1	2
RADIOACTIVITY	2	2	1	2	2	3	1	3
GEOLOGY	2	2	2	2	2	2	2	2
SOIL PERM.	2	3	2	3	2	3	2	3
ARCHITECTURE	2	-	1	-	1	-	1	-
GFE POINTS	0	-	0	-	0	-	0	-
TOTAL	10	9	7	8	9	9	7	10
RANKING	MOD	MOD	LOW	MOD	MOD	MOD	LOW	HIGH

FACTOR	Cretaceous Cent. Texas RI	Cretaceous Cent. Texas CI	East Texas RI	East Texas CI	Coastal Plain RI	Coastal Plain CI	South Texas Plain RI	South Texas Plain CI
INDOOR RADON	2?	1	1	2	1	2	1?	1
RADIOACTIVITY	2	2	1	3	1	3	1	3
GEOLOGY	2	2	2	2	2	2	2	2
SOIL PERM.	2	3	1	3	2	3	2	3
ARCHITECTURE	1	-	1	-	1	-	1	-
GFE POINTS	1	-	0	-	0	-	0	-
TOTAL	10	8	6	10	7	10	7	9
RANKING	MOD	MOD	LOW	HIGH	LOW	HIGH	LOW	MOD

- Not used in CI.

RADON INDEX SCORING:

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

Possible range of points = 3 to 17

CONFIDENCE INDEX SCORING:

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

Possible range of points = 4 to 12

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EPA's Map of Radon Zones

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

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

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

TEXAS MAP OF RADON ZONES

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

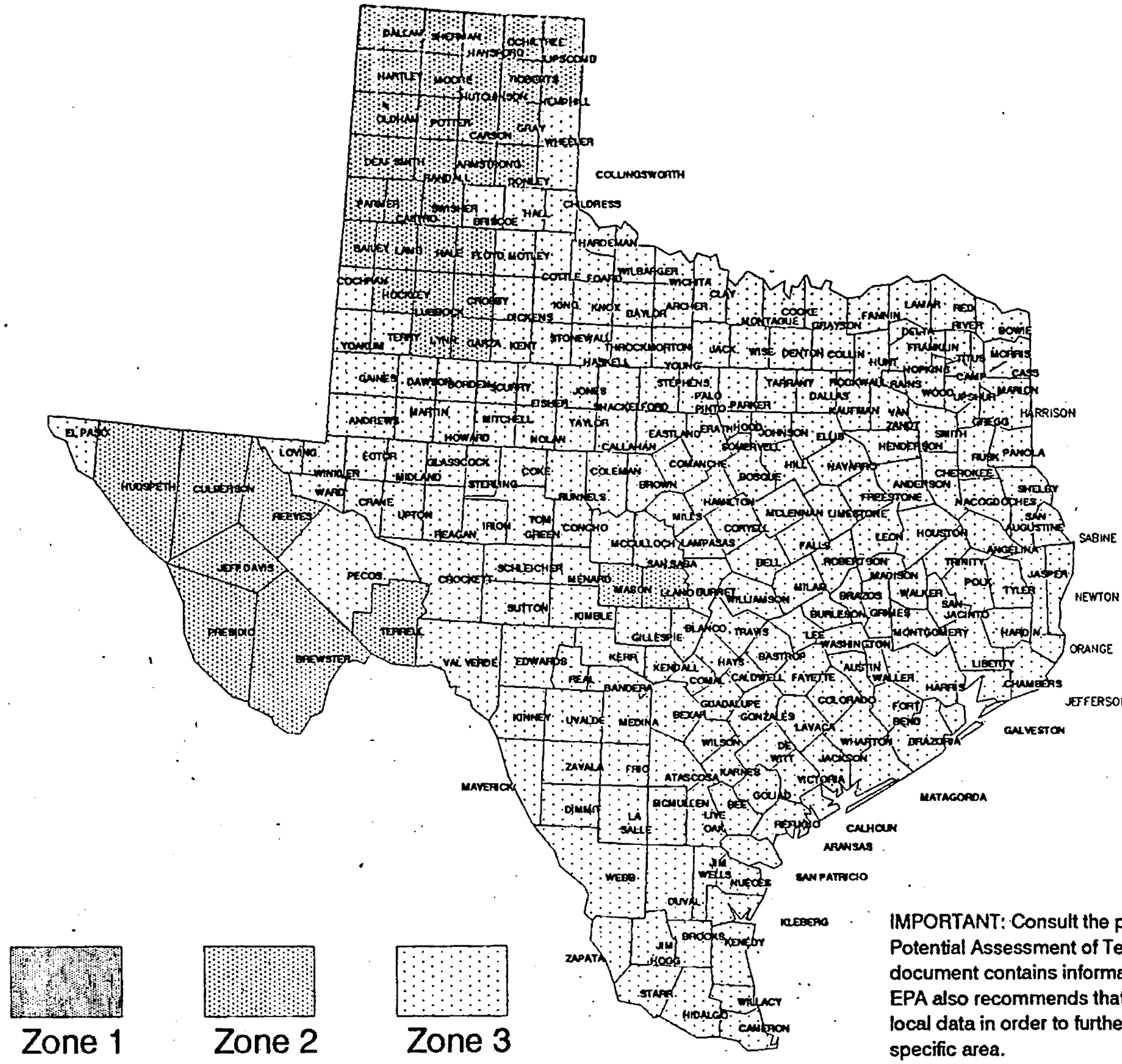
A few county designations do not strictly follow this methodology for adapting the geologic provinces to county boundaries. EPA and the Texas Department of Health have decided to designate Reagan, Upton, Glasscock, Borden, Howard, Scurry, Mitchell, Sterling, Grayson, Fannin, Collin, and El Paso as Zone 3 counties. Although the indoor radon data for these counties are limited, they indicate low indoor radon averages. However, these counties contain much variablility in geology and aerial radioacivity, and some elevated levels will be found in these counties.

Although the information provided in Part IV of this report -- the State chapter entitled "Preliminary Geologic Radon Potential Assessment of Texas" -- 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 6 EPA office or the Texas radon program for information on testing and fixing homes. Telephone numbers and addresses can be found in Part II of this report.

TEXAS - 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 Texas" 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.