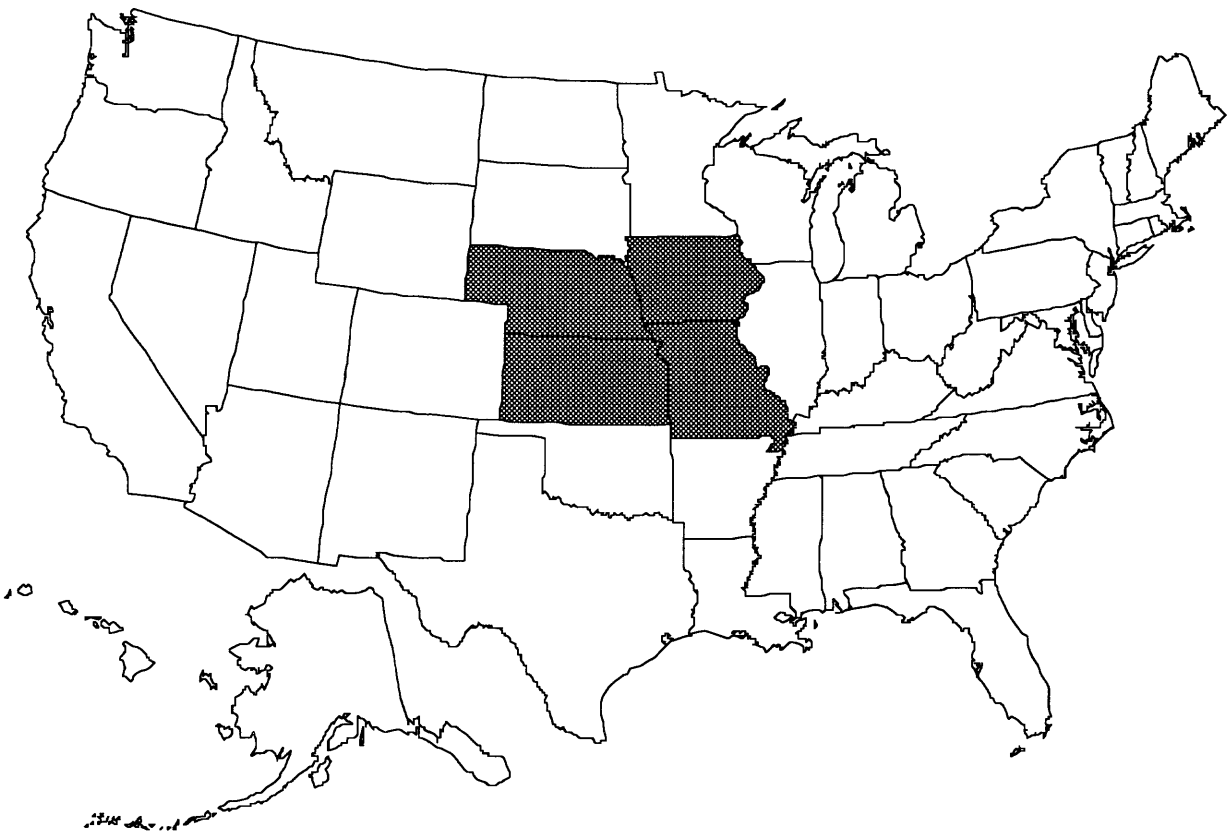
U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

GEOLOGIC RADON POTENTIAL OF EPA REGION 7

Iowa Kansas Missouri Nebraska



OPEN-FILE REPORT 93-292-G

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

1993

U.S. DEPARTMENT OF THE INTERIOR

U.S. GEOLOGICAL SURVEY

GEOLOGIC RADON POTENTIAL OF EPA REGION 7

Iowa, Kansas, Missouri, and Nebraska

R. Randall Schumann

EDITOR

OPEN-FILE REPORT 93-292-G

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

1993

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

CONTENTS

SECTION PAGE

1. The USGS/EPA State Radon Potential Assessments: An Introduction 1
   Linda C.S. Gundersen, R. Randall Schumann, and Sharon W. White

   Appendix A: Geologic Time Scale 19

   Appendix B: Glossary of Terms 20

   Appendix C: EPA Regional Offices, State Radon Contacts, and State Geological Surveys 26

2. EPA Region 7 Geologic Radon Potential Summary 36
   R. Randall Schumann, James K. Otton, and Sandra L. Szarzi

3. Preliminary Geologic Radon Potential Assessment of Iowa 46
   R. Randall Schumann

4. Preliminary Geologic Radon Potential Assessment of Kansas 71
   R. Randall Schumann

5. Preliminary Geologic Radon Potential Assessment of Missouri 96
   James K. Otton

6. Preliminary Geologic Radon Potential Assessment of Nebraska 124
   R. Randall Schumann

ACKNOWLEDGMENTS

These reports are the culmination of a 3-year cooperative project involving, almost literally, a "cast of thousands." Sharon W. White and R. Thomas Peake of the U.S. Environmental Protection Agency coordinated the project for EPA and provided data, comments, assistance, and support. They did an exemplary job and we appreciate their work and our association with the EPA Radon program. The Association of American State Geologists (AASG), through each of the State geological surveys, provided reviews and information that greatly aided in the preparation of the reports and enhanced the final products. Special thanks are due to the AASG committee, consisting of Walter Schmidt (chairman), Robert Fakundiny, Mark Davis, Michael Mudrey, Jonathan Price, Charles Robertson, and John Rold. We also thank the State radon program representatives, whose comments and technical assistance are greatly appreciated.

Technical assistance in preparation of the maps and materials was ably provided by Michele Killgore, Debra Mickelson, Michele Murray, Mark Pyle, and Sandra Szarzi. We thank Helen Britton, Carole Buntenbah, Marge Cunningham, Marian Nance, and Gwen Pilcher for their assistance in manuscript processing. The project chiefs, Linda Gundersen and Randall Schumann, express thanks to those named here and to many others unnamed, but appreciated nonetheless.

THE USGS/EPA RADON POTENTIAL ASSESSMENTS: AN INTRODUCTION

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

BACKGROUND

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

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

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

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

RADON GENERATION AND TRANSPORT IN SOILS

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

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

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

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

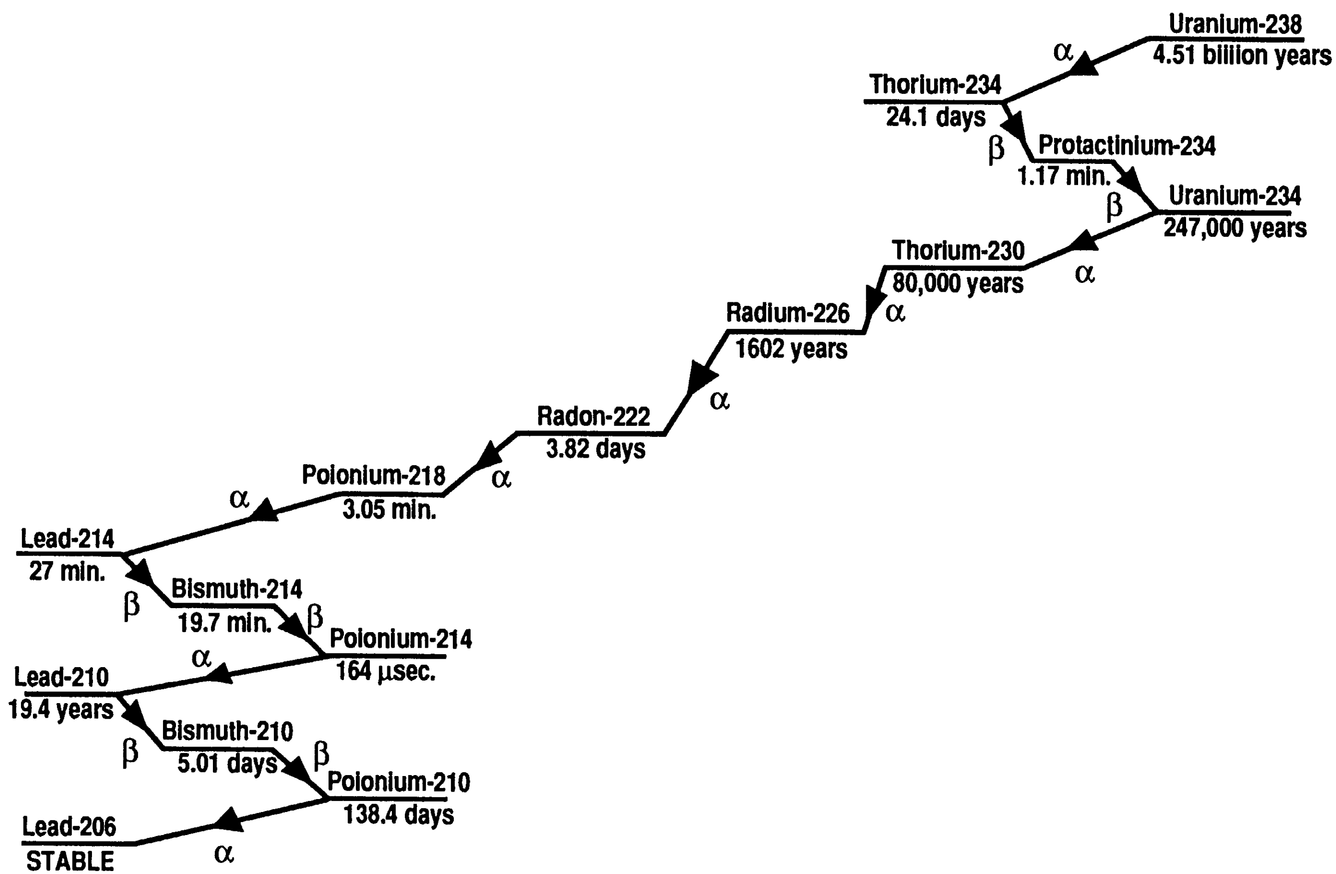


Figure 1. The uranium-238 decay series, showing the half-lives of elements and their modes of decay (after Wanty and Schoen, 1991). α denotes alpha decay, β denotes beta decay.

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

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

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

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

RADON ENTRY INTO BUILDINGS

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

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

METHODS AND SOURCES OF DATA

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

GEOLOGIC DATA

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

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

NURE AERIAL RADIOMETRIC DATA

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

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

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

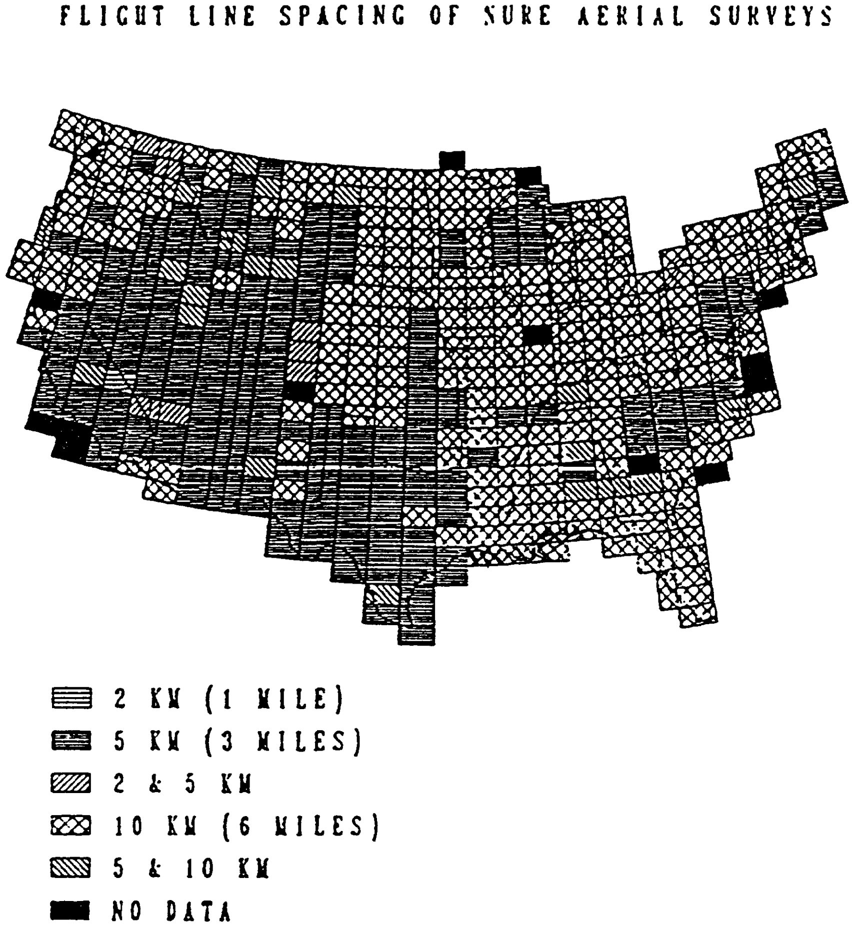


Figure 2. Nominal flightline spacings for NURE aerial gamma-ray surveys covering the contiguous United States (from Duval and others, 1990). Rectangles represent 1°x2° quadrangles.

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

SOIL SURVEY DATA

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

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

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

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

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

INDOOR RADON DATA

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

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

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

RADON INDEX AND CONFIDENCE INDEX

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

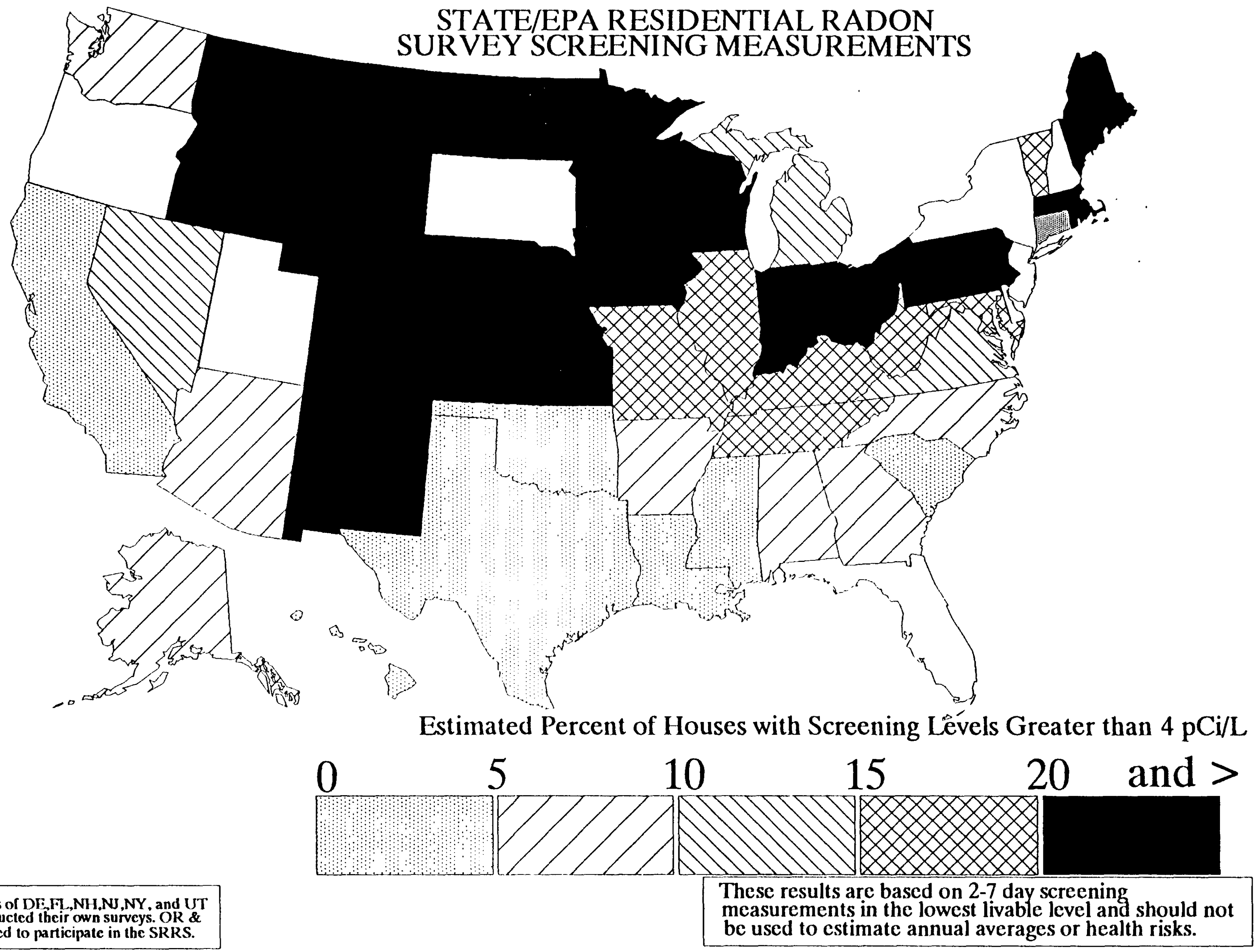


Figure 3. Percent of homes tested in the State/EPA Residential Radon Survey with screening indoor radon levels exceeding 4 pCi/L.

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

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

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

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

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

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

INCREASING RADON POTENTIAL →

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

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

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

SCORING:

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

POSSIBLE RANGE OF POINTS = 3 to 17

TABLE 2. CONFIDENCE INDEX MATRIX

INCREASING CONFIDENCE →

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

SCORING:

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

POSSIBLE RANGE OF POINTS = 4 to 12

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

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

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

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

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

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

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

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

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

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

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

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

EPA COUNTY RADON POTENTIAL MAPS

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

REFERENCES CITED

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

APPENDIX A
GEOLOGIC TIME SCALE

Subdivisions (and their symbols)						Age estimates of boundaries in mega-annum (Ma) [1]
Eon or Eonothem	Era or Erathem	Period, System, Subperiod, Subsystem		Epoch or Series		
Phanerozoic[2]	Cenozoic[2] (Cz)	Quaternary[2] (Q)		Holocene		0.010
				Pleistocene		1.6 (1.6–1.9)
		Tertiary (T)	Neogene[2] Subperiod or Subsystem (N)	Pliocene		5 (4.9–5.3)
				Miocene		24 (23–26)
			Paleogene[2] Subperiod or Subsystem (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 (TR)		Late	Upper	
				Middle	Middle	
				Early	Lower	~240
	Paleozoic[2] (Pz)	Permian (P)		Late	Upper	
				Early	Lower	290 (290–305)
		Carboniferous Systems (C)	Pennsylvanian (ℙ)	Late	Upper	
				Middle	Middle	
				Early	Lower	~330
			Mississippian (M)	Late	Upper	
				Early	Lower	360 (360–365)
		Devonian (D)		Late	Upper	
				Middle	Middle	
				Early	Lower	410 (405–415)
		Silurian (S)		Late	Upper	
				Middle	Middle	
				Early	Lower	435 (435–440)
		Ordovician (O)		Late	Upper	
				Middle	Middle	
				Early	Lower	500 (495–510)
		Cambrian (Ꞓ)		Late	Upper	
				Middle	Middle	
				Early	Lower	~570 [3]
Proterozoic (P)	Late Proterozoic (Z)	None defined				900
	Middle Proterozoic (Y)	None defined				1600
	Early Proterozoic (X)	None defined				2500
Archean (A)	Late Archean (W)	None defined				3000
	Middle Archean (V)	None defined				3400
	Early Archean (U)	None defined				3800 ?
pre-Archean (pA) [4]						

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

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

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

[4] Informal time term without specific rank.

APPENDIX B
GLOSSARY OF TERMS

Units of measure

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

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

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

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

Geologic terms and terms related to the study of radon

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

eolian Pertaining to sediments deposited by the wind.

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

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

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

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

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

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

formation A mappable body of rock having similar characteristics.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

placer deposit See heavy minerals

residual Formed by weathering of a material in place.

residuum Deposit of residual material.

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

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

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

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

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

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

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

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

shrink-swell clay See clay mineral.

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

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

slope An inclined part of the earth's surface.

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

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

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

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

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

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

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

uraniferous Containing uranium, usually more than 2 ppm.

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

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

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

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

APPENDIX C
EPA REGIONAL OFFICES

EPA Regional Offices

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

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

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

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

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

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

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

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

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

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

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

STATE RADON CONTACTS

May, 1993

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

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

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

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

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

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

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

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

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

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

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

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

Idaho

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

Illinois

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

Indiana

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

Iowa

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

Kansas

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

Kentucky

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

Louisiana

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

Maine

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

Maryland

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

Massachusetts

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

Michigan

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

Minnesota

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

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

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

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

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

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

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

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

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

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

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

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

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

Oklahoma

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

Oregon

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

Pennsylvania

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

Puerto Rico

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

Rhode Island

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

South Carolina

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

South Dakota

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

Tennessee

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

Texas

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

Utah

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

Vermont

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

Virgin Islands

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

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

STATE GEOLOGICAL SURVEYS

May, 1993

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

EPA REGION 7 GEOLOGIC RADON POTENTIAL SUMMARY

by
R. Randall Schumann, James K. Otton, and Sandra L. Szarzi
U.S. Geological Survey

EPA Region 7 includes the states of Iowa, Kansas, Missouri, and Nebraska. For each state, geologic radon potential areas were delineated and ranked on the basis of geologic, soil, housing construction, and other factors. Areas in which the *average screening indoor radon level of all homes within the area* is estimated to be greater than 4 pCi/L were ranked high. Areas in which the average screening indoor radon level of all homes within the area is estimated to be between 2 and 4 pCi/L were ranked moderate/variable, and areas in which the average screening indoor radon level of all homes within the area is estimated to be less than 2 pCi/L were ranked low. Information on the data used and on the radon potential ranking scheme is given in the introduction chapter. More detailed information on the geology and radon potential of each state in Region 7 is given in the individual state chapters. The individual chapters describing the geology and radon potential of the four states in EPA Region 7, though much more detailed than this summary, still are generalized assessments and there is no substitute for having a home tested. Radon levels, both high and low, can be quite localized, and within any radon potential area homes with indoor radon levels both above and below the predicted average will likely be found.

Figure 1 shows the geologic radon potential areas in EPA Region 7. Figure 2 shows average screening indoor radon levels in EPA Region 7 by county. The data for each state are from the State/EPA Residential Radon Survey and reflect screening charcoal canister measurements. Figure 3 shows the geologic radon potential of areas in Region 7, combined and summarized from the individual state chapters. Many rocks and soils in EPA Region 7 contain ample radon source material (uranium and radium) and have soil permeabilities sufficient to produce moderate or high radon levels in homes. The following sections summarize the geologic radon potential of each of the four states in Region 7. More detailed discussions may be found in the individual state radon potential chapters for the states in Region 7.

IOWA

Pre-Illinoian-age glacial deposits cover most of Iowa, and are at or near the surface in the southern, northwestern, and much of the northeastern parts of the state. These deposits generally consist of calcium-carbonate-rich loam and clay loam till containing pebbles and cobbles of granite, gabbro, basalt, rhyolite, greenstone, quartzite, chert, diorite, and limestone. Pre-Illinoian tills are covered by from less than 1 m to more than 20 m of Wisconsinan loess (windblown silt) in western, southern, and eastern Iowa. Illinoian glacial deposits occur a relatively small area along the Mississippi River in southeastern Iowa. These deposits consist of loamy to locally sandy till containing clasts of limestone and dolomite, with lesser amounts of igneous and metamorphic rocks, sandstone, and coal fragments. Illinoian deposits are covered by 1-5 m of loess. Wisconsinan drift is represented by the Cary and Tazewell drifts, consisting of calcareous loamy till containing clasts of shale, limestone, and dolomite, with minor amounts of basalt, diabase, granite, chert, and sandstone. Cary drift (now called the Dows Formation), which represents deposits of the Des Moines lobe, is generally not loess-covered; Tazewell drift is covered by as much as 2 m of loess.

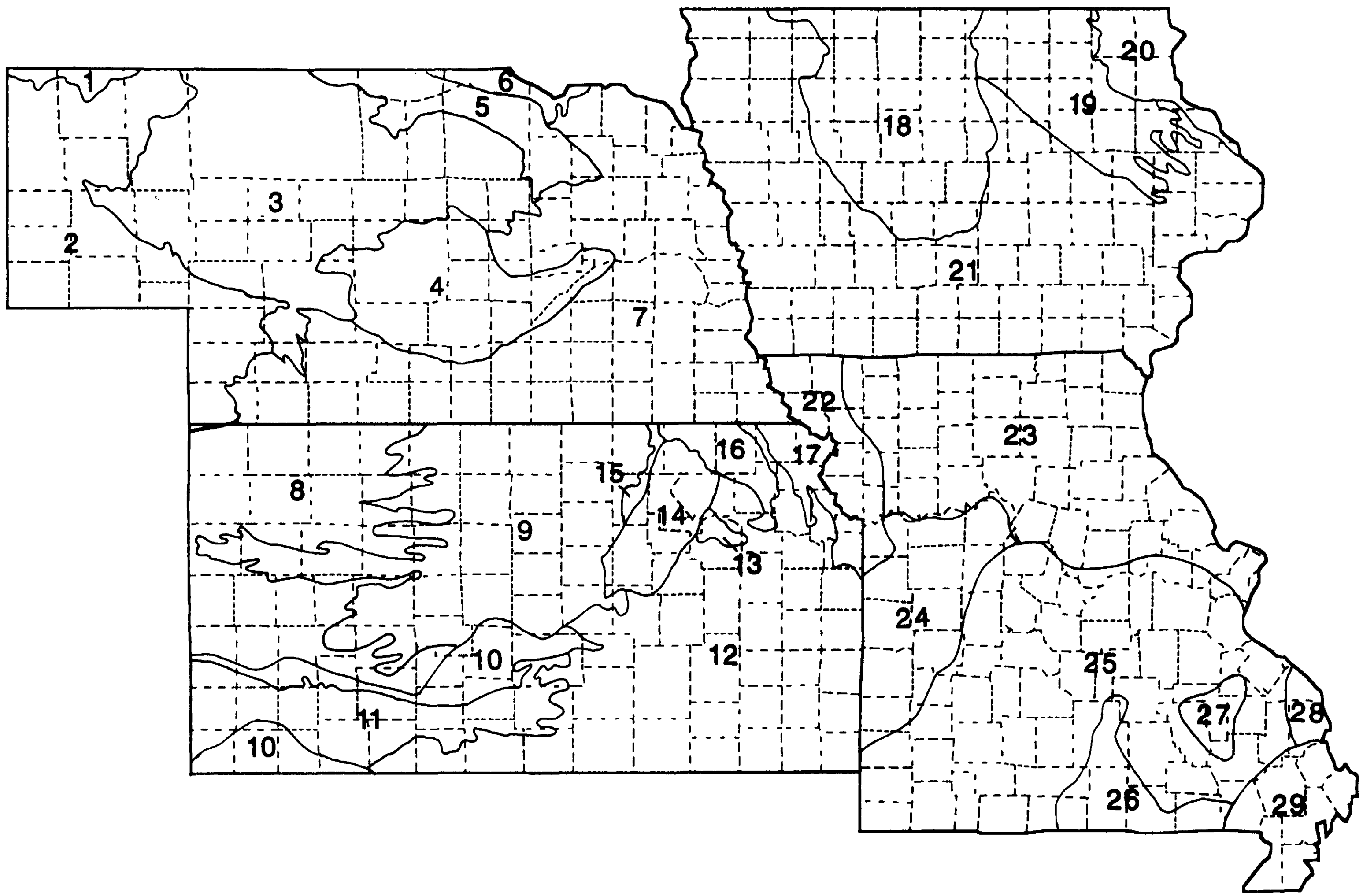


Figure 1. Geologic radon potential areas of EPA Region 7. See text for discussion of areas. 1, 6–Pierre Shale; 2, 5–Tertiary sedimentary rocks; 3–Sand Hills; 4, 8, 11–Tertiary sedimentary rocks covered by varying thicknesses of loess; 7, 13, 16, 21, 23–loess-covered glacial drift plains; 9–Cretaceous sedimentary rocks covered by varying thicknesses of loess; 10–dune sands in the Arkansas and Cimarron river valleys; 12, 15–area underlain by Pennsylvanian and Permian rocks; 14–part of the Mid-Continent Rift Zone; 17, 22–loess and glacial deposits along the Missouri River; 18–Des Moines lobe; 19–Iowan Surface; 20–Paleozoic Plateau; 24–unglaciated part of the Osage Plain; 25–Ozark Plateau; 26, 28–Area underlain by carbonate rocks; 27–St. Francois Mountains; 29–Coastal Plain.

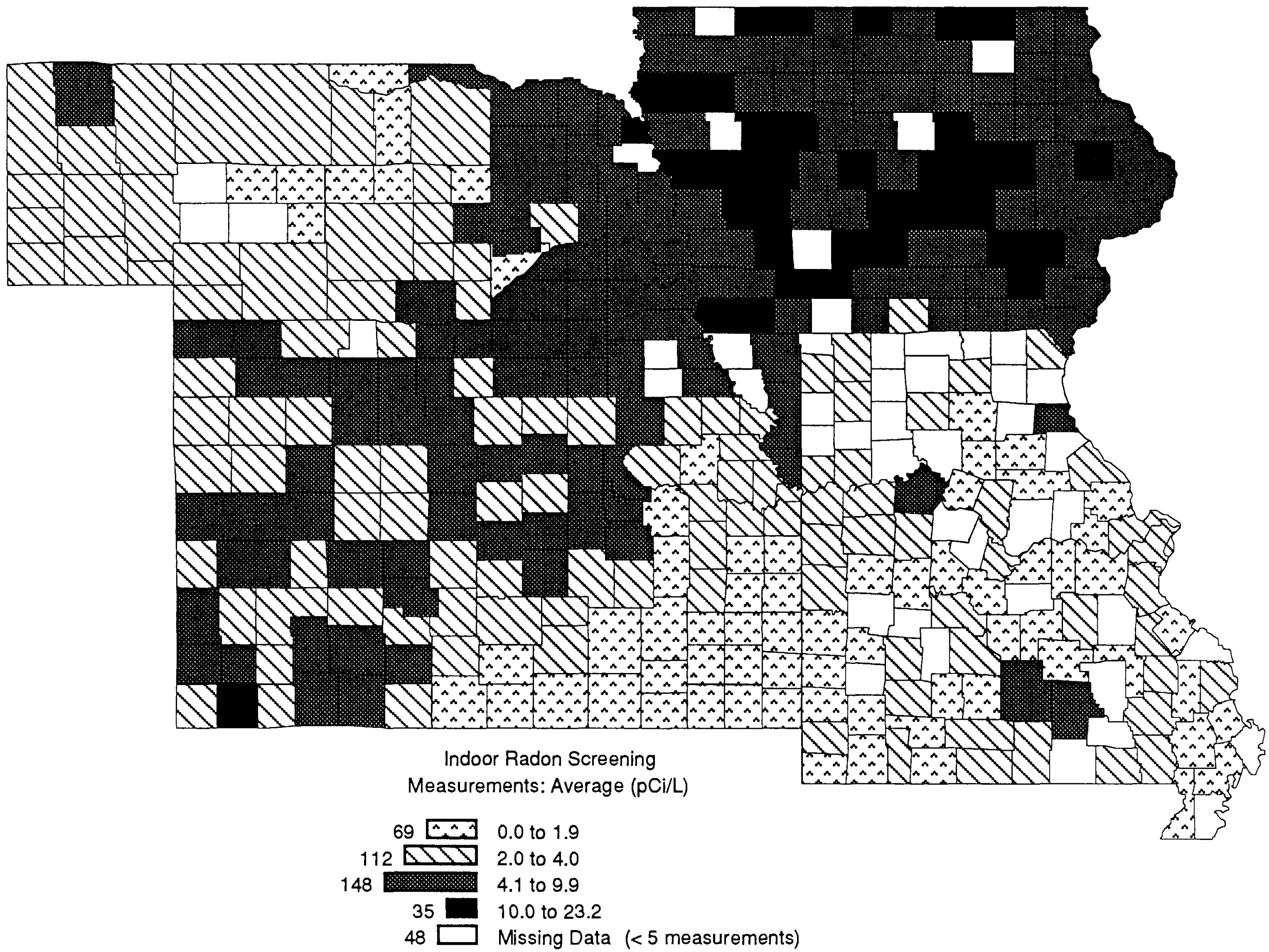


Figure 2. Average screening indoor radon levels by county for EPA Region 7. Data from the State/EPA Residential Radon Survey. Histograms in map legend indicate the number of counties in each measurement category.

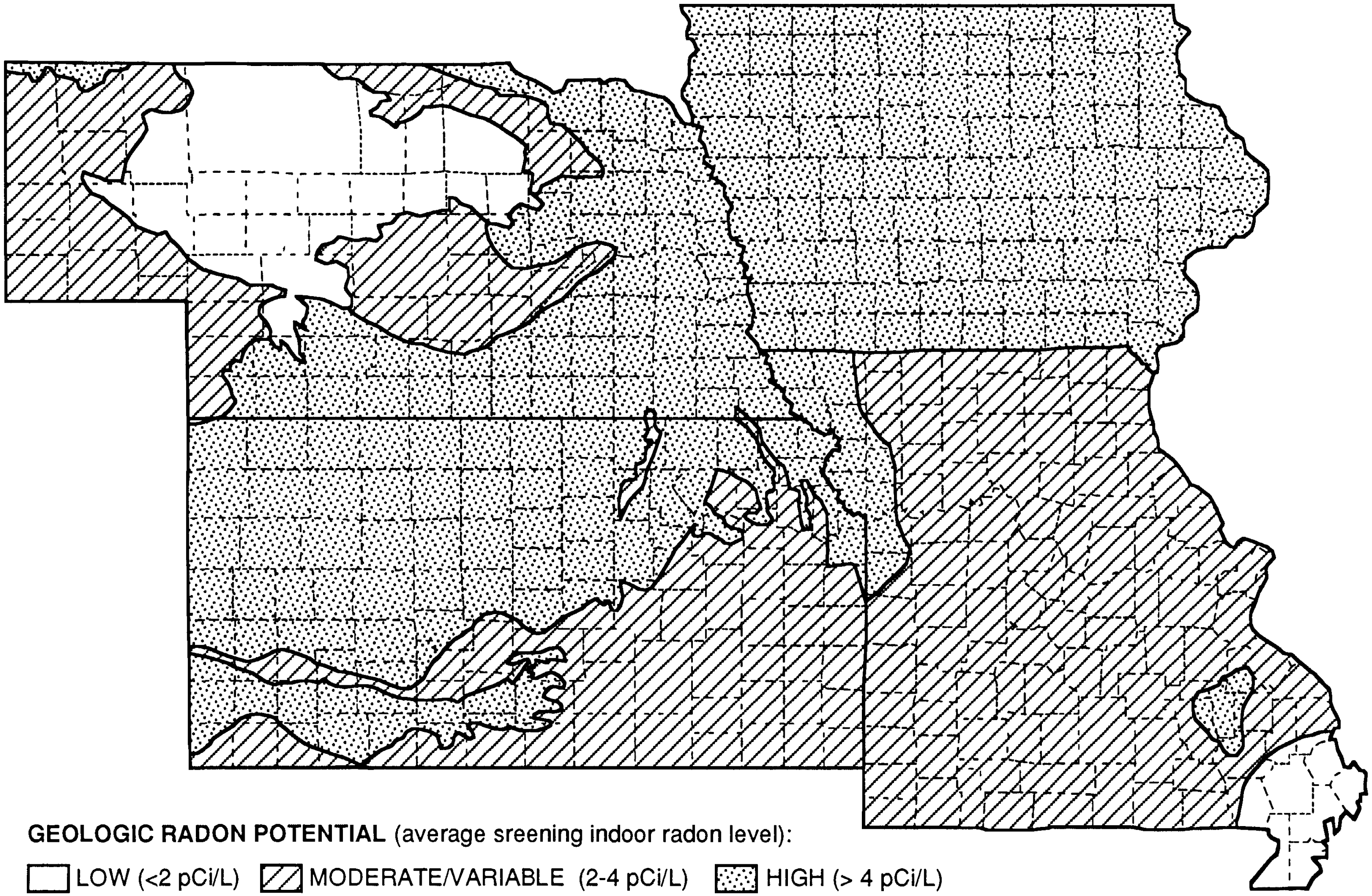


Figure 3. Geologic radon potential of EPA Region 7. Ranges next to each category label indicate the predicted average screening indoor radon level for all homes in each area.

The aeroradioactivity signature of surface deposits in Iowa, especially the Des Moines lobe deposits and other areas in which the loess cover is dicontinuous or absent, seems lower than would be expected in light of the elevated indoor radon levels. This may be because much of the radium in the near-surface soil horizons may have been leached and transported downward in the soil profile, giving a low surface radiometric signature while generating significant radon at depth (1-2 m? or greater) to produce elevated indoor radon levels. For example, a large area of low radioactivity (<1.5 ppm eU) in the northern part of the State corresponds roughly to the Des Moines lobe and the Iowan erosion surface, an area directly east of the Des Moines lobe in northeastern Iowa that is underlain by Pre-Illinoian glacial deposits and loess. However, these areas have high geologic radon potential. Most of the remainder of the State has eU values in the 1.5-2.5 ppm range. In general, soils developed from glacial deposits can be more rapidly leached of mobile ions than their bedrock counterparts, because crushing and grinding of the rocks by glacial action gives soil weathering agents (mainly moisture) better access to soil and mineral grain surfaces. Grinding of the rocks increases the mobility of uranium and radium in the soils by exposing them at grain surfaces, enhancing radionuclide mobility and radon emanation. In addition, poorly-sorted glacial drift may in many cases have higher permeability than the bedrock from which it is derived. Cracking of clayey glacial soils during dry periods can create sufficient permeability for convective radon transport to occur. This may be an important factor causing elevated radon levels in areas underlain by clay-rich glacial deposits.

Loess-covered areas have a higher radiometric signature than loess-free areas, and also appear to correlate roughly with higher average indoor radon levels than loess-free areas, although all areas of Iowa have average indoor radon levels exceeding 4 pCi/L. The Loess-Covered Drift Plains, which cover northwestern Iowa and all of southern Iowa, are underlain by Pre-Illinoian and Illinoian glacial deposits, and loess. The Loess-Covered Drift Plains have overall high radon potential. Valley bottoms with wet soils along the Mississippi and Missouri Rivers may have locally moderate to low radon potential because the gas permeability of the soils is extremely low due to the water filling the pore spaces.

The Paleozoic Plateau, in northeastern Iowa, is underlain primarily by Ordovician carbonate and Cambrian sandstone bedrock covered by varying amounts of Quaternary glacial deposits and loess. It was originally thought to have been unglaciated because it is deeply dissected and lacks glacial landforms. However, small patches of Pre-Illinoian drift have been preserved on uplands, indicating that at least part of the area had been glaciated. The Paleozoic Plateau also has high geologic radon potential. Soils developed from carbonate rocks are derived from the residue that remains after dissolution of the calcium carbonate that makes up the majority of the rock, including heavy minerals and metals such as uranium, and thus they may contain somewhat higher concentrations of uranium or uranium-series radionuclides than the parent rock. Residuum from weathered carbonate rocks may be a potential radon source if a structure is built on such a residual soil, or if the residuum constitutes a significant part of a till or other surficial deposit. In some areas underlain by carbonate bedrock, solution features such as sinkholes and caves increase the overall permeability of the rocks in these areas and generally increase the radon potential of these rocks, but few homes are built directly over major solution features.

KANSAS

Almost all of the bedrock exposed at the surface in Kansas consists of sedimentary units ranging in age from Mississippian to Quaternary. Igneous rocks native to Kansas and exposed at the surface are small localized exposures of Cretaceous lamproite in Woodson County and Cretaceous kimberlite in Riley County. Sedimentary rocks of Mississippian age underlie the extreme southeastern corner of the State. They consist primarily of limestones but also include shale, dolomite, chert, sandstone, and siltstone. Pennsylvanian rocks underlie approximately the eastern one-quarter of the State. They consist of an alternating sequence of marine and nonmarine shale, limestone, sandstone, and coal, with lesser amounts of chert and conglomerate. The shales range from green and gray (low organic content) to black (organic rich). Permian rocks are exposed in east-central and southern Kansas and consist of limestone, shale, gypsum, anhydrite, chert, siltstone, and dolomite. Red sandstone and shale of Permian age underlie the Red Hills along the southern border of Kansas.

The Mississippian, Pennsylvanian, and Permian rocks in eastern Kansas have relatively low uranium contents, generally low to moderate permeability and have generally low to moderate geologic radon potential. Homes situated on Pennsylvanian and Permian carbonate rocks (limestones and dolomites) may have locally elevated indoor radon levels if the limestones have developed clayey residual soils and(or) if solution features (karst topography), are present in the area. Because of the geologic variability of these units, the Mississippian, Pennsylvanian, and Permian rock outcrop area has been ranked moderate or variable in overall geologic radon potential. Homes sited on Pennsylvanian black shale units may be subject to locally high indoor radon levels. This may be the case in the Kansas City area, part of which is underlain by black shales.

Some elevated indoor radon levels in the northern part of the Permian outcrop area, specifically in Marshall, Clay, Riley, Geary, and Dickinson Counties, may be related to faults and fractures of the Mid-Continent Rift and Nemaha Uplift. Many of the subsurface faults reach and displace the surface sedimentary rock cover, and the density and spacing of faults and fractures within the rift zone is relatively high. Fault and shear zones are commonly areas of locally elevated radon because these zones typically have higher permeability than the surrounding rocks, because they are preferred zones of uranium mineralization, and because they are potential pathways through which uranium-, radium-, and(or) radon-bearing fluids and gases can migrate.

Cretaceous sedimentary rocks underlie much of north-central and central Kansas, and consist of green, gray, and black shale, sandstone, siltstone, limestone, chalk, and chalky shale. A discontinuous layer of loess of varying thickness covers the Cretaceous rocks in many areas, particularly in the western part of the Cretaceous outcrop area. Cretaceous rocks in Kansas contain sufficient uranium to generate elevated indoor radon levels. Soils developed on Cretaceous rocks have low to moderate permeability, but the shale-derived soils with low permeability to water likely have moderate permeability to soil gas when they are dry due to desiccation cracks. Areas underlain by these rocks have an overall high radon potential. Tertiary rocks cover much of western Kansas, though they are covered by loess deposits in many areas. Tertiary rocks consist of nonmarine sandstone, siltstone, and shale; volcanic ash deposits; and unconsolidated gravel, sand, silt, and clay. Areas underlain by the Tertiary Ogallala Formation have a moderate radioactivity signature and a moderate to high radon potential.

Loess ranging from 0 to more than 30 meters in thickness covers as much as 65 percent of the surface of Kansas and is thickest and most extensive in the western and north-central parts of the State and in proximity to glacial deposits in the northeastern corner of the State. Possible sources for the loess include: (1) glacial outwash, (2) sand dunes in the Arkansas and Cimarron River valleys or elsewhere (such as the Sand Hills of Nebraska), and (3) erosion of Tertiary sedimentary rocks by wind and rivers. Radon potential of loess-mantled areas depends on the thickness and source of the loess. In areas of very thin loess cover, the radon potential of the underlying bedrock is significant, and the loess both generates radon and transmits radon from the underlying bedrock, whereas if the loess is more than 7-10 m thick, it is probably the sole radon source for homes in the area. Loess-covered areas underlain by Cretaceous and Tertiary bedrock appear to have variably moderate to high radon potential across the State, and locally elevated indoor radon levels may be expected anywhere within areas underlain by these units. Areas underlain by loess-covered Pennsylvanian and Permian rocks appear to generate mainly moderate to locally elevated indoor radon levels.

Areas of windblown sand in the Arkansas and Cimarron River valleys have low uranium contents and low radon potential, but few homes are built directly on the sand dunes. The dune sands are intermixed with loess in parts of the Arkansas and Cimarron valleys, and the radon potential may be related to the relative proportions of sand, loess, and bedrock within these areas. Areas underlain by dune sand are expected to have lower radon levels, areas with considerable loess content are expected to have moderate to locally elevated radon levels. Where sand or loess is thin or absent, the radon levels in homes on Tertiary or Cretaceous bedrock are also expected to generally fall into the moderate to high category.

The area within the glacial limit in northeastern Kansas is underlain by discontinuous glacial drift and loess. The glacial deposits consist of a clay, silt, or sand matrix with cobbles and boulders of igneous and metamorphic rocks derived from as far away as the Lake Superior Region and southwestern Minnesota. The glacial deposits are discontinuous and till thickness varies markedly within the area, most likely because post-glacial erosion has removed and redistributed significant amounts of drift. Because the loess in this area is likely derived from nearby glacial drift, and because glacial deposits are known to generate elevated indoor radon levels throughout the northern Great Plains, this area should be considered to have a moderate to locally high radon potential.

MISSOURI

Missouri lies within the stable midcontinent area of the United States. The dominant geologic feature is the Ozark uplift in the southeastern part of the state which forms the Ozark Plateau Province. Precambrian crystalline rocks form the core of the uplift and crop out along its eastern side. Paleozoic sedimentary rocks dip away from this core in all directions. To the north, northwest, and west of the uplift these sedimentary sequences are folded into broad arches and sags. The Precambrian core of the Ozark uplift is primarily granite and rhyolite. Much of this rock is slightly enriched in uranium (2.5-5.0 ppm). The Precambrian core is surrounded by Cambrian and Ordovician sandstone, dolostone, shale, cherty dolostone, chert, and limestone. Pennsylvanian sandstone, shale and clay crop out in the north-central part of the uplift. To the north and west of the uplift, Mississippian and Pennsylvanian shale, limestone, sandstone, clay, coal, and fire clay occur. Silurian and Devonian sedimentary rocks crop out in central Missouri along the Missouri River and along the Mississippi River northeast of St. Louis and in Cape Girardeau and Perry Counties south of St. Louis.

Uraniferous granites and rhyolites, and residuum developed on carbonate rocks in the Ozark Plateau Province are likely to have significant percentages of homes with indoor radon levels exceeding 4 pCi/L. The most likely areas are those where elevated eU values occur. Where structures are sited on somewhat excessively drained soils in this area the radon potential is further increased. Extreme indoor radon levels may be expected where structures are sited on uranium occurrences and where the disturbed zone around a foundation is connected to solution openings in carbonate rocks or to open zones in soil and bedrock caused by mine subsidence.

The Ozark Plateau Province has a moderate overall radon potential. Several areas of somewhat excessively drained soils, scattered uranium occurrences, residual carbonate soils in which uranium has been concentrated, and areas of karst may generate locally elevated indoor radon levels in this area. The St. Francois Mountains have high radon potential owing to elevated levels of uranium in soils developed on granitic and volcanic rocks throughout these mountains and substantial areas of somewhat excessively to excessively drained soils.

The permeability of soils and subsoils in karst areas has been enhanced by solution openings in and near carbonate pinnacles and by zones of solution collapse. Where soils developed on such carbonate rocks are thin, foundations may encounter open bedrock fractures in the limestone. Karst underlies parts of the City and County of St. Louis and may locally cause elevated indoor radon levels. Elevated eU and significant karst development occur in Perry and Cape Girardeau Counties. Structures sited on locally highly permeable karst soils with elevated eU in these two counties will likely have elevated indoor radon levels. Broad karst areas have formed by dissolution of carbonate rocks in the central and western Ozark Plateau, the southern Osage Plain, and along the Mississippi River from Cape Girardeau County to Ralls County. These carbonate regions have overall moderate radon potential. However, areas of intense karst development, elevated uranium in residual soils developed on carbonate, and large areas of somewhat excessively drained to excessively drained soils may cause locally high indoor radon levels to occur.

Several very thin, highly uraniferous (as much as 180 ppm), black, phosphatic shales occur in the Devonian and Pennsylvanian sedimentary rock sequences in the unglaciated Osage Plain of southwestern Missouri. Elevated indoor radon levels may be expected where the foundations of structures intercept the thin Pennsylvanian uraniferous shales or the Chattanooga Shale in the southwestern part of the state from Kansas City south to McDonald and Barry Counties and in north-central Missouri in Boone, Randolph and Macon Counties, or where they intercept well-drained alluvium derived from these rocks. Because these uraniferous shales are so thin, such circumstances are likely to be very site- or tract-specific; thus detailed geologic and soil mapping will be necessary to outline areas of potential problems. Where these shales are jointed or fractured or soils formed on them are somewhat excessively drained on hillslopes, the radon potential is further increased. Residuum developed on limestones associated with these uraniferous shales may also have elevated uranium levels and have significant radon potential. The unglaciated Osage Plain province has a low overall radon potential; however, areas of thin soils underlain by the uraniferous shales in this province have high radon potential with locally extreme values possible.

Along the Missouri and Mississippi River valley floor, alluvial deposits (silt, sand, and gravel) dominate. Loess deposits occur on the flanks of the river valleys in several areas and are especially widespread in Platte, Buchanan, Holt, and Atchison Counties along the Missouri River north of Kansas City. Alluvium and loess along the upper Missouri River Valley upstream from Kansas City seem to be producing elevated indoor radon levels that may be related to the somewhat elevated uranium content of these materials and, possibly, to elevated radon emanation and diffusion associated with well-drained loess deposits. Detailed studies of indoor radon data in this area would be necessary to determine more closely the origin of elevated indoor radon levels. Thin, somewhat excessively drained soils developed on limestone that occur as part of one soil association in the southern suburbs of Kansas City may also be related to elevated indoor radon levels in Jackson County.

The northernmost part of the Mississippi Embayment occupies the southeastern corner of the state and forms the Coastal Plain Province, or southeastern lowlands. This area is underlain by Tertiary and Quaternary alluvium. The Coastal Plain Province has a low radon potential overall. Only one value exceeding 4 pCi/L is reported for a six-county area, and very poorly drained soils are widespread. However, some aeroradiometric anomalies occur in this area, and some excessively drained soils occur locally. Elevated indoor radon levels may be associated with these locales. Although elevated eU occurs over some of the sedimentary rocks in this province, the high soil moisture, the very poorly drained soils, and the low indoor radon values all point towards low radon potential.

The surficial geology north of the Missouri River is dominated by glacial deposits covered with a thin veneer of loess; however, several areas of residual soils developed on underlying sedimentary rocks occur in the eastern and western parts of this region. Residual soils are those soils formed by weathering of the material beneath the soil. These surficial deposits (both glacial deposits and residuum) are generally 50-200 feet thick, but they locally exceed 200 feet along the northern edge of the state. The dissected till plain of northern Missouri has moderate overall radon potential, although elevated indoor radon levels are common in areas of similar geology in adjacent states, particularly Iowa, Nebraska (fig. 1), and Illinois. Except for counties along the Missouri River, the indoor radon data for the counties in the dissected till plain are sparse and appear to be generally in the low to moderate range.

NEBRASKA

Rocks ranging in age from Pennsylvanian to Quaternary are exposed in Nebraska. Pennsylvanian rocks are exposed in southeastern Nebraska and include limestones, shales, and sandstones. Only some of the Upper Pennsylvanian strata are exposed in Nebraska; these rocks are a repeated sequence of marine shales and limestones alternating with nonmarine sandstones and shales, and thin coals. Exposed Permian rocks consist of green, gray, and red shales, limestone, and gypsum. Exposures of Pennsylvanian and Permian rocks are generally limited to valley sides along streams because much of the eastern part of the State is mantled with Pleistocene glacial deposits and loess. Black shales of Pennsylvanian age may constitute a significant radon source where the shales are a source component of the glacial tills.

Cretaceous rocks are exposed in much of eastern Nebraska, in parts of northern and northwestern Nebraska, and along the Republican River Valley. Lower Cretaceous rocks consist of sandstones, shales, and thin coals. Upper Cretaceous rocks consist primarily of shale, limestone, and sandstone. The Upper Cretaceous Pierre Shale consists of gray, brown, and black shales, with thin layers of bentonite, chalk, limestone, and sandstone. Although the permeability of soils developed on the Pierre Shale is listed as low, the shales contain numerous fractures and partings and are likely to have sufficient permeability for radon transport during dry periods. The stratigraphically lowest unit in the Pierre Shale is the Sharon Springs Member, a black shale of widespread occurrence in Nebraska, South Dakota, Kansas, and Colorado. The Sharon Springs Member is exposed in a relatively broad area along the Niobrara and Missouri Rivers from Keya Paha to Cedar Counties and along the Republican River in southern Nebraska. The gray-shale units of the Pierre Shale, while not as uraniferous as the black shale of the Sharon Springs Member, generally contain higher-than-average (i.e., >2.5 ppm) amounts of uranium and are correlated with elevated indoor radon levels in several areas. Outcrops of the Pierre Shale in the northwestern corner of Nebraska have the highest surface radioactivity in the State. Areas underlain by Cretaceous rocks, particularly the Pierre Shale, have overall high radon potential.

Tertiary rocks have the most widespread exposure in the State. The White River Group consists of mudstone, siltstone, sandstone, and thin layers of volcanic ash, and is exposed in the North and South Platte valleys and in northwestern Nebraska. The Arikaree Group overlies the White River Group and consists of siltstone and sandstone. The Tertiary Ogallala Group covers about two-thirds of the State. It consists of sandstone, siltstone, gravel, sand, silt, clay, and thin volcanic ash layers. The Ogallala is covered by the Sand Hills, an area of Quaternary windblown sand deposits, in the north-central part of Nebraska. Pre-Sand Hills sediments of Pliocene and Quaternary age also overlie portions of the Ogallala in this area. The Ogallala, Arikaree, and White River Groups all have high surface radioactivity (for purposes of this report, high radioactivity is defined as greater than 2.5 ppm eU) and are known to host uranium deposits. Soils developed on the Tertiary units have moderate permeability and generate moderate to locally high indoor radon. The White River and Arikaree Groups have significant amounts of uranium-bearing volcanic glass and may be somewhat more likely to generate elevated indoor radon concentrations. Areas underlain by Tertiary sedimentary rocks have overall moderate radon potential. Some homes in this area are likely to have high indoor radon levels, particularly those sited on uranium-bearing parts of the White River and Arikaree Groups in northwestern Nebraska.

Eastern Nebraska and southern Nebraska south of the Platte River are underlain by Permian through Tertiary rocks mantled with Pleistocene glacial deposits of Pre-Illinoian age and loess. The glacial deposits generally consist of a clay, silt, or sand matrix with pebbles and cobbles of limestone, igneous rocks, and quartzite. Source material for the glacial deposits includes locally-derived Permian and Pennsylvanian limestone and shale and Cretaceous sandstone and shale, as well as lesser amounts of sandstone, limestone, shale, and igneous and metamorphic rocks from bedrock sources to the north and northeast. Of the source rocks underlying the glacial deposits and those to the north and northeast, Cretaceous sandstones and shales, Pennsylvanian black shales, and Precambrian crystalline rocks all contain sufficient amounts of uranium-series radionuclides (uranium and(or) radium) to generate radon at elevated levels.

Loess covers most of the glacial deposits in eastern Nebraska as well as bedrock in the south-central part of the State. Loess is a generally good radon source because it consists of silt and clay-sized particles, which are more likely to be associated with radionuclides and have higher emanation coefficients than larger sized particles, and it typically has moderate permeability. Average indoor radon levels are consistently greater than 4 pCi/L in areas underlain by loess-mantled glacial drift. The majority of homes in the area underlain by loess-mantled bedrock in the south-central part of the State also have radon levels exceeding 4 pCi/L, but indoor radon levels are likely to be more variable from house to house in south-central Nebraska, depending on the distribution, thickness, or weathering extent of the loess. Areas underlain by glacial drift and most areas underlain by loess have overall high radon potential. The area mapped as loess between the Platte River and the Sand Hills in the central part of the State has generally moderate radon potential. Homes sited on thicker loess along the north side of the Platte River in Dawson and Buffalo Counties may have locally high indoor radon levels. The Sand Hills have low surface radioactivity and generally low radon potential.

PRELIMINARY GEOLOGIC RADON POTENTIAL ASSESSMENT OF IOWA

by
R. Randall Schumann
U.S. Geological Survey

INTRODUCTION

Many of the rocks and soils in Iowa have the potential to generate levels of indoor radon exceeding the U.S. Environmental Protection Agency's guideline of 4 pCi/L. In a survey of 1381 homes conducted during the winter of 1988-89 by the Iowa Department of Public Health and the EPA, using short-term charcoal canister screening tests, 71 percent of the homes had indoor radon levels exceeding this value. About 7 percent of the screening measurements exceeded 20 pCi/L. The surficial materials covering most of Iowa are glacial and glacially-derived deposits composed of material from local and distant bedrock sources. Radon at levels of concern can be generated from these deposits in most areas of the state. At the scale of this evaluation, all areas of Iowa are considered to have high radon potential.

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

PHYSIOGRAPHIC AND GEOGRAPHIC SETTING

Iowa is part of the Central Lowlands physiographic province and is characterized by a flat to gently rolling landscape. Total relief varies from 146 m (480 ft) in the southeast corner to 509 m (1670 ft) in the northwestern part of Iowa (Prior, 1976). Iowa is subdivided into seven physiographic regions (fig. 1), each having distinct landscape character. The following discussion of physiography is summarized from Prior (1976).

The Paleozoic Plateau, in the northeastern corner of Iowa (fig. 1), was once thought to be completely untouched by Pleistocene glaciers; however, it is now known that at least one glacier entered the region in Pre-Illinoian time (Anderson, 1983). The topography of this area is controlled by the underlying Silurian, Ordovician, and Cambrian bedrock consisting primarily of carbonate rock (limestone and dolomite), sandstone, and shale. Deeply dissected valleys and abundant bedrock outcrops characterize the landscape. Karst topography (sinkholes, caves, and disappearing drainages) occurs locally. The western part of this region is covered with a thin mantle of loess and Pre-Illinoian glacial deposits, although the topography is still largely bedrock-controlled.

Along the southeastern and southwestern edges of the State are the alluvial plains of the Mississippi and Missouri Rivers (fig. 1). These areas are characterized by low-relief alluvial

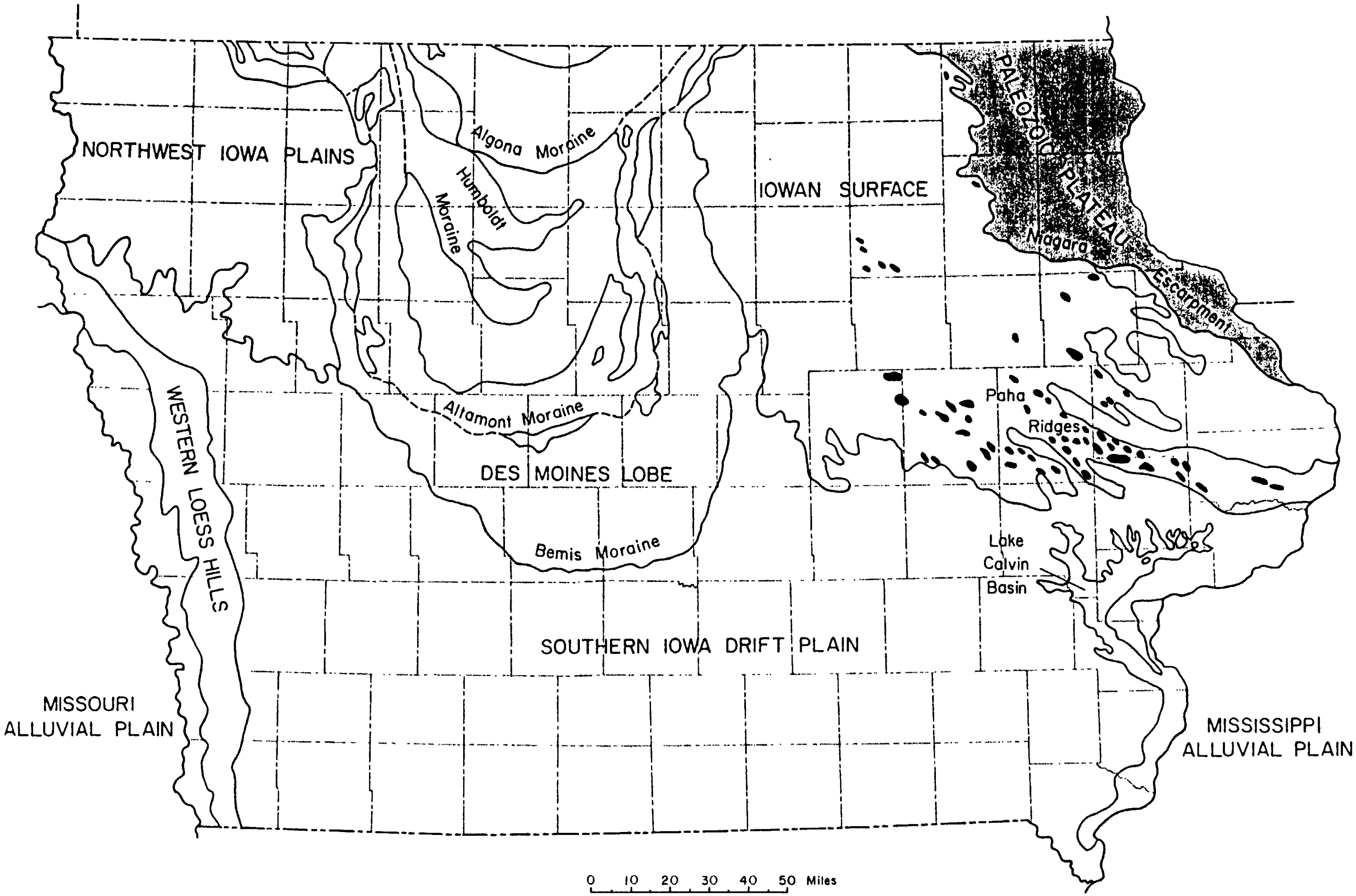


Figure 1. Physiographic regions of Iowa (from Prior, 1976).

plains, terraces, and wetlands. The Western Loess Hills parallel the Missouri River valley (fig. 1). This area is characterized by steep, dissected ridges and hills, and thick loess (windblown silt) deposits.

The Southern Iowa Drift Plain covers most of the southern half of Iowa. Disecction of the gently sloping surface by streams produced the rolling to hilly terrain.

The Northwest Iowa Plains is similar to the High Plains of the Dakotas. This area of loess-mantled, gently rolling landscapes is higher, drier, and less wooded than any other part of Iowa.

The topography of the Des Moines Lobe of north-central Iowa (fig. 1) consists of glacial landforms, including knob and kettle topography, end moraines, eskers, and lakes. It is one of the few areas of the state not covered by loess.

The Iowan Surface is a distinctive topographic region in northeastern Iowa. The land surface is level to gently rolling with long slopes and low relief. The gradual progression from drainage divides to stream valleys gives this area a gently stepped appearance. Loess cover in this region is thin and discontinuous. In the southern third of the Iowan Surface, prominent elongate ridges and isolated elliptical hills of loess, called paha, are common. Karst features have developed in small, localized areas where limestone bedrock is close to the surface.

Iowa is divided into 99 counties (fig. 2). Most of the State's population is rural. Counties with populations exceeding 50,000 are those that include major metropolitan areas, such as Woodbury (Sioux City), Pottawattamie (Council Bluffs), Polk (Des Moines), Black Hawk (Waterloo), Linn (Cedar Rapids), Dubuque (Dubuque), and Scott (Quad Cities) (fig. 3).

GEOLOGY

The geology discussion is divided into three sections: bedrock geology, glacial geology, and the occurrence of uranium in rocks and soils. A bedrock geologic map (fig. 4) shows rock units that underlie glacial deposits or are exposed at the surface in some areas. The glacial deposits are composed of material derived from underlying bedrock and from rock units to the north, northwest, and east. The discussion of bedrock geology is summarized from Anderson (1983) and Iowa Geological Survey (1969). The section on glacial geology is summarized from Wright and Ruhe (1965), Hallberg (1980), and Richmond and others (1991). The reader is encouraged to consult these and other reports for more detailed discussions and maps than presented herein.

Bedrock geology: Rocks ranging in age from Precambrian to Cretaceous underlie the glacial deposits in Iowa. Most of these are sedimentary rocks, including limestone, shale, siltstone, and sandstone, of marine and nonmarine origin. A small area of Precambrian granite directly underlies the glacial deposits in southeastern Pocahontas County (fig. 4). Outcrops of the Precambrian Sioux Quartzite, a pink to red, tightly cemented, quartz sandstone that is the oldest rock exposed in the State, occur in the northwestern corner of Iowa.

Cambrian rocks, primarily sandstones, and Ordovician carbonate rocks (limestones and dolomites), sandstone, and shale are exposed in northeastern Iowa, and Ordovician rocks also directly underlie glacial deposits in other parts of the State (fig. 4). Glauconite is found in several of the Cambrian rock units but is especially abundant in the Lone Rock Formation, in which it has formed "greensands", named for the green color of the glauconite. The Ordovician Maquoketa Formation contains phosphatic dolomites and iron-rich shales. Karst features, including sinkholes, disappearing streams, and caves are common in upland outcrop areas of the Ordovician Galena Group in northeastern Iowa.

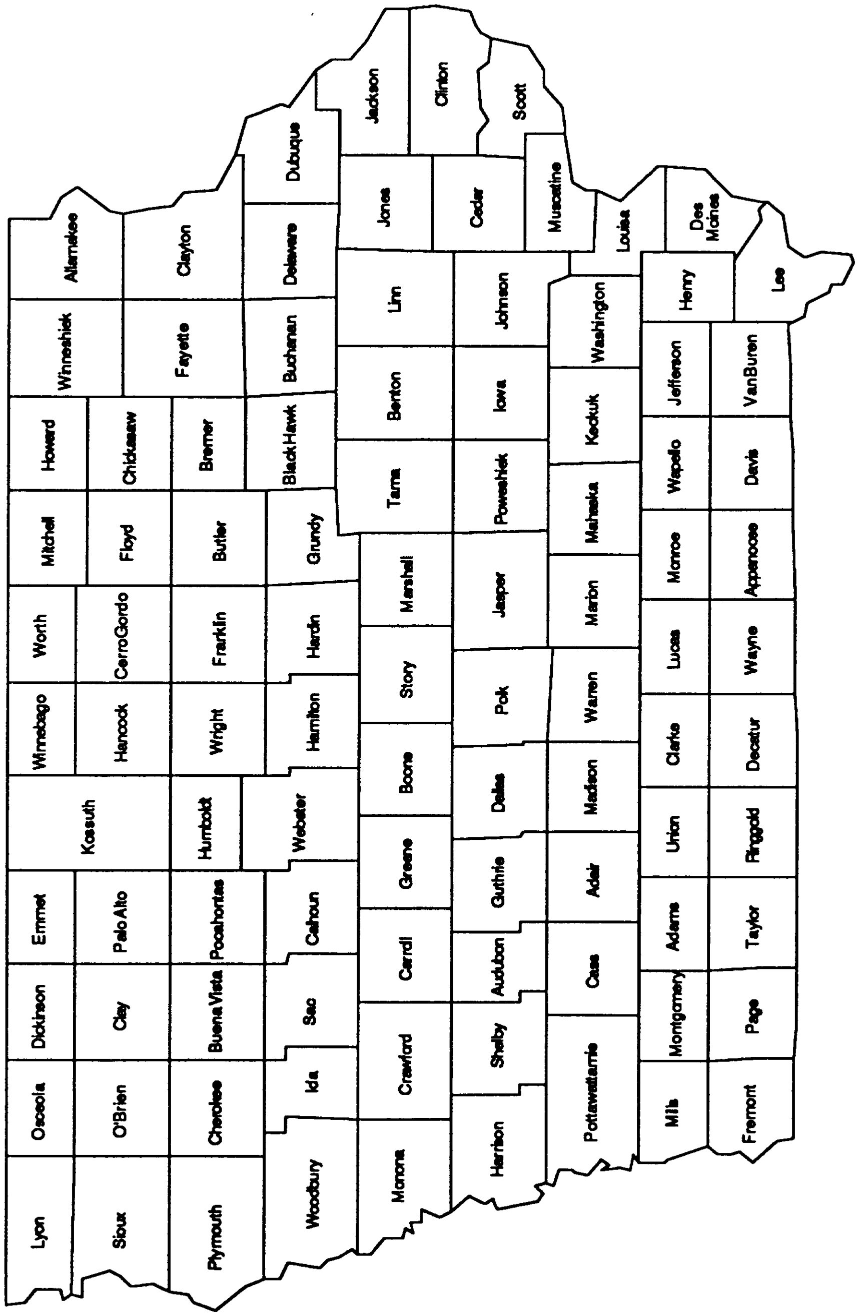


Figure 2. Iowa counties.

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

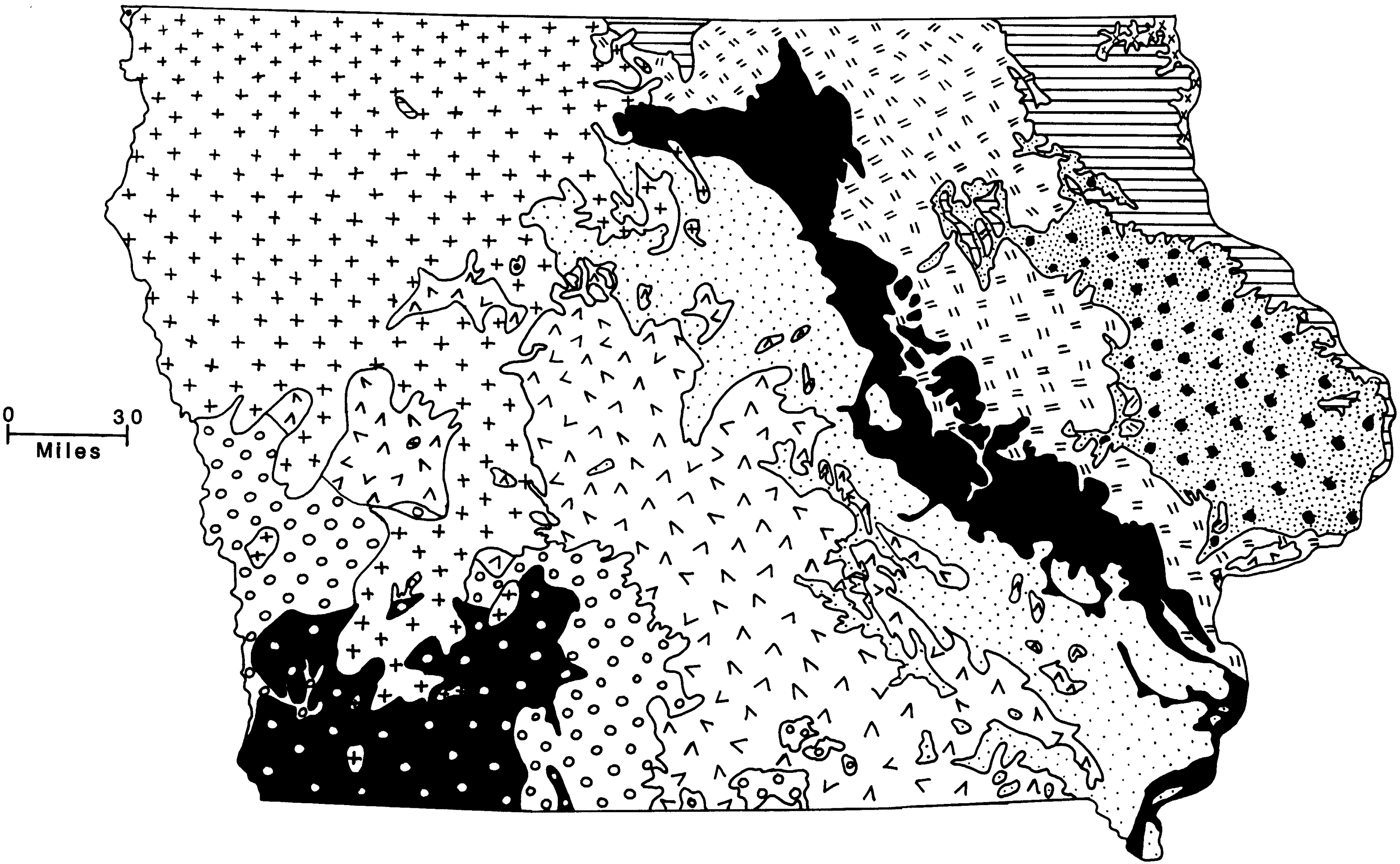


Figure 4. Generalized bedrock geologic map of Iowa (after Iowa Geological Survey, 1969).

Generalized Geologic Map of Iowa
Explanation

Cretaceous

Shale, limestone, and sandstone.

Jurassic

Fort Dodge Beds - Gypsum, red and green shales.

Pennsylvanian

Virgil - Alternating shale and limestone.

Missouri - Alternating shale and limestone with some thin coal beds.

Des Moines - Alternating limestone and shale with some sandstone, thin limestones, and coal.

Mississippian

Shale, limestone, sandy limestone, oolitic limestone, dolomite, cherty dolomite, and siltstone.

Devonian

Upper - Siltstone, shale, dolomite, and limestone.

Middle - Limestone and dolomites, shales in middle.

Silurian

Dolomite, cherty dolomite, and sandy dolomite.

Ordovician

Dolomite, shale, chert, limestone, sandstone, sandy and cherty dolomite.

Cambrian

Sandstone, dolomite, glauconitic sandstone, siltstone, and shale.

Precambrian

Sediments (sandstones), igneous, and metamorphic rocks.

SYSTEM	SERIES	GROUP	FORMATION
QUATERNARY	Pleistocene		
	Holocene Ep.		DeForest
	Wisconsin Ep.		Peoria Loess
			Dows
			Noah Creek
			Sheldon Creek
			Roxana Silt / Pisgah
			St. Charles
	Illinoian Ep.		Glasford
	Pre-Illinoian		Wolf Creek
			Alburnett
TERTIARY			Unnamed alluvial deposits
			"Fullerton"
			"Elk Creek"
			Unnamed alluvial deposits
CRETACEOUS			Pierre
			Niobrara
			Carlile Sh.
			Greenhorn Ls.
			Graneros Sh.
			Dakota / Windrow
JURASSIC			Fort Dodge
PENNSYLVANIAN	Virgilian	Wabaunsee	Wood Siding
			Root
			Stotler
			Pillsbury
			Zeandale
			Willard Sh.
			Emporia
			Auburn Sh.
			Bern
			Scranton
			Howard Ls.
			Severy Sh.
		Shawnee	Topeka
			Calhoun Sh.
			Deer Ck.
			Tecumseh Sh.
			Lecompton
			Kanwaka Sh.
			Oread
		Douglas	Lawrence
			Stranger
	Missourian	Lansing	Stanton
			Vilas Sh.
			Plattsburg
		Kansas City	Lane-Bonner Springs Sh.
			Wyandotte
			Liberty Memorial Sh.
			Iola
			Chanute Sh.
			Dewey
			Nellie Bly Sh.
			Cherryvale
		Bronson	Dennis
			Galesburg Sh.
			Swope
			Ladore Sh.
			Hertha
			Pleasanton
	Desmoinesian	Marmaton	Lost Branch
			"Memorial" Sh.
			Lenapah
			Nowata Sh.
			Altamont

Figure 4 (continued). Stratigraphic column of Iowa, showing names, ages, and relative positions of rock units in the State (from Iowa Geological Survey, 1992).

SYSTEM	SERIES	GROUP	FORMATION
PENNSYLVANIAN			Bandera Sh.
			Pawnee
			Labette
			Stephens Forest
			Morgan School Sh.
			Mouse Ck.
		Cherokee	Swede Hollow
			Floris
			Spoon
	Atokan		Kalo
			Kilbourn
	Morrowan		Caseyville
MISSISSIPPIAN	Chesterian		
	Meramecian		Pella (Ste. Genevieve)
			St. Louis
			"Spergen"
			Warsaw
	Osagean		Keokuk
			\ Burlington
	Kinderhookian		Gilmore City \
			"Maynes Creek"
		North Hill	"Chapin"
			Starrs Cave
			Prospect Hill
			McCraney
DEVONIAN	Upper	"Yellow Spring"	Maple Mill
			Aplington
			Sheffield
			Lime Creek / Sweetland Creek
		Cedar Valley	Shell Rock
			Lithograph City
	Middle		Coralville
			Little Cedar
		Wapsipinicon	Pinicon Ridge
			Otis / Spillvile
			Bertram
SILURIAN			Gower
			Scotch Grove \ Laporte
			Hopkinton \ City
			Waucoma
			Blanding
			Tete des Morts
			Mosalem
ORDOVICIAN	Upper		Maquoketa
		Galena	Dubuque
			Wise Lake
	Middle		Dunleith
			Decorah
			Platteville
		Ancell	Glenwood
			St. Peter Ss.
	Lower	Prairie du Chien	Shakopee
			Oneota
CAMBRIAN	Upper		Jordan
			St. Lawrence
		Tunnel City	Lone Rock
			Adel
			Wonewoc
			Bonneterre
			Eau Claire
			Mt. Simon
PROTEROZOIC			
ARCHEAN			

Figure 4 (continued). Stratigraphic column of Iowa (from Iowa Geological Survey, 1992).

Silurian rocks in Iowa consist almost entirely of dolomite and underlie glacial deposits in eastern Iowa, except where they are exposed in the valleys of the Maquoketa, Wapsipinicon, Cedar, and Mississippi rivers. Solution features such as sinkholes occur in Silurian rocks in some areas of eastern Iowa.

Devonian rocks, consisting of limestone, dolomite, and shale, underlie glacial deposits in a northwest-southeast trending band in east-central Iowa (fig. 4). In southeastern Iowa the Devonian Sheffield Formation consists of dark gray and black shale. Mississippian rocks include limestone and dolomite with lesser amounts of sandstone, siltstone, and shale. Chert is a common constituent of several Mississippian carbonates.

Pennsylvanian rocks occur beneath the glacial cover in the central and south-central part of the State. The Pennsylvanian strata consist of interbedded sequences of shale, siltstone, claystone, coal, and limestone. Coal deposits of economic potential are found in rocks of the Pennsylvanian Cherokee, Marmaton, and Wabaunsee Groups. Some of the Pennsylvanian shales are carbonaceous, or organic-rich (black shales). Thick beds of Pennsylvanian sandstone form cliffs at Ledges and Dolliver State Parks, northwest of Des Moines, and at Wildcat Den State Park east of Muscatine.

Permian and Triassic rocks are absent in Iowa, and Jurassic rocks are represented only by exposures of the Fort Dodge Formation in Webster County, which consists of gypsum, red, gray, and green shale, and minor beds of sandstone and conglomerate.

Cretaceous rocks underlie northwestern and west-central Iowa (fig. 4) and include sandstone, shale, conglomerate, coal, and limestone. Isolated exposures of Cretaceous iron-oxide-cemented (limonitic) sands and gravels occur in Allamakee County in northeast Iowa, but they are too small to be shown on figure 4.

Glacial geology: Pre-Illinoian (formerly called "Nebraskan" and "Kansan") glacial deposits cover most of Iowa, and are at or near the surface in the southern, northwestern, and much of the northeastern parts of the state (fig. 5a). These deposits generally consist of calcareous (calcium-carbonate-rich) loam and clay loam till containing pebbles and cobbles of granite, gabbro, basalt, rhyolite, greenstone, quartzite, chert, diorite, and limestone. Igneous and metamorphic rocks become less abundant in the till as one moves southward; limestone, dolomite, and chert become more abundant in south-central Iowa and limestone and shale become more abundant in southwestern Iowa. Several Pre-Illinoian till units are recognized in Iowa; most of the tills are separated by paleosols (buried soils). Pre-Illinoian tills are covered by a variable thickness of Wisconsinan loess in western, southern, and eastern Iowa (fig. 5b).

Illinoian glacial deposits occur in a relatively small area along the Mississippi River in southeastern Iowa. These deposits consist of loamy to locally sandy till containing clasts of limestone and dolomite, with lesser amounts of igneous and metamorphic rocks, sandstone, and coal fragments. Unlike the Pre-Illinoian and Wisconsinan deposits, which were derived from northern and northwestern sources, Illinoian tills were deposited by the Lake Michigan lobe, which moved from northeast to southwest across Illinois, terminating in eastern Iowa. Illinoian deposits are covered by 1-5 m of loess.

Wisconsinan drift is represented by the Cary and Tazewell drifts (fig. 5a), consisting of calcareous loamy till containing clasts of shale, limestone, and dolomite, with minor amounts of basalt, diabase, granite, chert, and sandstone. Cary drift (now called the Dows Formation) is generally not loess-covered; Tazewell drift is covered by as much as 2 m of loess. Wisconsinan and Pre-Illinoian tills contain significant amounts of expandable clays (smectites).

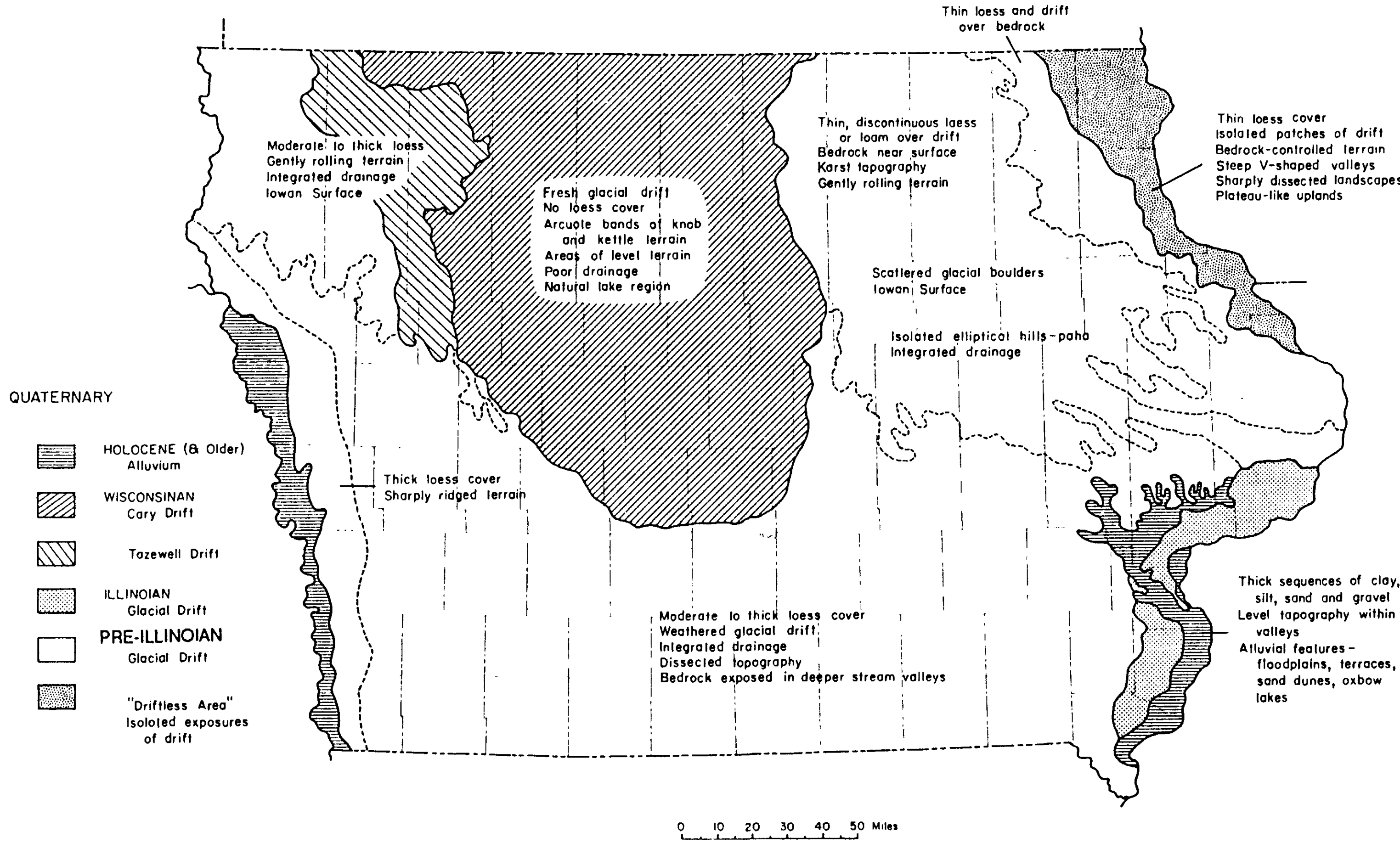


Figure 5a. Glacial features and surface materials map of Iowa (modified from Prior, 1976).

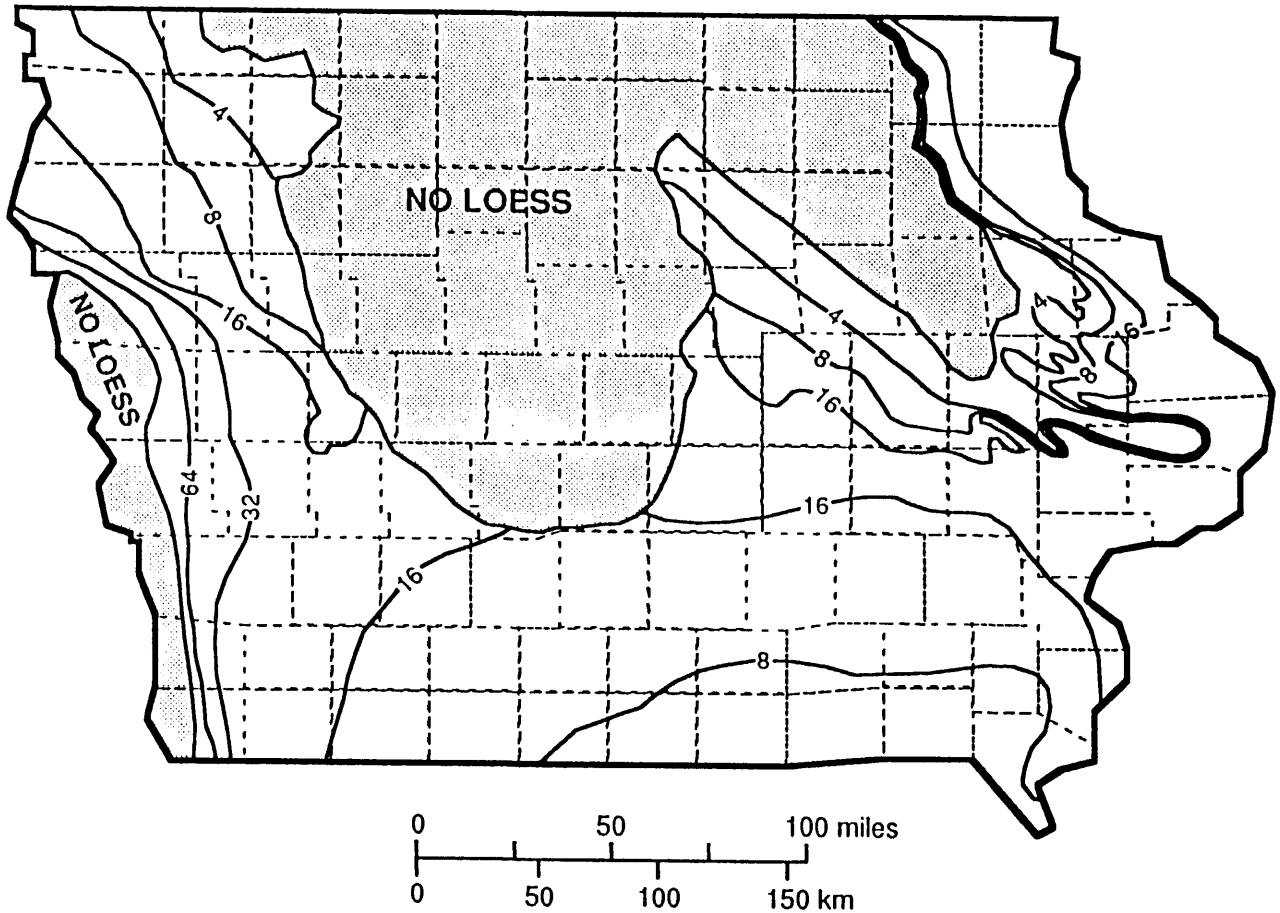


Figure 5b. Loess thickness in Iowa, in feet (after Anderson, 1983).

The Paleozoic Plateau of northeastern Iowa was originally thought to have been unglaciated because it is deeply dissected and lacks glacial landforms, and was formerly called the "Dirftless Area". However, small patches of Pre-Illinoian drift have been preserved on uplands, indicating that at least part of the area had been glaciated (Anderson, 1983).

Uranium geology: No uranium deposits or occurrences of commercial grade are known to exist in Iowa, although uranium deposits of potentially commercial grade may exist in the subsurface at the contact between the Precambrian Sioux Quartzite and underlying igneous and metamorphic rocks in northwestern Iowa (Anderson and Bunker, 1982). However, some rock types in Iowa likely contain sufficient uranium or uranium-series radionuclides to generate radon at levels of concern. Because most of the glacial deposits in Iowa contain a mixture of locally-derived and transported bedrock source components, and because few studies of uranium in tills or loess are known to exist, it is important to consider the occurrence and abundance of radon sources in bedrock in light of the presence and relative abundances of such rocks as source components of the tills.

Black shales are well-known concentrators of uranium and are known causes of radon problems in a number of areas in the United States. Uranium is concentrated with organic compounds in the shales or in phosphate layers within the shales (Ostrom and others, 1955). Two rock units, the Devonian Sheffield and Maple Mill Formations and the Pennsylvanian Cherokee Group, are identified as containing black shale beds in the subsurface (Iowa Geological Survey, 1969).

Carbonate rocks (limestone, dolomite) may also constitute a source for low-level uranium concentrations. Although the carbonate rocks themselves are low in uranium and radium, soils and residual deposits developed from these rocks are derived from the dissolution of the calcium carbonate that makes up the majority of the rock. As the calcium carbonate is dissolved away, the soils become relatively enriched in the remaining impurities—predominantly base metals, including uranium. Rinds containing relatively high concentrations of uranium and uranium minerals can be formed on the surfaces of rocks involved with calcium carbonate dissolution.

SOILS

Udolls (Mollisols of temperate climates) cover most of Iowa. Most soils in southern Iowa are Agriudolls, moist soils with a subsurface horizon of clay accumulation (U.S. Soil Conservation Service, 1987). Soils in northern Iowa are generally Hapludolls, which generally lack a subsurface horizon of clay accumulation. Hapludalfs, moist soils with a thin subsurface clay horizon, occur along the Mississippi River and its tributaries in eastern Iowa. Most soils of Iowa have loam, sandy loam, silt loam, silty clay loam, or clay loam textures (Oschwald and others, 1965). Soils in the northern half of Iowa generally have moderate permeability, whereas most of the southern half of the State is covered by soils with low permeability (fig. 6).

INDOOR RADON DATA

Indoor radon data from 1381 homes sampled in the State/EPA Residential Radon Survey conducted in Iowa during the winter of 1988-89 are shown in figure 7 and listed in Table 1. The data are derived from short-term (2-7 day) screening measurements using charcoal canister radon detectors placed in the lowest level of the home (in Iowa, usually the basement). Data are only shown on figure 7 for those counties with 5 or more data values. The overall average indoor radon value for the State was 8.9 pCi/L. The maximum value recorded in the survey was 130 pCi/L in

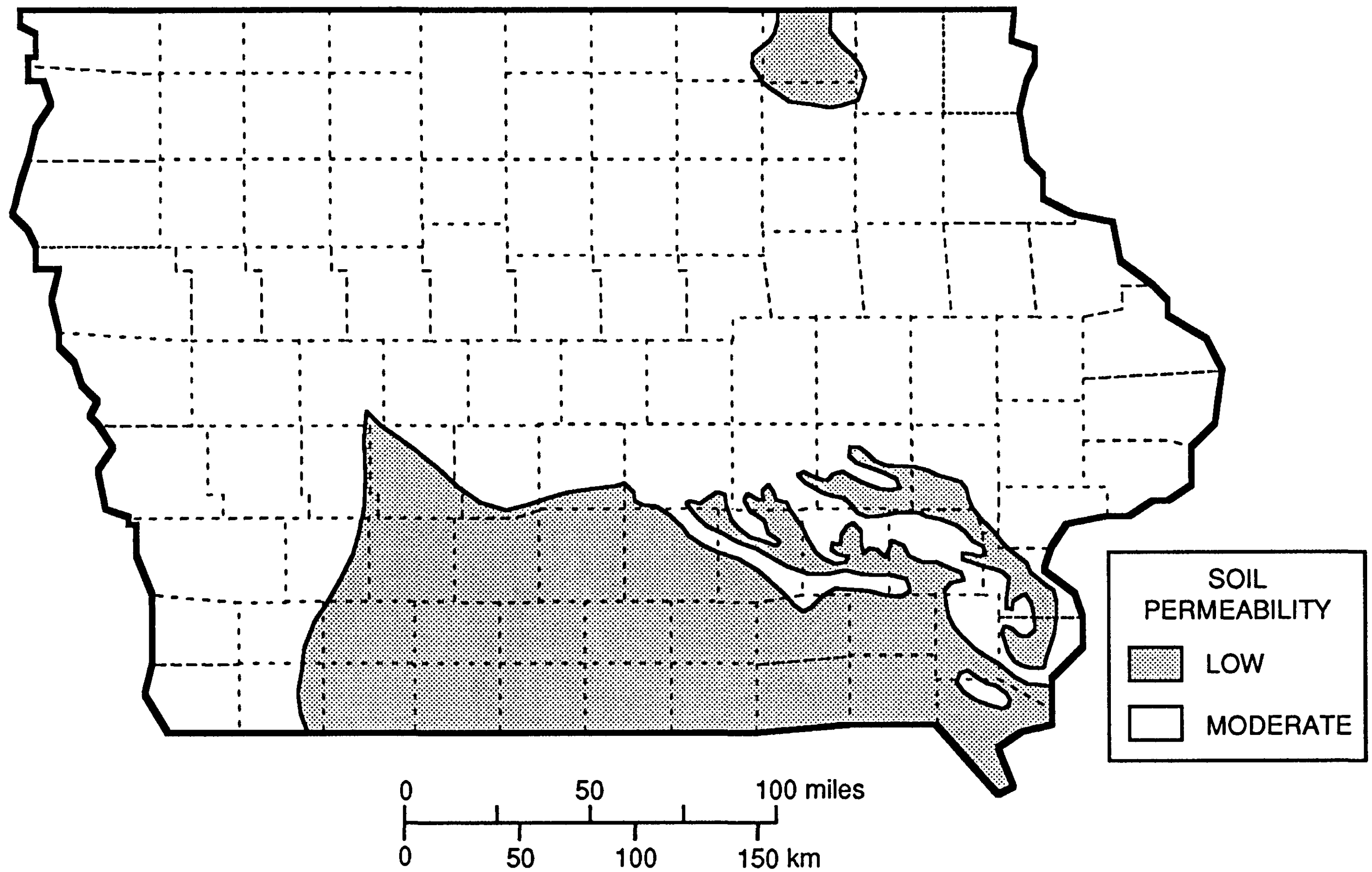
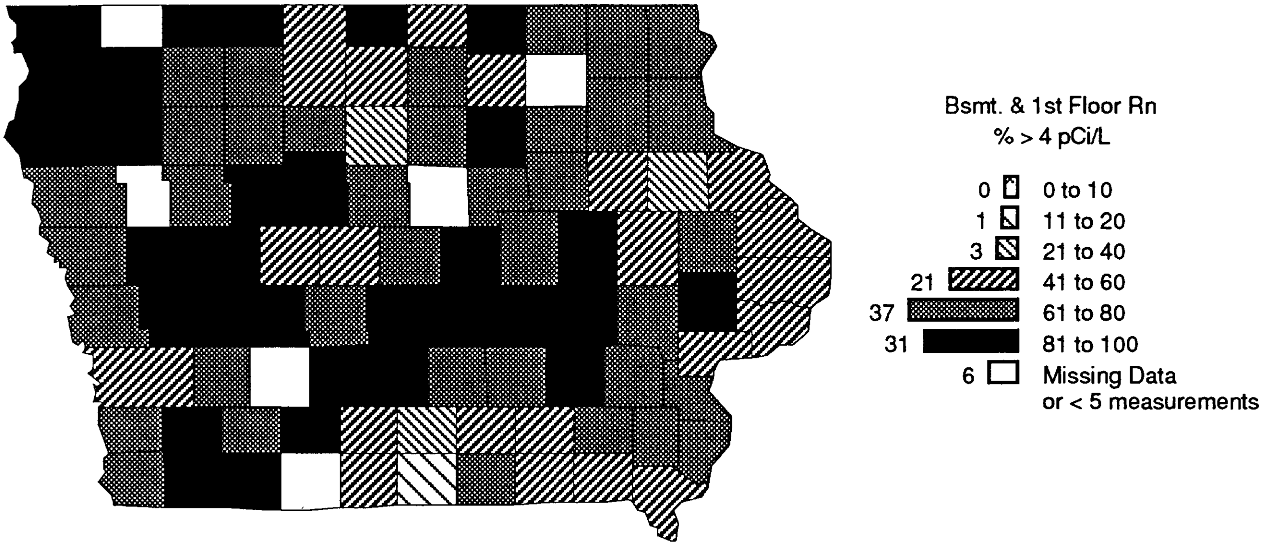


Figure 6. Generalized soil permeability map of Iowa (data from Oschwald and others, 1965).



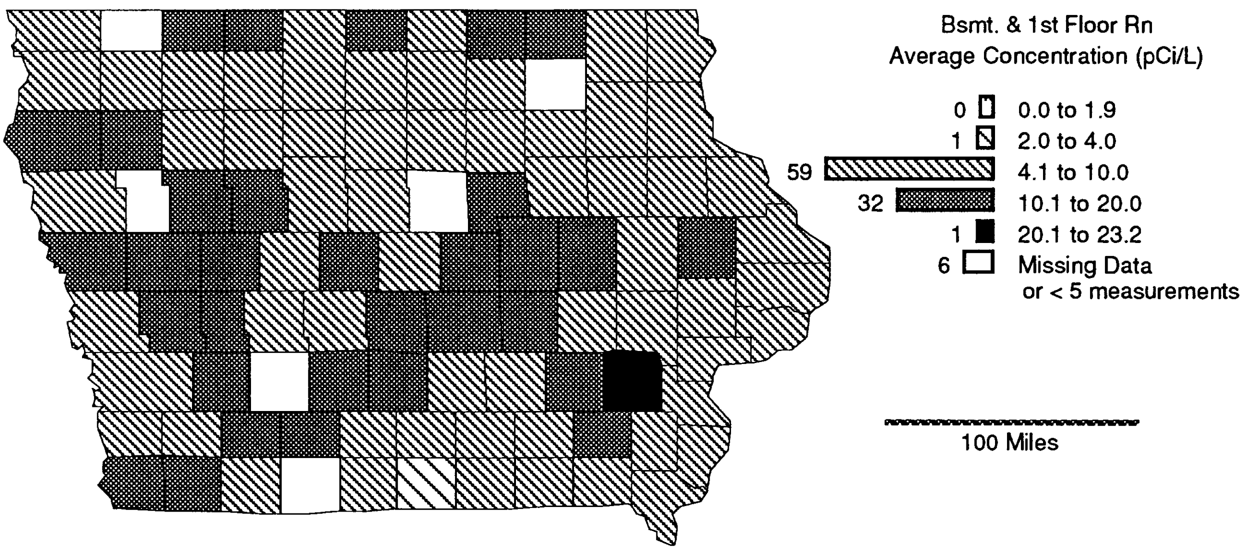


Figure 7. Screening indoor radon data from the EPA/State Residential Radon Survey of Iowa, 1988-89, for counties with 5 or more measurements. Data are from 2-7 day charcoal canister tests. Histograms in map legends show the number of counties in each category. The number of samples in each county (See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

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

COUNTY	NO. OF MEAS.	MEAN	GEOM. MEAN	MEDIAN	STD. DEV.	MAXIMUM	%>4 pCi/L	%>20 pCi/L
ADAIR	3	10.1	6.3	13.1	7.8	15.9	67	0
ADAMS	5	12.8	9.6	12.0	7.6	20.0	80	0
ALLAMAKEE	6	8.1	4.7	9.8	6.1	13.9	67	0
APPANOOSE	13	8.1	5.1	6.3	7.6	30.0	77	8
AUDUBON	6	13.8	13.0	12.6	5.2	21.6	100	17
BENTON	11	12.6	10.7	11.6	8.1	32.3	91	18
BLACK HAWK	55	7.6	5.5	5.6	8.4	53.5	67	5
BOONE	11	11.4	7.0	4.3	12.3	36.5	55	18
BREMER	17	8.3	6.1	5.9	8.8	39.2	65	6
BUCHANAN	14	4.6	3.6	3.8	3.1	10.4	50	0
BUENA VISTA	17	7.1	6.2	7.7	3.6	15.8	76	0
BUTLER	17	8.4	7.0	6.4	5.8	22.0	88	6
CALHOUN	5	11.9	8.6	7.5	12.3	33.5	100	20
CARROLL	17	12.3	10.2	9.6	9.4	42.9	94	12
CASS	14	10.8	8.8	8.3	6.6	23.6	79	7
CEDAR	6	7.9	6.3	8.8	4.3	12.4	83	0
CERRO GORDO	24	6.7	5.1	4.3	5.4	19.6	63	0
CHEROKEE	15	11.7	10.2	10.5	6.1	27.3	93	7
CHICKASAW	4	5.3	4.3	4.4	3.9	10.5	50	0
CLARKE	9	7.1	4.8	7.0	5.6	15.1	56	0
CLAY	9	7.0	6.0	5.4	4.5	16.3	78	0
CLAYTON	13	8.4	4.8	6.7	9.1	33.5	62	8
CLINTON	15	6.5	3.9	4.8	6.2	22.9	60	7
CRAWFORD	12	10.6	9.7	9.6	5.1	23.2	100	8
DALLAS	10	9.3	6.2	7.3	8.5	27.7	70	10
DAVIS	8	5.8	3.8	4.6	5.5	17.3	50	0
DECATUR	11	6.7	5.0	4.8	7.0	26.7	55	9
DELAWARE	9	4.7	3.7	2.9	3.9	13.0	33	0
DES MOINES	24	8.0	5.8	5.8	6.3	22.1	71	8
DICKINSON	12	10.2	8.6	7.7	6.6	22.6	92	8
DUBUQUE	38	5.6	4.0	5.0	4.7	24.0	58	3
EMMET	11	12.5	7.7	6.1	18.8	68.3	91	9
FAYETTE	11	8.3	5.3	7.2	6.9	22.4	73	9
FLOYD	12	5.0	3.9	4.3	4.4	17.9	58	0
FRANKLIN	17	7.5	6.5	7.9	3.8	15.4	76	0
FREMONT	5	11.9	10.0	13.0	6.4	19.8	80	0
GREENE	8	6.1	3.9	4.6	5.9	18.5	50	0
GRUNDY	6	10.2	7.1	8.2	8.5	24.3	67	17
GUTHRIE	10	9.1	8.0	7.4	4.8	19.9	90	0
HAMILTON	10	7.4	6.0	6.4	5.1	18.6	70	0
HANCOCK	8	4.3	3.4	4.0	2.5	8.1	50	0

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

COUNTY	NO. OF MEAS.	MEAN	GEOM. MEAN	MEDIAN	STD. DEV.	MAXIMUM	%>4 pCi/L	%>20 pCi/L
HARDIN	4	10.9	9.6	11.2	5.6	16.8	100	0
HARRISON	12	7.1	5.5	4.8	5.1	17.4	67	0
HENRY	7	8.8	7.2	7.2	5.8	18.9	71	0
HOWARD	10	18.5	7.2	6.2	39.3	130.1	70	10
HUMBOLDT	9	9.3	6.7	9.9	6.3	17.2	67	0
IDA	3	10.0	9.5	10.0	3.7	13.7	100	0
IOWA	8	9.0	7.0	8.2	5.5	18.8	88	0
JACKSON	9	9.1	6.2	5.2	9.8	33.0	56	11
JASPER	13	12.5	9.4	11.1	9.9	37.6	85	15
JEFFERSON	13	13.3	5.6	8.8	16.2	59.0	62	23
JOHNSON	16	7.3	5.7	7.0	4.2	15.1	75	0
JONES	8	10.8	6.2	5.5	14.8	46.5	63	13
KEOKUK	7	17.5	11.4	10.9	13.6	35.0	86	43
KOSSUTH	19	5.4	3.7	4.3	4.9	21.1	58	5
LEE	17	5.5	3.9	3.9	4.8	20.5	47	6
LINN	41	6.3	3.7	3.7	7.4	32.6	44	10
LOUISA	8	6.5	5.7	5.8	3.7	13.0	75	0
LUCAS	8	4.3	3.0	2.5	4.3	13.9	38	0
LYON	11	8.4	8.2	8.3	2.3	12.1	100	0
MADISON	11	10.4	8.5	10.4	5.5	23.0	91	9
MAHASKA	12	9.1	7.4	8.5	5.7	19.8	75	0
MARION	33	8.5	4.9	7.5	7.0	30.5	67	9
MARSHALL	10	10.5	9.7	10.9	4.3	16.9	100	0
MILLS	12	9.2	6.9	8.1	8.0	31.1	67	8
MITCHELL	6	13.0	11.2	12.8	7.2	21.3	100	33
MONONA	10	10.2	8.8	10.4	5.2	21.0	80	10
MONROE	11	5.8	4.3	3.6	4.6	14.7	45	0
MONTGOMERY	7	9.5	8.8	9.4	3.7	14.1	100	0
MUSCATINE	20	6.4	4.1	4.4	6.4	23.0	60	10
O'BRIEN	13	9.1	8.2	8.1	3.9	15.9	92	0
OSCEOLA	4	7.0	6.5	5.9	3.4	11.9	100	0
PAGE	17	10.9	8.6	10.8	7.1	30.2	82	12
PALO ALTO	10	7.1	5.6	7.8	4.2	14.7	70	0
PLYMOUTH	15	16.4	11.4	9.2	15.3	49.9	87	20
POCAHONTAS	6	8.1	6.4	5.8	6.1	17.7	67	0
POLK	77	11.4	8.4	8.8	8.2	45.6	86	12
POTTAWATTAMIE	45	6.3	4.4	5.0	4.7	20.4	56	2
POWESHIEK	12	15.9	8.8	12.8	11.5	37.4	92	33
RINGGOLD	3	15.0	14.5	13.2	4.9	20.5	100	33
SAC	9	11.4	9.1	10.9	8.7	32.2	78	11
SCOTT	35	8.2	5.2	6.7	8.5	47.4	60	6
SHELBY	14	12.4	10.6	12.3	6.6	25.2	93	14
SIOUX	21	8.6	7.9	8.1	3.3	14.2	90	0

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

COUNTY	NO. OF MEAS.	MEAN	GEOM. MEAN	MEDIAN	STD. DEV.	MAXIMUM	%>4 pCi/L	%>20 pCi/L
STORY	19	7.8	5.9	6.8	6.1	25.9	68	5
TAMA	8	11.3	8.0	8.9	8.9	27.0	75	25
TAYLOR	6	9.6	8.4	8.1	5.4	19.0	83	0
UNION	11	10.3	8.6	9.2	5.9	21.3	82	9
VAN BUREN	7	8.3	5.7	8.7	6.5	17.2	57	0
WAPELLO	15	7.7	5.2	4.1	10.2	42.8	53	7
WARREN	29	13.5	8.4	9.2	19.2	106.9	86	10
WASHINGTON	7	23.2	8.5	9.8	33.0	92.8	71	29
WAYNE	6	2.5	1.6	2.4	1.9	5.1	17	0
WEBSTER	11	6.7	6.1	5.9	3.1	13.0	91	0
WINNEBAGO	10	10.4	9.1	8.0	6.4	25.9	90	10
WINNESHIEK	10	8.6	6.1	5.6	7.5	25.7	70	10
WOODBURY	62	9.1	6.0	6.9	9.5	65.4	71	6
WORTH	6	8.3	4.7	3.7	10.2	27.7	50	17
WRIGHT	10	7.0	4.1	3.6	7.5	25.2	40	10

Howard County. Only 7 percent of the homes tested in the state had indoor radon levels exceeding 20 pCi/L. Except for Wayne County, which had a screening indoor radon average of 2.5 pCi/L, every county for which data are shown in figure 7 had an indoor radon average greater than 4 pCi/L in the State/EPA survey.

Long-term radon measurements on the main floors of 213 homes in central and eastern Iowa yielded geometric means of 2.1 pCi/L in central Iowa and 1.6 pCi/L in the eastern part of the State (Wiffenbach and Hart, 1990). Significant differences in radon levels among different categories of homes were attributed to differences in ventilation rates, basement construction, and extent of cracks and openings in basement floors and walls. Fifty homes with private wells were also tested for radon in water, yielding an average radon concentration of 490 pCi/L, a geometric mean of 350 pCi/L, and a maximum radon concentration of 1700 pCi/L (Wiffenbach and Hart, 1990).

GEOLOGIC RADON POTENTIAL

An aerial radiometric map of Iowa (fig. 8) shows gamma radioactivity of surficial deposits and soils. A large area of low (< 1.5 ppm) equivalent uranium (eU) in the northern part of the State corresponds roughly to the Des Moines lobe and the Iowan erosion surface. Most of the remainder of the State has eU values in the 1.5-2.5 ppm range (fig. 8). Areas of eU greater than 2.5 ppm occur in the east-central and west-central parts of the State (fig. 8), but do not appear to correlate with specific surface features. The eU signature of surface deposits in Iowa, especially the Des Moines lobe deposits and other areas of thin loess cover (fig. 5b), seems lower than would be expected in light of the elevated indoor radon levels. Recent studies (for example, Lively and others, 1991; Schumann and others, 1991) suggest that much of the radium in the near-surface soil horizons may have been leached and transported downward in the soil profile, giving a low surface radiometric signature while generating significant radon at depth (1-2 m? or greater) to produce elevated indoor radon levels. In general, soils developed from glacial deposits can be more rapidly leached of mobile ions than their bedrock counterparts, because crushing and grinding of the rocks by glacial action gives soil weathering agents (mainly moisture) better access to soil and mineral grain surfaces (Jenny, 1935). Grinding of the rocks increases the mobility of uranium and radium in the soils by exposing them at grain surfaces, enhancing radionuclide mobility and radon emanation. In addition, poorly-sorted glacial drift may in many cases have higher permeability than the bedrock from which it is derived. Cracking of clayey glacial soils during dry periods can create sufficient permeability for convective radon transport to occur. This may be an important factor causing elevated radon levels in areas underlain by clay-rich glacial deposits. Loess-covered areas have a higher radiometric signature than loess-free areas, and also appear to correlate roughly with higher average indoor radon levels than loess-free areas, although all areas of Iowa have average indoor radon levels exceeding 4 pCi/L.

Areas underlain by carbonate bedrock in the northeastern part of the state also have high geologic radon potential. As discussed in the uranium section of this report, soils developed from carbonate rocks are derived from the residue that remains after dissolution of the calcium carbonate that makes up the majority of the rock, including heavy minerals and metals such as uranium, and thus they may contain somewhat higher concentrations of uranium or uranium-series radionuclides than the parent rock. Residuum from weathered carbonate rocks may be a potential radon source if a structure is built on such a residual soil, or if the residuum constitutes a significant part of a till or other surficial deposit. In some areas underlain by carbonate bedrock, solution features such as

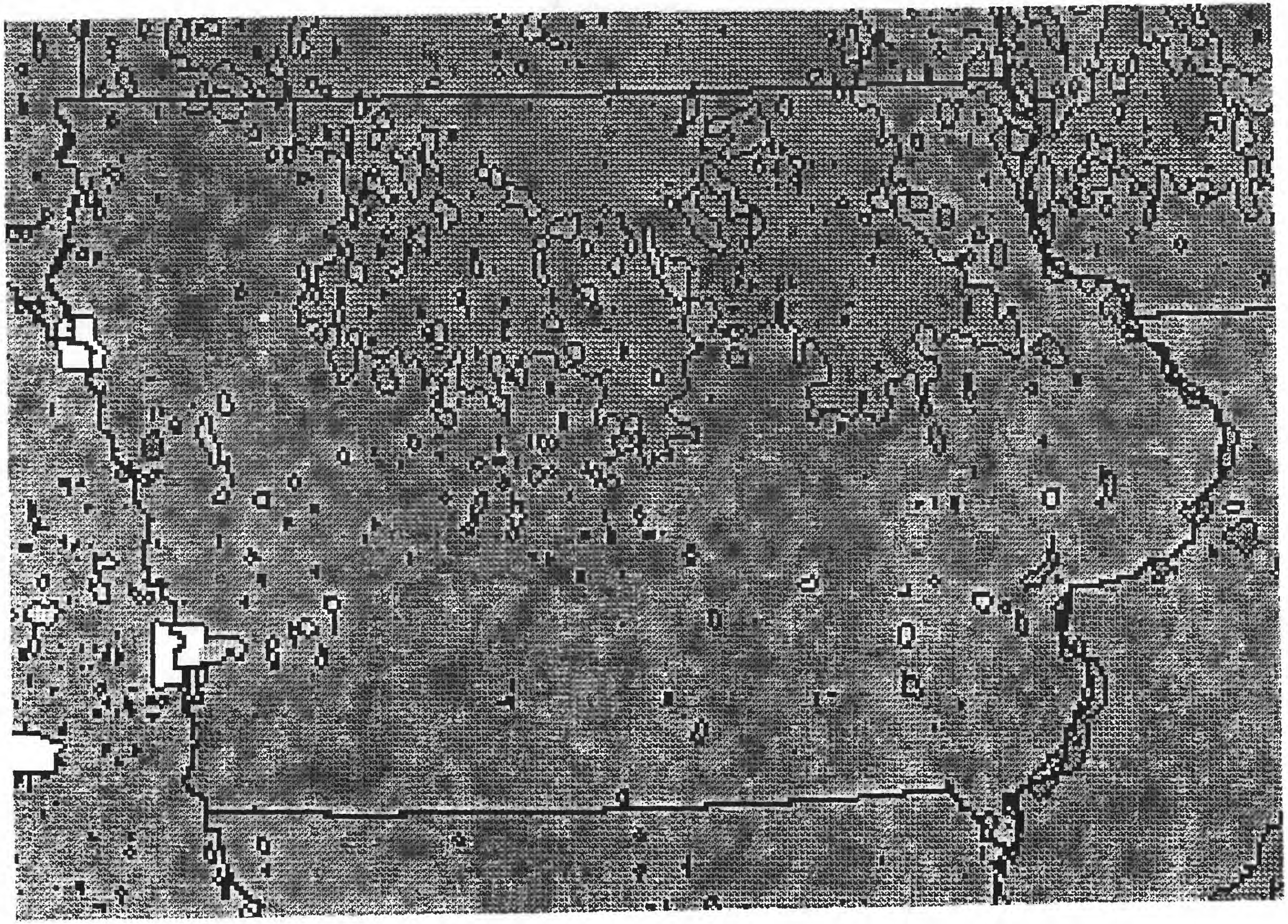


Figure 8. Aerial radiometric map of Iowa (after Duval and others, 1989). Contour lines at 1.5 and 2.5 ppm equivalent uranium (eU). Pixels shaded from 0 to 6.0 ppm eU at 0.5 ppm eU increments; darker pixels have lower eU values; white indicates no data.

sinkholes and caves increase the overall permeability of the rocks in these areas and generally increase the radon potential of these rocks, but these features provide unstable foundations for building construction, so homes are generally not built in such areas.

RADON INDEX AND CONFIDENCE INDEX SCORES

For the purposes of this assessment, Iowa is divided into four geologic radon potential areas (fig. 9) and each area assigned Radon Index (RI) and Confidence Index (CI) scores (Table 2). The Radon Index is a semiquantitative measure of radon potential based on geologic, soil, and indoor radon factors, and the Confidence Index is a measure of the relative confidence of the RI assessment based on the quality and quantity of data used to make the predictions (see the Introduction chapter for more information on the methods and data used).

The Des Moines Lobe is underlain by Wisconsinan-age loam tills. It has a high radon potential (RI=12) with high confidence (CI=10).

The Iowan Surface is underlain by Pre-Illinoian glacial deposits and loess. As shown in figure 9, the Iowan Surface radon potential area includes only that part of the Iowan Surface that is covered by less than 4 ft of loess (see figure 5b). The Iowan Surface has a high radon potential (RI=12) with high confidence (CI=10).

The Paleozoic Plateau is underlain primarily by Ordovician carbonate and Cambrian sandstone bedrock covered by varying amounts of Quaternary glacial deposits and loess. This area has a high radon potential (RI=13) with high confidence (CI=10).

The Loess-Covered Drift Plains (fig. 9) covers the remainder of the State, and is underlain by Pre-Illinoian and Illinoian glacial deposits, and loess. Valley bottoms with wet soils along the Mississippi and Missouri Rivers may have locally moderate to low radon potential because the gas permeability of the soils is extremely low due to the water filling the pore spaces. The Loess-Covered Drift Plains has an overall high radon potential (RI=13) with high confidence (CI=10).

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 Iowa. See figure 9 for locations of areas.

	AREA							
	Des Moines Lobe		Iowan Surface		Paleozoic Plateau		Loess-covered Drift Plains	
FACTOR	RI	CI	RI	CI	RI	CI	RI	CI
INDOOR RADON	3	3	3	3	3	3	3	3
RADIOACTIVITY	1	2	1	2	2	2	2	2
GEOLOGY	3	3	3	2	3	2	3	2
SOIL PERM.	2	3	2	3	2	3	2	3
ARCHITECTURE	3	--	3	--	3	--	3	--
GFE POINTS	0	--	0	--	0	--	0	--
TOTAL	12	10	12	10	13	10	13	10
RANKING	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH

RADON INDEX SCORING:

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

Possible range of points = 3 to 17

CONFIDENCE INDEX SCORING:

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

Possible range of points = 4 to 12

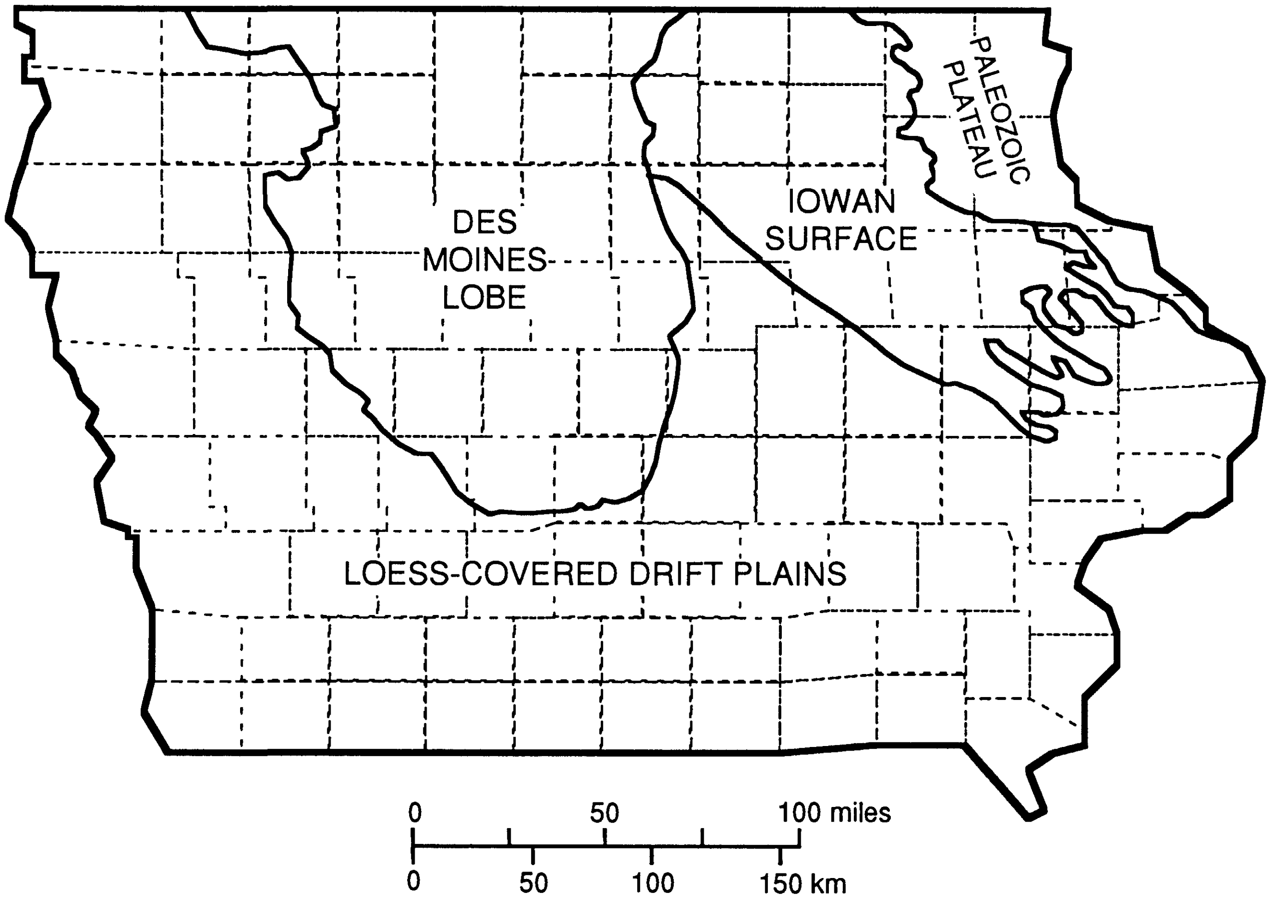


Figure 9. Geologic radon potential areas of Iowa. See Table 1 for radon potential scores of areas.

REFERENCES USED IN THIS REPORT AND GENERAL REFERENCES PERTAINING TO RADON IN IOWA

Anderson, W.I., 1983, Geology of Iowa over two billion years of change: Ames, Iowa, The Iowa State University Press, 268 p.

Anderson, R.R., and Bunker, W.J., 1982, Oil and uranium potential in Iowa: Iowa Geology, no. 7, p. 14-16.

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

Hallberg, G.R., 1980, Pleistocene stratigraphy in east-central Iowa: Iowa Geological Survey Technical Information Series no. 10, 168 p.

Iowa Geological Survey, 1969, Geologic map of Iowa, scale 1:500,000.

Jenny, H., 1935, The clay content of the soil as related to climatic factors, particularly temperature: Soil Science, v. 40, p. 111-128.

Lively, R., Steck, D., and Brasaemle, B., 1991, A site study of soil characteristics and soil gas radon in Rochester, Minnesota: Minnesota Center for Urban and Regional Affairs report CURA 91-2, 15 p.

Oschwald, W.R., Riecken, F.F., Dideriksen, R.I., Scholtes, W.H., and Schaller, F.W., 1965, Principal soils of Iowa: Iowa State University Cooperative Extension Service Special Report 42, 77 p.

Ostrom, M.E., Hopkins, M.E., White, W.A., and McVicker, L.D., 1955, Uranium in Illinois black shales: Illinois State Geological Survey Circular 203, 15 p.

Prior, Jean Cutler, 1976, A regional guide to Iowa landforms: Iowa Geological Survey Educational Series 3, 72 p.

Richmond, G.R., Fullerton, D.S., and Christiansen, Ann C., (eds.), 1991, Quaternary Geologic Atlas of the United States: U.S. Geological Survey Miscellaneous Investigations Map I-1420, sheet NK-15, Des Moines 4°x6° quadrangle, scale 1:1,000,000.

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

U.S. Soil Conservation Service, 1987, Soils: U.S. Geological Survey National Atlas sheet 38077-BE-NA-07M-00, scale 1:7,500,000.

Wiffenbach, C.V., and Hart, T.J., 1990, Radon measurements in houses in eastern and central Iowa: Journal of the Iowa Academy of Science, v. 97, p. 98-104.

Wright, H.E., Jr., and Ruhe, R.V., 1965, Glaciation of Minnesota and Iowa, *in* Wright, H.E., Jr., and Frey, D.G. (eds.), The Quaternary of the United States: Princeton, NJ, Princeton University Press, p. 29-41.

PRELIMINARY GEOLOGIC RADON POTENTIAL ASSESSMENT OF KANSAS

by
R. Randall Schumann
U.S. Geological Survey

INTRODUCTION

Many of the rocks and soils in Kansas have the potential to generate levels of indoor radon exceeding the U.S. Environmental Protection Agency's guideline of 4 pCi/L. In a survey of 2009 homes conducted during the winter of 1987-88 by the State of Kansas and the EPA, 25 percent of the homes had indoor radon levels exceeding this value. At the scale of this evaluation, all areas in Kansas have moderate/variable or high geologic radon potential.

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

PHYSIOGRAPHIC AND GEOGRAPHIC SETTING

Kansas lies within the Great Plains and Central Lowlands physiographic provinces of the United States. Within the State the landscape is subdivided into 11 physiographic areas (fig. 1). The extreme southeastern corner of the State is part of the Ozark Plateau, in which beds of limestone and chert form hills similar to those in Missouri and Arkansas. The Cherokee Lowlands lie adjacent to the Ozark Plateau in southeastern Kansas. This area is relatively flat and poorly drained because it is underlain by easily erodible sandstones and shales. The Cherokee Lowlands is a major coal-producing area. Underground mining for coal and metals occurred in the Cherokee Lowlands and Ozark Plateau regions (Wilson, 1984). The Osage Cuestas (fig. 1) is an area of parallel ridges, with a steep escarpment on their east sides and a gentle slope on their west sides, formed by gently dipping, alternating resistant and soft rocks. The Chautauqua Hills extend northward from the southern border of the State into the Osage Cuestas region. The Chautauqua Hills are rolling uplands capped by sandstones and limestones (Steeples and Buchanan, 1983; Wilson, 1984). To the west of the Chautauqua Hills are the Flint Hills, grassy uplands formed on limestone and chert with intervening lowlands underlain by shales. Because chert is more resistant to erosion than limestone, the Flint Hills are significantly higher than the surrounding landscape (Wilson, 1984). The Wellington-McPherson Lowlands lie west of, and adjacent to, the Flint Hills (fig. 1). The Red Hills, along the central southern border of Kansas, are composed of red shale and siltstone, called "red beds", capped by gray gypsum and dolomite, and are characterized by butte-and-mesa topography (Wilson, 1984). In Meade and Clark Counties, on the western border

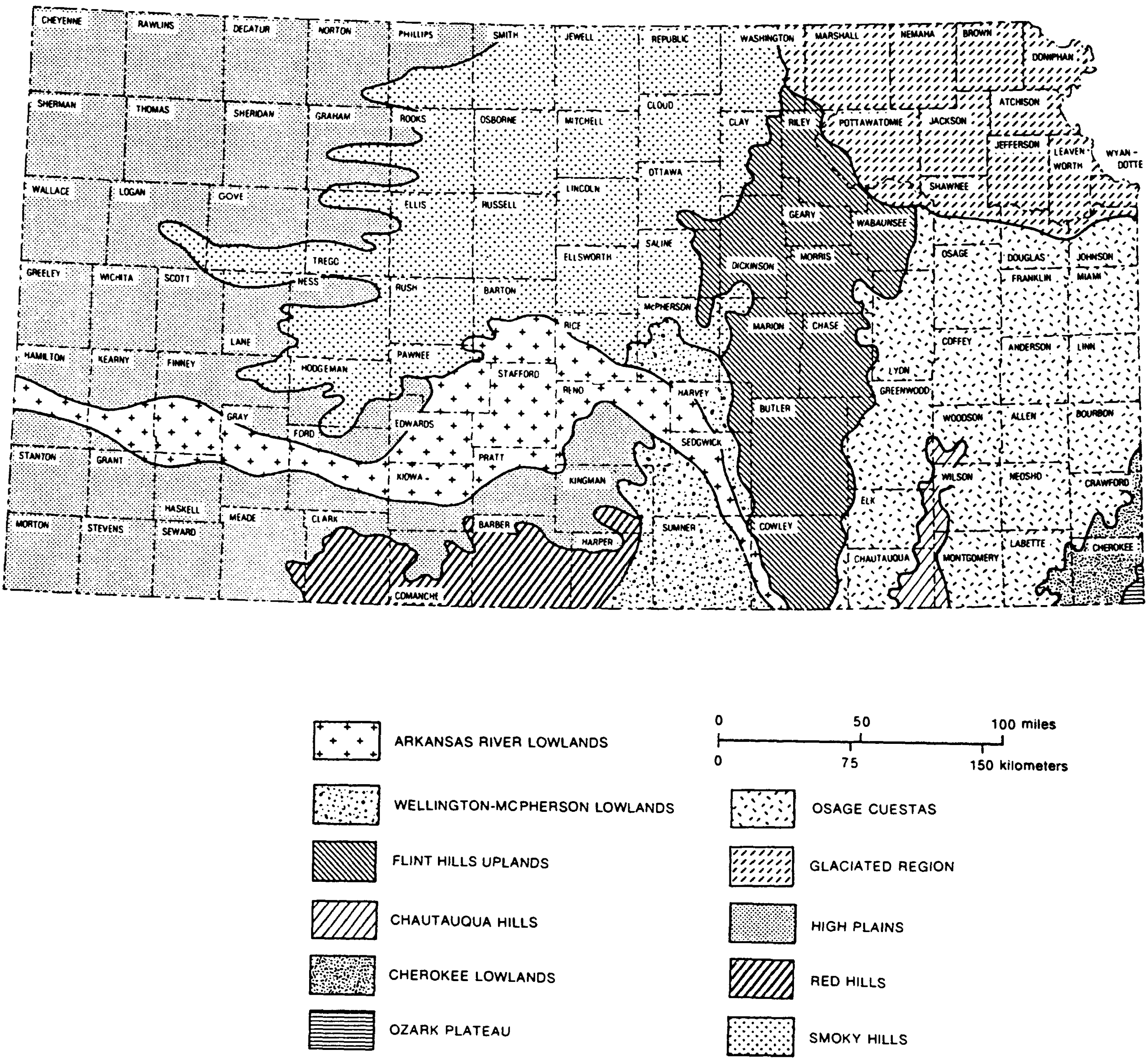


Figure 1. Physiographic regions of Kansas (from Wilson, 1984).

of the Red Hills, sinkholes have formed from dissolution of the salt and gypsum beds underlying the area.

The northeastern part of Kansas is a distinctive hilly region formed on Pleistocene glacial deposits, called the glaciated region (fig. 1). In this area the rolling hills are covered by scattered cobbles and boulders of crystalline rocks such as red Precambrian quartzite from southern Minnesota and northern Iowa (Wilson, 1984). The Smoky Hills occupy much of north-central Kansas (fig. 1). The eastern part of the Smoky Hills is characterized by sandstone hills and buttes that rise sharply above the surrounding plains. The uplands in the middle part of the Smoky Hills region are underlain by limestones and chalky shales. This is the "Fencepost Limestone country", in which beds of one-foot-thick limestone were used for masonry and for fenceposts on rangeland (Wilson, 1984). The western part of the Smoky Hills region is developed on thick chalks of the Cretaceous Niobrara Formation, which form hills and buttes with a badlands appearance. Most of the western part of the State is in the High Plains region, a subset of the High Plains Province that begins at the foot of the Rocky Mountains and covers much of the central interior of the United States from Texas to the Dakotas. The Arkansas River Lowlands (fig. 1) are formed in the broad, flat valley of the Arkansas River. Much of the valley and surrounding plains are covered by dunes of windblown sand. Extensive windblown silt deposits, called loess, cover large parts of the Kansas landscape as well.

Kansas is divided into 105 counties (fig. 2). The population of Kansas is largely rural, with farming and livestock as major industries. Most counties have populations less than 10,000 (fig. 3); counties with more than 100,000 inhabitants are those with large urban centers, including Johnson and Wyandotte (Kansas City), Shawnee (Topeka), and Sedgewick (Wichita) (fig. 3).

GEOLOGY

Almost all of the bedrock exposed at the surface in Kansas consists of sedimentary units ranging in age from Mississippian to Quaternary (fig. 4) (Ross, 1991). Igneous rocks native to Kansas and exposed at the surface are small localized exposures of Cretaceous lamproite in Woodson County (Wagner, 1954; Cullers and others, 1985) and Cretaceous kimberlite in Riley County (Brookins, 1970). Sedimentary rocks of Mississippian age underlie the extreme southeastern corner of the State (fig. 4). They consist primarily of limestones but also include shale, dolomite, chert, sandstone, and siltstone. Pennsylvanian rocks underlie approximately the eastern one-quarter of the State. They consist of an alternating sequence of marine and nonmarine shale, limestone, sandstone, and coal, with lesser amounts of chert and conglomerate. The shales range from green and gray (low organic content) to black (organic rich). Permian rocks are exposed in east-central and southern Kansas (fig. 4) and consist of limestone, shale, gypsum, anhydrite, chert, siltstone, and dolomite. Red sandstone and shale (red beds) of Permian age underlie the Red Hills along the southern border of Kansas (figs. 1, 4). Triassic rocks are exposed at the surface only in a small area in Morton County and consist chiefly of sandstone and shale. Jurassic rocks are not exposed at the surface in Kansas. Cretaceous sedimentary rocks underlie much of north-central and central Kansas (fig. 4), and consist of green, gray, and black shale, sandstone, siltstone, limestone, chalk, and chalky shale. A discontinuous layer of loess (windblown silt) of varying thickness covers the Cretaceous rocks in many areas, particularly in the western part of the Cretaceous outcrop area. Tertiary rocks cover much of western Kansas, though they are covered by loess deposits in many areas (fig. 4). Tertiary rocks consist of

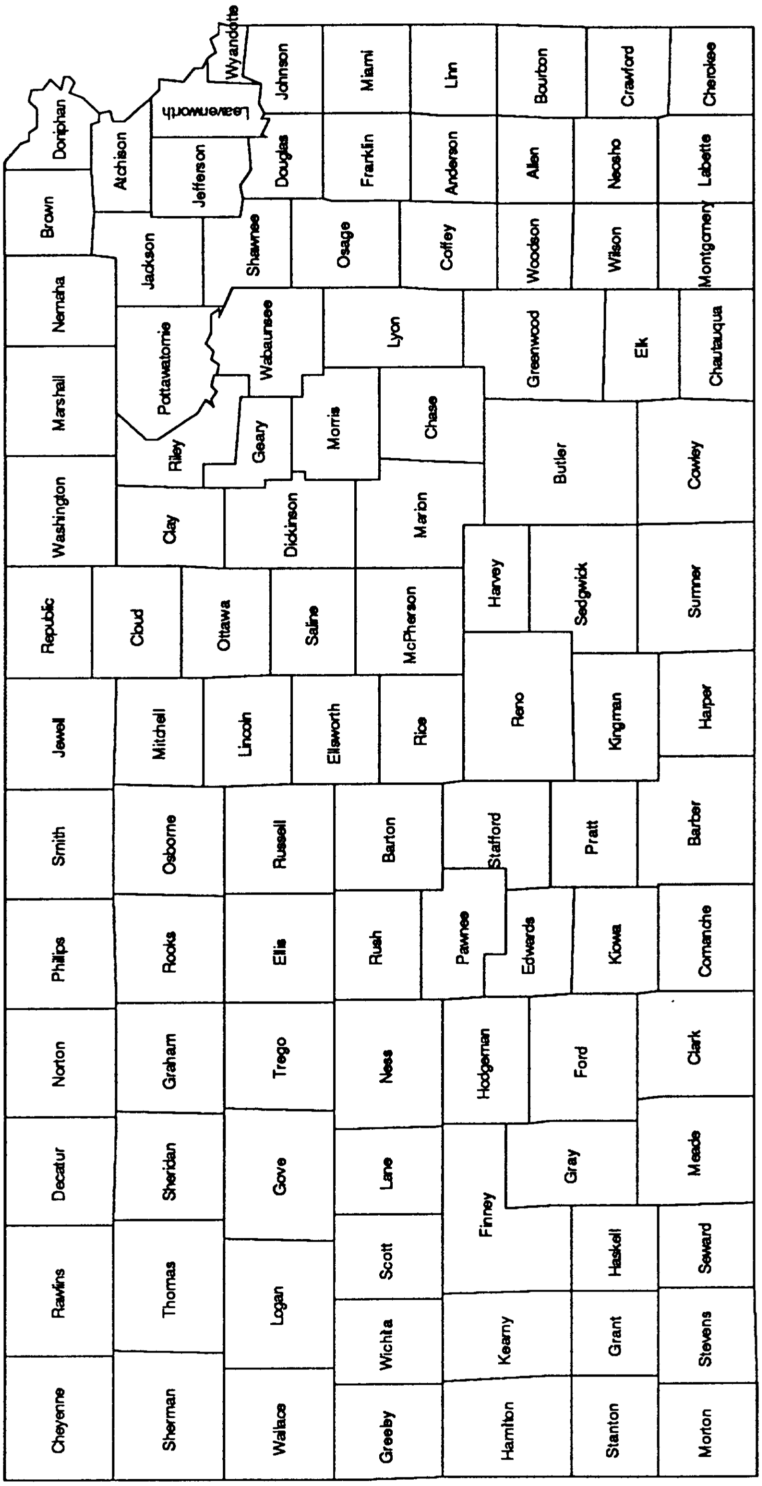


Figure 2. Kansas counties.

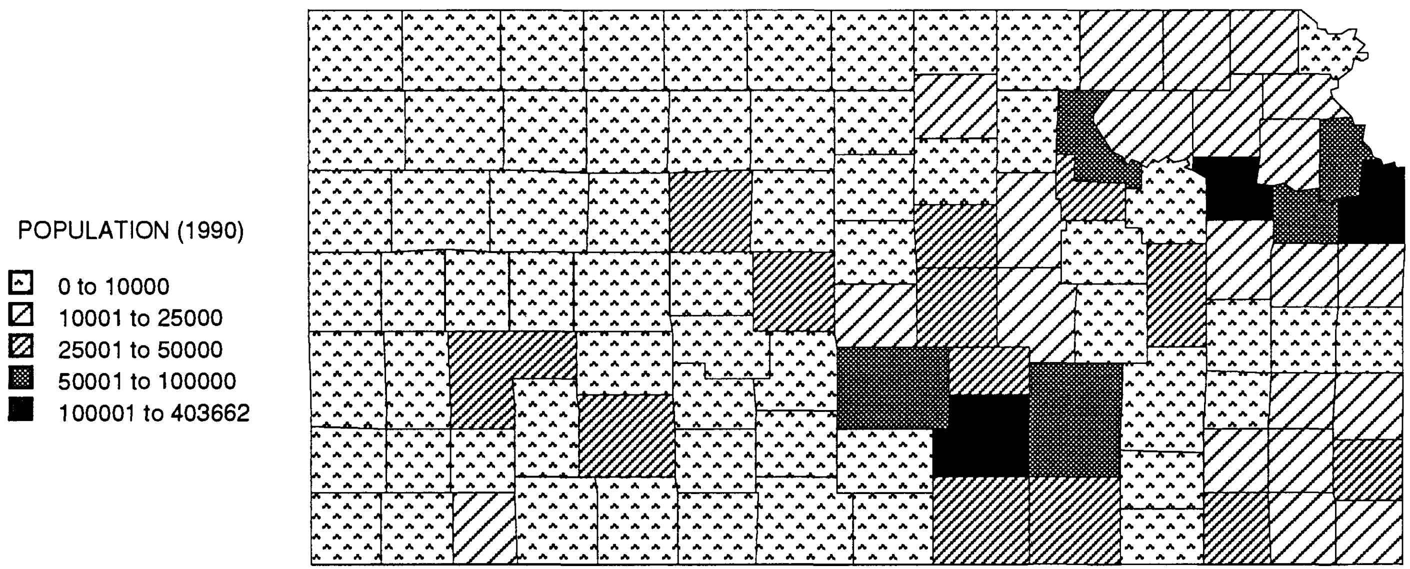


Figure 3. Population of counties in Kansas (1990 U.S. Census data).

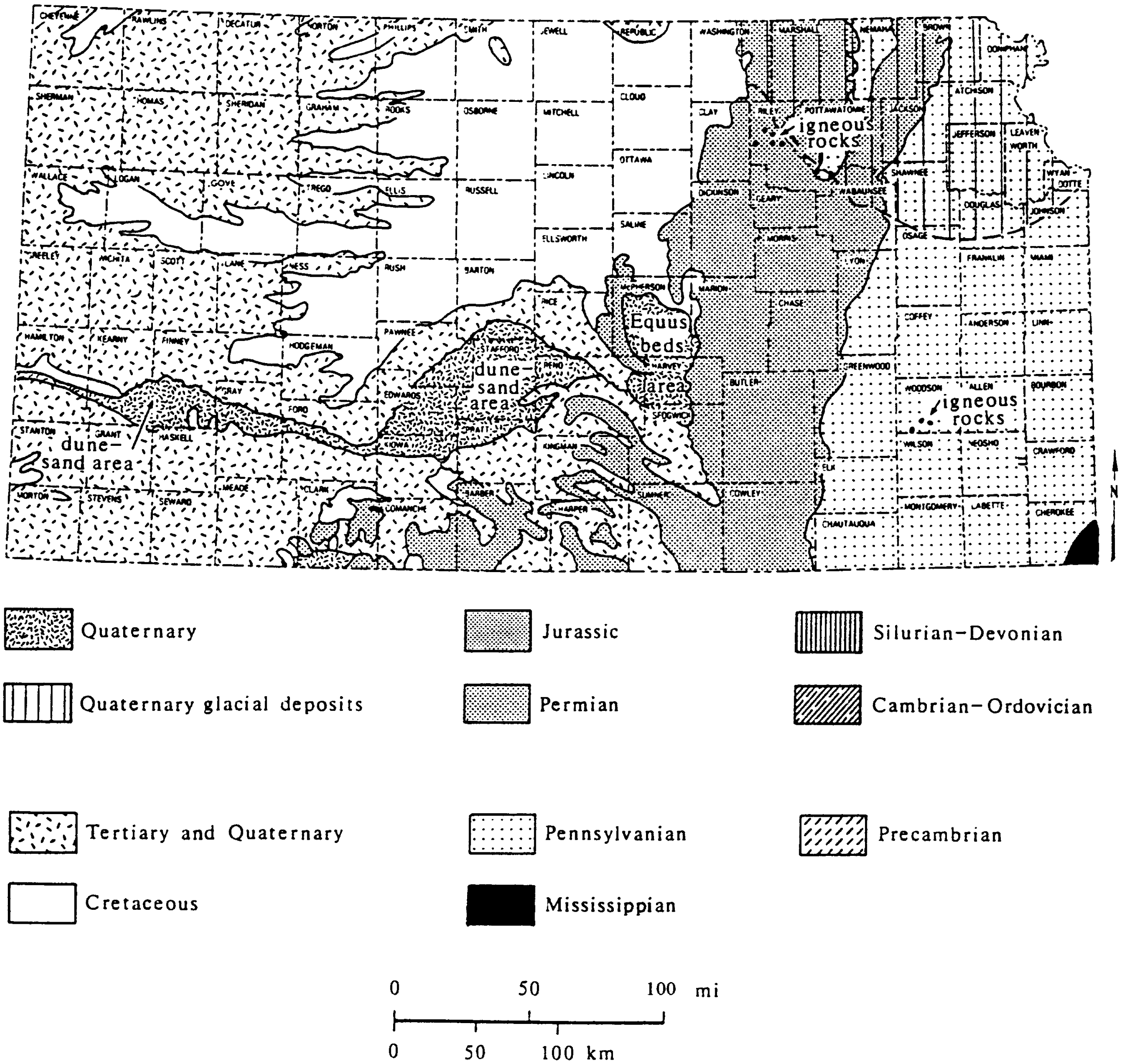


Figure 4. Generalized geologic map of Kansas (modified from Kansas Geological Survey).

ERAS	PERIODS	EPOCHS	EST. LENGTH IN YEARS	TYPE OF ROCK IN KANSAS	MILLION YEARS PAST
CENOZOIC	QUATERNARY	HOLOCENE	10,000 +	Glacial drift; river silt, sand, and gravel; dune sand; wind-blown silt (loess); volcanic ash.	0.010
		PLEISTOCENE	1,990,000		2
	TERTIARY	PLIOCENE	3,000,000	River silt, sand, gravel, fresh-water limestone; volcanic ash; bentonite; diatomaceous marl; opaline sandstone.	5
		MIOCENE	19,000,000		24
		OLIGOCENE	14,000,000		38
		EOCENE	17,000,000		55
		PALEOCENE	8,000,000		63
MESOZOIC	CRETACEOUS		75,000,000	Limestone, chalk, chalky shale, dark shale, varicolored clay, sandstone, conglomerate. Outcropping igneous rock.	138
	JURASSIC		67,000,000	Sandstones and shales, chiefly subsurface. Siltstone, chert, and gypsum.	205
	TRIASSIC		35,000,000		240
PALEOZOIC	PERMIAN		50,000,000	Limestone, shale, evaporites (salt, gypsum, anhydrite), red sandstone; chert, siltstone, dolomite, and red beds.	290
	PENNSYLVANIAN		40,000,000	Alternating marine and nonmarine shale, limestone, sandstone, coal; chert and conglomerate.	~330
	MISSISSIPPIAN		30,000,000	Limestone, shale, dolomite, chert, oölites, sandstone, and siltstone.	360
	DEVONIAN		50,000,000	Subsurface only. Limestone, predominantly black shale; sandstone.	410
	SILURIAN		25,000,000	Subsurface only. Limestone.	435
	ORDOVICIAN		65,000,000	Subsurface only. Dolomite, sandstone.	500
	CAMBRIAN		70,000,000	Subsurface only. Dolomite, sandstone, limestone, and shale.	~570
PRECAMBRIAN			1,930,000,000	Subsurface only. Granite, other igneous rocks, and metamorphic rocks.	
			1,100,000,000 +		2,500

Figure 4 (continued) Kansas stratigraphic chart (modified from Kansas Geological Survey).

nonmarine sandstone, siltstone, and shale; volcanic ash deposits; and unconsolidated gravel, sand, silt, and clay.

Pre-Illinoian (Pleistocene) glacial drift covers bedrock in the northeastern part of the State (fig. 4). The glacial deposits consist of a clay, silt, or sand matrix with cobbles and boulders of igneous and metamorphic rocks derived from as far away as the Lake Superior Region and southwestern Minnesota (Dort, 1987). The glacial deposits are discontinuous and till thickness varies markedly within the area, most likely because post-glacial erosion has removed and redistributed significant amounts of drift (Dort, 1987). Loess, windblown silt deposits ranging from 0 to more than 30 meters in thickness, covers as much as 65 percent of the surface of Kansas (Welch and Hale, 1987) and is thickest and most extensive in the western and north-central parts of the State and in proximity to glacial deposits in the northeastern corner of the State (fig. 5). Possible sources for the loess include: (1) glacial outwash, (2) sand dunes in the Arkansas and Cimarron River valleys (fig. 4) or elsewhere (such as the Sand Hills of Nebraska), and (3) erosion by wind and rivers of the Tertiary Ogallala Formation (Welch and Hale, 1987).

Uranium in above-average concentrations (according to Carmichael (1989), average crustal abundance of uranium is 2.5 ppm) is found in a number of rocks in Kansas. Uranium is found in phosphatic black shales of Pennsylvanian age in eastern Kansas. Uranium contents in the black shales range from about 15 ppm to 100 ppm; concentrations of as much as 350 ppm uranium are found in phosphate nodules within the shales (Berendsen and others, 1988). Pennsylvanian phosphatic black shales exposed in eastern Kansas include the Heebner, Eudora, Muncie Creek, Quindaro, Stark, Hushpuckney, Anna, Little Osage, and Excello Shale Members, the Pleasanton Group, and shales above the Bevier and Croweburg coals (Berendsen and others, 1988; Coveney and others, 1988). The Cretaceous Sharon Springs Member, a black shale unit at the base of the Pierre Shale, contains from 10 to 40 ppm uranium in western Kansas (Landis, 1959). Uranium is associated with silica-cemented layers in the Tertiary Ogallala Formation in several localities in western Kansas. The uranium content of the rocks appears to correlate directly with the amount of silica cementation of the rocks, with as much as 125 ppm uranium in the most intensely silicified layers (Berendsen and Hathaway, 1981; Berendsen and others, 1988). A continuously silicified area of the Ogallala Formation about 10 miles long and 1.5 miles wide is located in Meade and Clark Counties (Berendsen and Hathaway, 1981). The source of the uranium and silica in the Ogallala is postulated to be volcanic ash that is mixed in with the sediments throughout their outcrop area (Carey and others, 1952; James, 1977; Zielinski, 1983). Eighteen samples of volcanic ash from Tertiary and younger rocks in Kansas yielded from 3.9 to 9.1 ppm uranium (James, 1977). Other uranium occurrences have been found in kimberlite pipes in Riley County, in the Cretaceous Dakota Sandstone in Ellsworth County, in the Cretaceous Smoky Hill Member of the Niobrara Chalk in a large area of Gove County, and in Tertiary volcanic ash outcrops in Meade and Clark Counties (Zeller and others, 1976).

Anomalous concentrations of uranium in ground water were found in wells producing from the Permian Nippewalla Group, Cretaceous Kiowa-Cheyenne Sandstones, and Quaternary alluvium (Berendsen and others, 1988); anomalous uranium concentrations in ground water (from 2 to 172 parts per billion uranium) have also been noted in wells producing from the Ogallala aquifer and Arkansas River alluvium in western Kansas (Berendsen and Hathaway, 1981). Ground water in southeastern Kansas is generally low in uranium but contains elevated concentrations of ^{226}Ra (Macfarlane, 1981), suggesting that these waters may also contain high levels of dissolved radon in some areas.

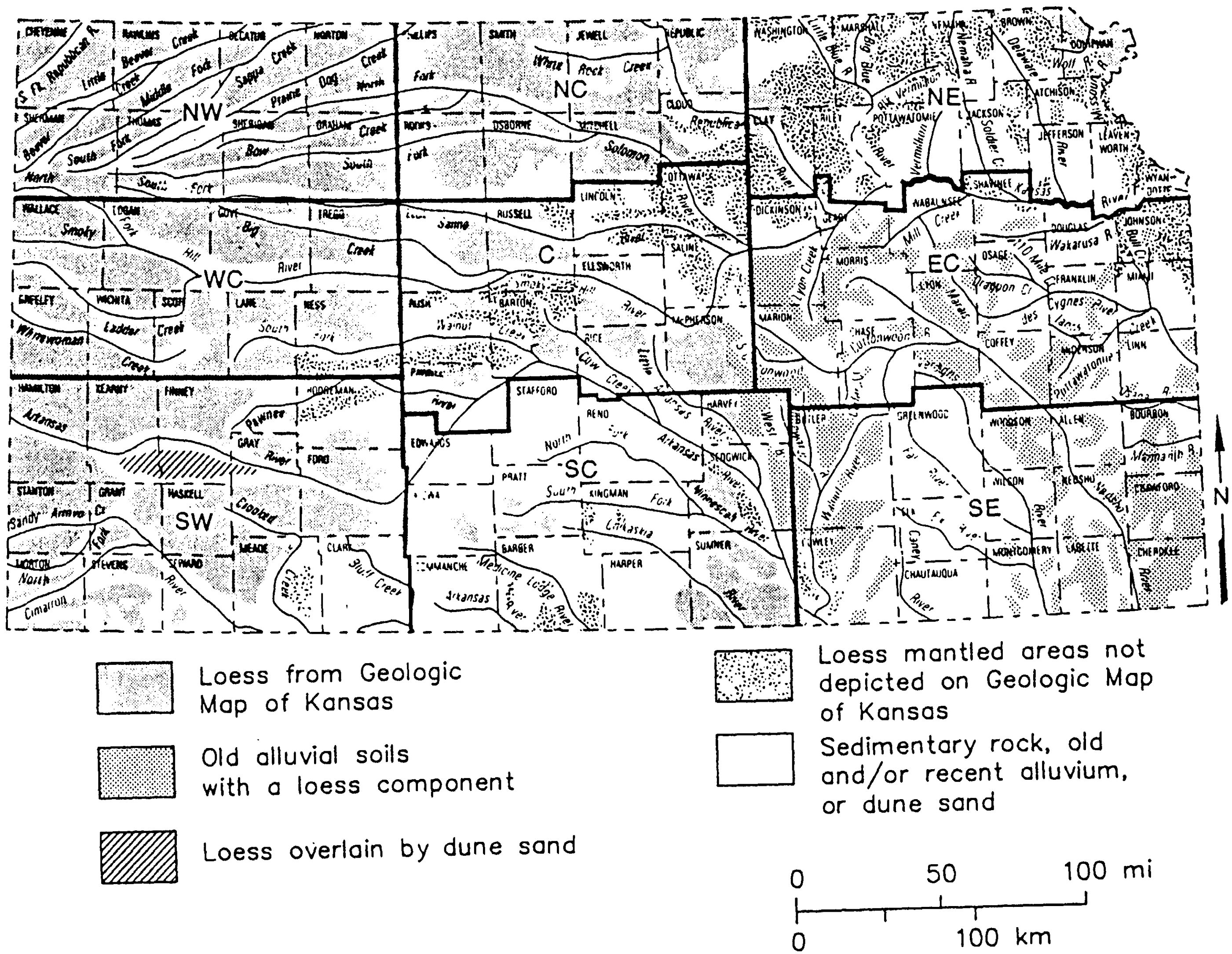


Figure 5. Map showing distribution of loess in Kansas (from Welch and Hale, 1987). Loess in the area marked "Loess mantled areas not shown on Geologic Map of Kansas" is generally less than 2 feet thick.

SOILS

Most soils in Kansas belong to the suborders Ustolls and Udolls (Bidwell and McBee, 1973). If Kansas is vertically divided into quarters, the western quarter of the State is covered by Aridic Ustolls, the west-central quarter is covered by Typic Ustolls, the east-central quarter is covered by Udic Ustolls, and the eastern quarter is covered by Typic Udolls. Aridic Ustolls are deep, grayish-brown silt loams and sandy loams with a layer of calcium carbonate accumulation at approximately one meter (Bidwell and McBee, 1973). These soils have generally low to moderate permeability (fig. 6). The western part of the State that is covered by Aridic Ustolls receives 508 mm (20 in) or less of precipitation annually (Steeples and Buchanan, 1983). Typic Ustolls, which cover the west-central quarter of Kansas, are deep and moderately deep, dark grayish-brown to reddish-brown silt loams and clays with calcium carbonate accumulations at 1-2 m depth (Bidwell and McBee, 1973) and generally low permeability (fig. 6). This part of the State receives 508-635 mm (20-25 in) of precipitation annually. Approximately the east-central quarter of the State is covered by Udic Udolls, shallow to deep, grayish-brown silt loams and clay loams with secondary carbonate horizons at more than 1 m depth (Bidwell and McBee, 1973). These soils have low to moderate permeability (fig. 6), and this part of the State receives between 635 mm (25 in) and 889 mm (35 in) of precipitation annually (Steeples and Buchanan, 1983). Eastern Kansas receives from 889 mm (35 in) to more than 1000 mm (40 in) of precipitation annually and is covered by Typic Udolls, black and dark brown silt loams to clay loams with secondary carbonate accumulations at depths exceeding 1.5 m. These soils have generally low permeability (fig. 6) and many of the soils in eastern Kansas have seasonally high water tables (Olson, 1974). Soils developed on alluvium in river valleys, most notably that of the Arkansas River, are sand and sandy loams with high permeability (fig. 6). The extreme southeastern corner of Kansas is covered by Typic Udults, deep, brown cherty silt loams with secondary calcium carbonate horizons at more than 1.5 m depth (Bidwell and McBee, 1973) and high permeability (fig. 6).

INDOOR RADON DATA

Screening indoor radon data from 2009 homes sampled in the State/EPA Residential Radon Survey conducted in Kansas during the winter of 1987-88 are shown in figure 7 and listed in Table 1. Data are only shown in figure 7 for those counties with 5 or more data values. The maximum value recorded in the survey was 48 pCi/L in Marshall County. Except for counties in the Kansas City, Topeka, and Wichita areas, most counties in the survey are represented by 20 or fewer indoor radon measurements (fig. 7); 19 counties have more than 20 measurements. Given the relatively sparse distribution of data, observations concerning the distribution of indoor radon concentrations based on these data should not be considered conclusive statements on indoor radon distributions within Kansas, but they are useful in establishing geologically-related trends.

Most counties in southeastern and south-central Kansas have low (0-2 pCi/L) to moderate (2-4 pCi/L) indoor radon averages. Counties in northeastern Kansas have moderate to high (> 4 pCi/L) indoor radon averages (fig. 7). Berendsen and others (1988) report that elevated indoor radon levels were found in the Kansas City area and in Chanute in a survey of indoor radon levels by the Kansas Department of Health and Environment. Most of the counties in north-central and central Kansas have high indoor radon averages in the State/EPA survey, and western Kansas has an approximately equal mixture of counties with moderate and high indoor radon averages (fig. 7). The highest maximum radon readings occur in northeastern and central Kansas (Table 1).

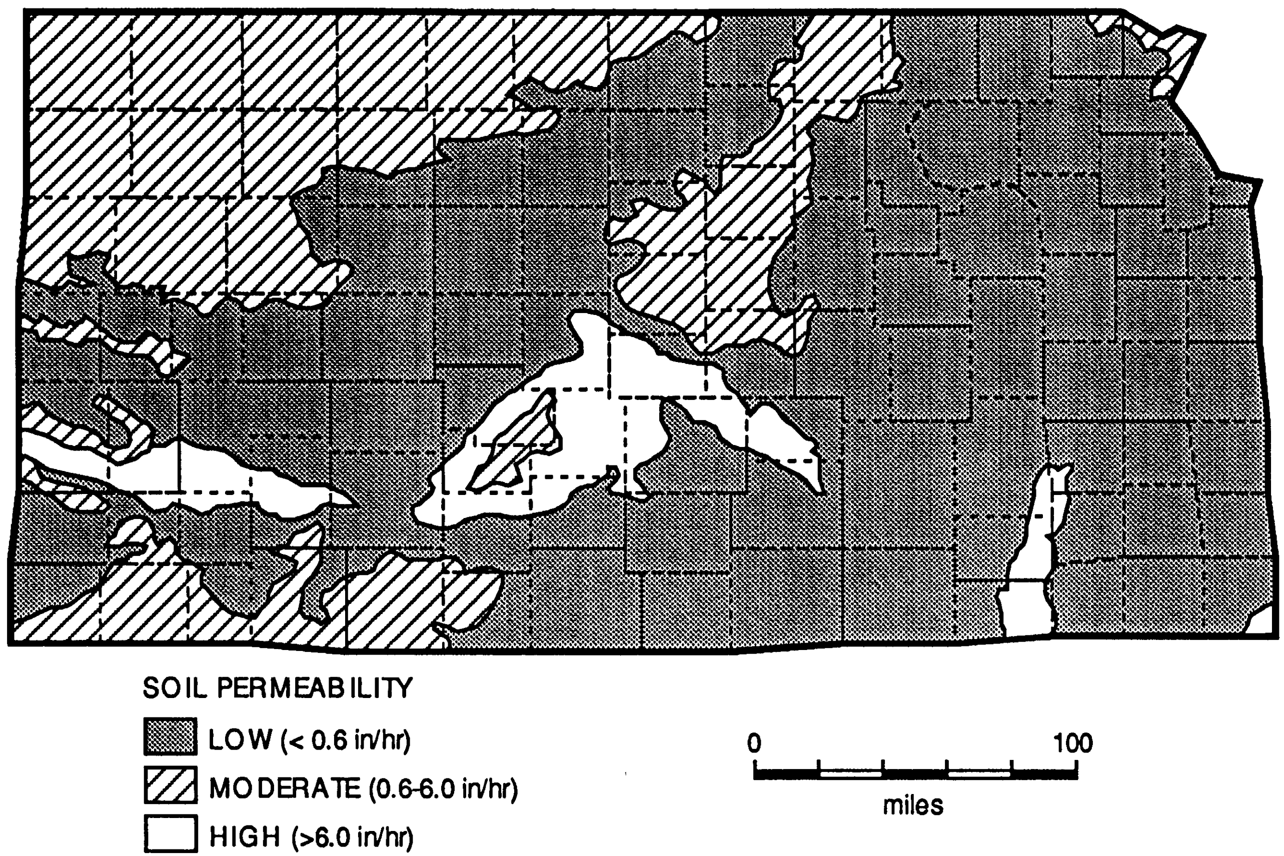
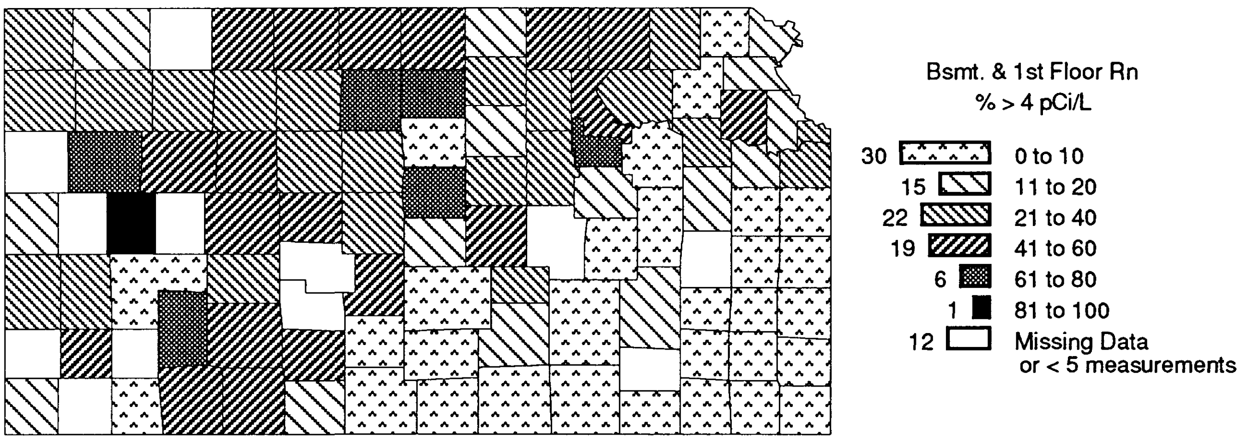


Figure 6. Generalized soil permeability map of Kansas (data from Olson, 1974; map units from Bidwell and McBee, 1973).



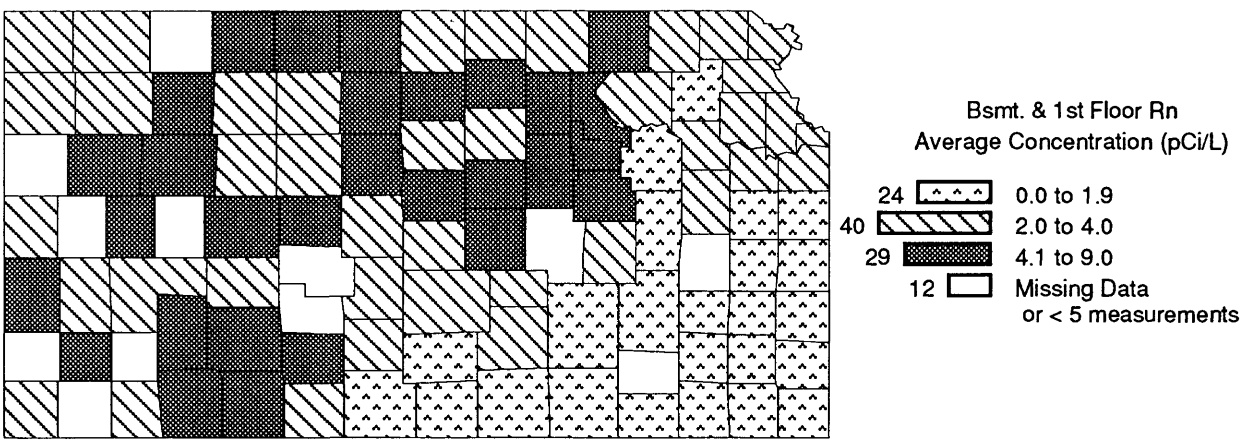


Figure 7. Screening indoor radon data from the EPA/State Residential Radon Survey of Kansas, 1987-88, for counties with 5 or more measurements. Data are from 2-7 day charcoal canister tests. Histograms in map legends show the number of counties in each category. The number of samples in each county (See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

TABLE 1. Screening indoor radon data from the EPA/State Residential Radon Survey of Kansas conducted during 1986-87. Data represent 2-7 day charcoal canister measurements from the lowest level of each home tested.

COUNTY	NO. OF MEAS.	MEAN	GEOM. MEAN	MEDIAN	STD. DEV.	MAXIMUM	%>4 pCi/L	%>20 pCi/L
ALLEN	20	0.6	0.3	0.4	0.6	2.4	0	0
ANDERSON	9	0.8	0.6	0.7	0.6	2.0	0	0
ATCHISON	10	2.9	2.3	2.3	2.1	6.9	20	0
BARBER	9	1.9	1.6	1.7	1.0	3.7	0	0
BARTON	24	3.4	2.0	1.9	4.7	23.0	21	4
BOURBON	15	1.7	1.2	1.3	1.3	4.3	7	0
BROWN	7	2.4	2.1	2.5	1.2	4.0	0	0
BUTLER	29	1.6	0.9	1.1	1.7	7.6	7	0
CHASE	10	2.0	1.5	1.3	1.9	6.7	10	0
CHAUTAUQUA	6	0.8	0.5	0.4	1.0	2.7	0	0
CHEROKEE	20	0.9	0.5	0.4	1.1	4.0	0	0
CHEYENNE	11	3.9	3.1	2.9	3.2	12.6	36	0
CLARK	6	4.6	3.7	4.4	3.0	9.3	50	0
CLAY	7	9.0	3.7	2.4	12.0	28.1	29	29
CLOUD	11	4.2	3.1	3.1	3.2	9.5	36	0
COFFEY	4	2.6	1.7	2.5	1.9	4.9	25	0
COMANCHE	5	2.0	1.0	1.0	2.9	7.1	20	0
COWLEY	29	1.9	1.6	1.6	1.1	4.4	7	0
CRAWFORD	46	1.1	0.7	0.8	1.2	6.0	4	0
DECATUR	4	3.1	2.4	2.4	2.4	6.4	25	0
DICKINSON	15	4.1	3.2	3.3	3.8	16.5	33	0
DONIPHAN	5	3.0	2.6	3.2	1.4	4.5	20	0
DOUGLAS	36	2.6	1.6	2.0	2.5	12.9	19	0
EDWARDS	4	3.1	2.5	2.9	2.0	5.6	25	0
ELK	3	0.7	0.7	0.6	0.3	1.0	0	0
ELLIS	26	3.6	3.2	3.6	1.8	8.6	38	0
ELLSWORTH	17	5.9	4.5	5.7	3.7	13.2	65	0
FINNEY	15	2.0	1.9	1.7	0.9	4.7	7	0
FORD	14	5.4	4.2	4.3	3.8	12.2	50	0
FRANKLIN	22	1.6	1.1	1.0	1.5	5.9	5	0
GEARY	8	6.6	5.2	5.2	5.6	19.3	63	0
GOVE	8	4.4	3.7	3.7	2.5	8.2	50	0
GRAHAM	6	4.0	2.8	3.1	3.2	9.2	33	0
GRANT	8	4.2	3.4	3.2	3.1	10.1	50	0
GRAY	5	6.2	5.8	6.4	2.5	8.8	80	0
GREELEY	5	2.9	2.6	3.0	1.4	4.9	20	0
GREENWOOD	5	1.9	1.2	1.1	1.9	4.9	20	0
HAMILTON	8	4.7	3.4	2.8	4.5	14.8	38	0
HARPER	7	1.6	1.4	1.0	1.1	3.7	0	0
HARVEY	13	3.0	2.3	2.2	2.5	9.9	23	0
HASKELL	2	3.4	3.2	3.4	1.7	4.6	50	0

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

COUNTY	NO. OF MEAS.	MEAN	GEOM. MEAN	MEDIAN	STD. DEV.	MAXIMUM	%>4 pCi/L	%>20 pCi/L
HODGEMAN	6	3.5	2.7	3.6	2.1	6.7	33	0
JACKSON	8	1.1	1.0	1.0	0.6	2.1	0	0
JEFFERSON	10	4.0	2.7	4.3	2.7	7.5	60	0
JEWELL	8	3.4	2.6	3.3	2.4	7.4	50	0
JOHNSON	339	3.8	2.5	2.6	4.1	32.0	29	1
KEARNY	9	3.0	2.4	3.4	1.7	5.6	33	0
KINGMAN	7	1.3	0.8	1.2	1.2	3.0	0	0
KIOWA	8	5.2	3.7	4.2	4.8	16.2	50	0
LABETTE	17	1.9	0.5	0.4	4.6	19.5	6	0
LANE	3	2.9	1.9	1.6	3.1	6.4	33	0
LEAVENWORTH	28	2.5	1.6	2.0	2.0	7.3	18	0
LINCOLN	7	2.0	1.7	1.2	1.2	3.5	0	0
LINN	8	1.4	0.9	1.1	1.1	3.1	0	0
LOGAN	8	5.3	4.7	6.1	2.4	8.7	63	0
LYON	17	1.2	0.9	0.7	1.0	3.6	0	0
MARION	2	3.2	3.2	3.2	0.1	3.3	0	0
MARSHALL	12	8.5	3.7	3.9	13.4	48.0	50	8
MCPHERSON	21	4.6	3.6	3.7	3.6	17.0	43	0
MEADE	12	4.9	3.3	3.3	4.3	13.4	50	0
MIAMI	22	1.8	1.4	1.5	1.3	5.6	5	0
MITCHELL	8	6.7	4.8	5.4	5.2	16.1	63	0
MONTGOMERY	41	0.7	0.5	0.4	0.7	3.5	0	0
MORRIS	5	6.3	2.3	2.6	9.8	23.7	20	20
MORTON	8	2.5	1.7	1.4	2.4	7.8	13	0
NEMAHA	9	3.3	2.2	2.9	3.0	9.8	33	0
NEOSHO	11	1.3	1.0	0.9	0.9	3.2	0	0
NESS	19	4.8	3.1	3.8	5.4	24.6	47	5
NORTON	10	4.8	4.2	4.2	2.4	8.6	50	0
OSAGE	12	2.5	1.8	1.6	2.5	9.6	17	0
OSBORNE	9	7.0	5.6	7.7	4.6	16.1	67	0
OTTAWA	6	3.7	1.5	1.2	6.4	16.6	17	0
PAWNEE	2	8.9	7.8	8.9	6.1	13.2	100	0
PHILLIPS	27	4.5	3.5	3.9	2.9	13.5	48	0
POTTAWATOMIE	11	3.6	1.8	1.4	4.9	15.3	27	0
PRATT	9	2.0	1.9	1.7	0.8	3.5	0	0
RAWLINS	10	2.7	2.2	2.3	1.7	5.8	20	0
RENO	45	2.2	1.4	1.7	2.2	11.7	7	0
REPUBLIC	8	2.8	2.2	2.8	1.9	6.8	13	0
RICE	7	2.5	1.9	1.8	2.4	7.8	14	0
RILEY	32	4.6	2.4	2.5	5.6	25.5	41	3
ROOKS	10	3.9	2.9	3.8	2.7	9.3	40	0
RUSH	8	5.1	3.6	4.2	4.8	15.6	50	0
RUSSELL	8	4.5	3.9	3.4	2.7	10.0	38	0

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

COUNTY	NO. OF MEAS.	MEAN	GEOM. MEAN	MEDIAN	STD. DEV.	MAXIMUM	%>4 pCi/L	%>20 pCi/L
SALINE	32	4.8	3.4	3.5	4.5	20.7	38	3
SCOTT	21	5.8	4.9	5.4	3.2	15.7	81	0
SEDGWICK	217	2.1	1.6	1.6	1.7	8.0	12	0
SEWARD	12	2.9	2.6	2.7	1.2	5.6	8	0
SHAWNEE	109	2.9	1.9	2.1	3.1	19.7	22	0
SHERIDAN	8	4.6	3.3	3.0	4.0	12.2	38	0
SHERMAN	8	4.0	3.2	2.8	2.9	9.3	38	0
SMITH	7	4.6	4.1	4.4	2.2	7.5	57	0
STAFFORD	7	3.8	3.0	3.7	2.4	7.0	43	0
STANTON	4	5.7	5.0	6.5	2.8	7.9	75	0
STEVENS	3	13.0	6.4	9.1	14.4	29.0	67	33
SUMNER	10	1.5	1.1	1.7	1.0	3.2	0	0
THOMAS	14	3.6	3.0	3.0	2.3	9.9	36	0
TREGO	14	3.8	3.1	3.1	2.5	9.1	43	0
WABAUNSEE	7	1.9	1.7	1.7	1.0	3.4	0	0
WALLACE	3	4.8	4.8	4.7	0.4	5.2	100	0
WASHINGTON	7	3.4	2.4	2.7	2.4	7.0	43	0
WICHITA	3	5.5	5.4	5.0	1.1	6.8	100	0
WILSON	15	1.4	0.8	0.5	2.1	7.7	7	0
WOODSON	17	0.7	0.5	0.5	0.6	2.1	0	0
WYANDOTTE	110	3.6	2.5	3.1	3.1	16.3	35	0

GEOLOGIC RADON POTENTIAL

An examination of geologic (fig. 4), soil (fig. 6), indoor radon (fig. 7), and radioactivity (fig. 8) data allows identification of rocks and sediments in Kansas that have the potential to generate indoor radon levels exceeding the EPA's 4 pCi/L guideline. A northeast-southwest trending line of high radioactivity (for this evaluation, "high" is defined as greater than 2.5 ppm equivalent uranium [eU]) in southeastern Kansas (fig. 8) is likely associated with Pennsylvanian black shales. However, most of the Pennsylvanian black shale outcrops are thin, usually no more than a few meters thick, so they are too narrow to detect on the aerial radioactivity map, which has a grid cell, or "pixel", size of about 2.5 km (1.6 mi) (Duval and others, 1989). Permian sedimentary rocks comprising the Chautauqua Hills (fig. 1) have a low (<1.5 ppm eU) radioactivity signature (fig. 8). With these exceptions, Pennsylvanian and Permian rocks in the State have an overall intermediate (1.0-2.5 ppm eU) radioactivity signature. Because the majority of Pennsylvanian and Permian rocks have relatively low uranium contents, and because soils developed on these rocks have generally low permeability and many are subject to seasonally high water tables, these rocks have a generally low radon potential. However, homes situated on Pennsylvanian and Permian carbonate rocks (limestones and dolomites) may have locally elevated indoor radon levels if the limestones have developed clayey residual soils and(or) if solution features (karst topography), are present in the area. Although the carbonate rocks themselves are generally low in uranium and radium, the soils developed on these rocks are typically derived from the residual materials of dissolution of the $CaCO_3$ that makes up the majority of the rock. When the $CaCO_3$ has been dissolved away, the soils are enriched in the remaining impurities, predominantly base metals, including uranium. Carbonates also form karst topography, characterized by solution cavities, sinkholes, and caves, which increase the overall permeability of the rocks in these areas and may induce or enhance convective flow of radon. Homes sited on Pennsylvanian black shale units are likely subject to locally high indoor radon levels. This appears to be the case in the Kansas City area, part of which is underlain by black shales (fig. 7; Berendsen and others, 1988).

Some elevated indoor radon levels in the northern part of the Permian outcrop area, specifically in Marshall, Clay, Riley, Geary, and Dickinson Counties, may be related to faults and fractures of the Mid-Continent Rift and Nemaha Uplift (Berendsen and others, 1988). The Mid-Continent Rift (MCR) zone is an area of NNE-SSW-trending faults and fractures which were most active during Late Mississippian to Early Pennsylvanian time (Berendsen and others, 1989), but have been active during modern times, as evidenced by modern microearthquakes (Wilson, 1979). Many of the subsurface faults reach and displace the surface sedimentary rock cover, and the density and spacing of faults and fractures within the rift zone is relatively high (Berendsen and Blair, 1986; Berendsen and others, 1989). Soil-gas helium surveys conducted jointly by the Kansas Geological Survey and the U.S. Geological Survey indicate that faults and fractures within the MCR are areas of high permeability and they show evidence that fluids and gases are able to migrate upward from deeper source rocks (G.M. Reimer, unpublished report, 1985). Fault and shear zones are commonly areas of locally elevated radon because these zones typically have higher permeability than the surrounding rocks, because they are preferred zones of uranium mineralization, and because they are pathways for potentially uranium-, radium-, and(or) radon-bearing fluids and gases to migrate (Gundersen, 1991).

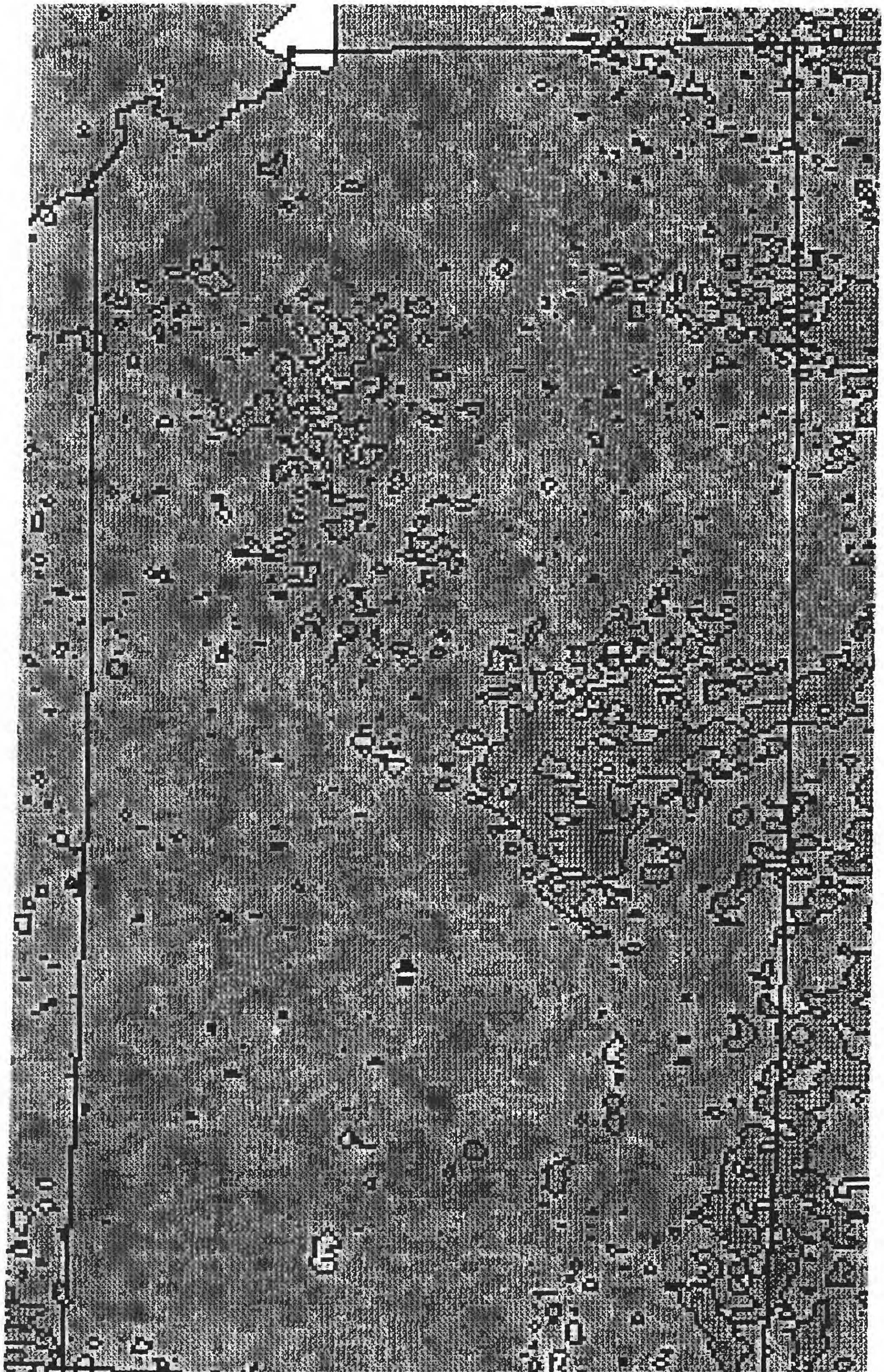


Figure 8. Aerial radiometric map of Kansas (after Duval and others, 1989). Contour lines at 1.5 and 2.5 ppm equivalent uranium (eU). Pixels shaded from 0 to 6.0 ppm eU at 0.5 ppm eU increments; darker pixels have lower eU values; white indicates no data.

Cretaceous rocks in northern, central, northwestern, and west-central Kansas include sandstones, shales, and local volcanic ash deposits that contain sufficient uranium to generate elevated indoor radon levels. The Cretaceous rocks overall have a moderate (1.5-2.5 ppm eU) radioactivity signature (fig. 8). Some areas of higher radioactivity may be masked by surface accumulations of loess. A few scattered radioactivity anomalies in western and central Kansas (fig. 8) may be associated with outcrops of the Sharon Springs Member of the Pierre Shale or with alluvium in major drainages. Soils developed on Cretaceous rocks have low to moderate permeability (fig. 6), but the shale-derived soils with low permeability to water likely have moderate permeability to soil gas when they are dry due to desiccation cracks (Schumann and others, 1989, 1991). Areas underlain by these rocks have an overall high radon potential. Areas underlain by the Tertiary Ogallala Formation have a moderate radioactivity signature and a moderate to high radon potential. Again, the radioactivity of the bedrock may be masked in some areas by surficial loess deposits.

Although loess in many cases has lower radioactivity than underlying bedrock units, it typically is able to generate as much or more radon than the bedrock it covers. Radon potential of loess-mantled areas depends on the thickness and source of the loess. In areas of very thin loess cover, the radon potential of the underlying bedrock is significant, and the loess both generates radon and transmits radon from the underlying bedrock, whereas if the loess is more than 7-10 m thick, it is probably the sole radon source for homes in the area. Because several sources are postulated for loess in Kansas, and loess thickness in the State has not yet been mapped in detail (Welch and Hale, 1987), it is difficult to make definitive statements concerning the radon potential of loess-mantled areas in Kansas. However, similar loess deposits in southern Nebraska generate widespread elevated indoor radon levels (see the Nebraska radon potential chapter in this volume). Loess-covered areas underlain by Cretaceous and Tertiary bedrock appear to have variably moderate to high radon potential across the State, and locally elevated indoor radon levels may be expected anywhere within areas underlain by these units. Areas underlain by loess-covered Pennsylvanian and Permian rocks appear to generate moderate to locally elevated indoor radon levels.

The area within the glacial limit in northeastern Kansas is underlain by discontinuous glacial drift and loess. Because the loess in this area is likely derived from nearby glacial drift, and because glacial deposits are known to generate elevated indoor radon levels throughout the northern Great Plains, this area should be considered to have a moderate to locally high radon potential. Areas of windblown sand in the Arkansas and Cimarron River valleys have a low radiometric signature (fig. 8). The sand dunes themselves have low uranium contents and low radon potential, but few homes are built directly on the sand dunes. The dune sands are intermixed with loess in parts of the Arkansas and Cimarron valleys, and the radon potential may be related to the relative proportions of sand, loess, and bedrock within these areas. Areas underlain by dune sand are expected to have lower radon levels, areas with considerable loess content are expected to have moderate to locally elevated radon levels. Where sand or loess is thin or absent, the radon levels in homes on Tertiary or Cretaceous bedrock are also expected to generally fall into the moderate to high category.

SUMMARY

For the purposes of this assessment, Kansas is divided into six geologic radon potential areas (fig. 9) and each area assigned Radon Index (RI) and Confidence Index (CI) scores (Table 2). The Radon Index is a semiquantitative measure of radon potential based on geologic, soil, and indoor radon factors, and the Confidence Index is a measure of the relative confidence of the RI assessment based on the quality and quantity of data used to make the predictions (see the Introduction chapter for more information on the methods and data used). At the scale of this report the outlines of the areas shown on figure 9 are generalized, and the descriptions given in this text should be compared with more detailed geologic and other maps.

Area PPR is underlain by Pennsylvanian and Permian rocks. Homes in this area may have indoor radon levels ranging from low (<2 pCi/L) to high (>4 pCi/L), depending on the local underlying geology and presence and thickness of loess cover. Additional indoor radon data compiled by the Kansas Department of Health and Environment (written communication, 1992) suggest that more homes in this area have moderate to high indoor radon levels than are indicated by the State/EPA Residential Radon Survey data, so the indoor radon factor was assigned 2 points, but because the data are partially from a non-randomly-sampled volunteer source, the factor is given 2, rather than 3, confidence index points. Homes built on uranium-bearing Pennsylvanian black shales within this area may have locally high indoor radon levels. Some areas underlain by carbonate rocks (limestones and dolomites) may have locally elevated indoor radon levels, especially if solution features or clay-rich residual soils have developed (the residual soils are commonly red or orange-red in color due to concentration of iron oxides in the residuum). Some domestic wells drawing water from lower Paleozoic aquifers in this area may contribute to elevated radon levels by release of dissolved radon from the water into the indoor air. Area PPR is assigned a moderate or variable overall radon potential (RI=9) with moderate confidence (CI=9).

Area GLA is underlain by glacial drift and loess of varying thickness. Although the bedrock source for the glacial drift can be traced as far as the Canadian Shield, a large proportion of the drift is relatively locally derived from underlying and nearby Paleozoic sedimentary rocks that are relatively poor radon sources. Higher permeability of the drift relative to bedrock, the presence of crystalline glacial erratics, and the variability of loess cover and source (primarily glacially derived) cause this area to have moderate to high radon potential, and it is assigned an overall high geologic radon potential (RI=12), with a high confidence index (CI=10).

Area MCR is an area of faults and fractures related to the Mid-Continent Rift zone. Homes sited on unfaulted Permian bedrock in this area are likely to have low radon levels, but those sited on surface or near-surface faults or fractures may have locally high indoor radon levels. The boundaries of the area are drawn along major subsurface faults that delineate the rift system (Berendsen and others, 1989). Overall, area MCR is assigned a high radon potential (RI=12) with high confidence (CI=10).

Area KR delineates the bedrock outcrop pattern of Cretaceous sedimentary rocks in Kansas. Parts of this area, particularly the western part, are covered by discontinuous loess deposits. Gray and black shale units of the Pierre Shale typically generate moderate to high indoor radon levels. The Dakota and Niobrara Formations and the Pierre Shale are known to contain locally anomalous amounts of uranium and are known producers of elevated radon in some areas. Overall, area KR has a high radon potential (RI=12) with high confidence (CI=11).

Area TL is mostly underlain by Tertiary rocks, specifically the Ogallala Formation, that are mostly covered by younger loess deposits. The highest radon levels in this area are expected to occur in homes sited on siliceous (silica-cemented) Ogallala Formation, particularly in the southwestern part of the State. Radon levels in structures built on loess deposits are expected to range from moderate to high depending on the thickness and mineralogy of the loess. Because the indoor radon data indicate that many areas underlain by loess or Tertiary sedimentary rocks have county average indoor radon levels exceeding 4.0 pCi/L, and because many of the counties in western Kansas have relatively few sampled homes in the State/EPA survey, a conservative approach to ranking the area was adopted. Indoor radon levels in this area are expected to range from low (< 2 pCi/L) to high (> 4 pCi/L) but are most likely to be in the moderate to high range, so area TL is assigned an overall high radon potential (RI=12) with high confidence (CI=11).

DS denotes areas underlain by dune sands in the Arkansas and Cimarron River valleys. The dune sands are highly permeable, but because they are composed almost entirely of quartz grains containing little or no uranium or radium, they generally generate low radon levels. If the deposits are thin (less than approximately 15 ft thick), the sands are likely to transmit radon from the underlying bedrock toward the surface and into homes built on these deposits. Relatively higher indoor radon levels are also more likely to occur where the sands are mixed with loess deposits. Area DS is assigned a moderate or variable geologic radon potential (RI=10), with a high confidence index (CI=11).

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 Kansas. See figure 9 for locations of areas.

	AREA					
	PPR		GLA		MCR	
FACTOR	RI	CI	RI	CI	RI	CI
INDOOR RADON	2	2	2	3	3	3
RADIOACTIVITY	2	3	2	2	2	3
GEOLOGY	2	2	3	3	3	2
SOIL PERM.	1	2	2	2	1	2
ARCHITECTURE	2	–	3	–	3	–
GFE POINTS	0	–	0	–	0	–
TOTAL	9	9	12	10	12	10
RANKING	MOD	MOD	HIGH	HIGH	HIGH	HIGH

	KR		TL		DS	
FACTOR	RI	CI	RI	CI	RI	CI
INDOOR RADON	2	3	2	3	2	3
RADIOACTIVITY	2	3	2	3	1	3
GEOLOGY	3	3	3	3	2	3
SOIL PERM.	2	2	2	2	2	2
ARCHITECTURE	3	–	3	–	3	–
GFE POINTS	0	–	0	–	0	–
TOTAL	12	11	12	11	10	11
RANKING	HIGH	HIGH	HIGH	HIGH	MOD	HIGH

RADON INDEX SCORING:

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

Possible range of points = 3 to 17

CONFIDENCE INDEX SCORING:

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

Possible range of points = 4 to 12

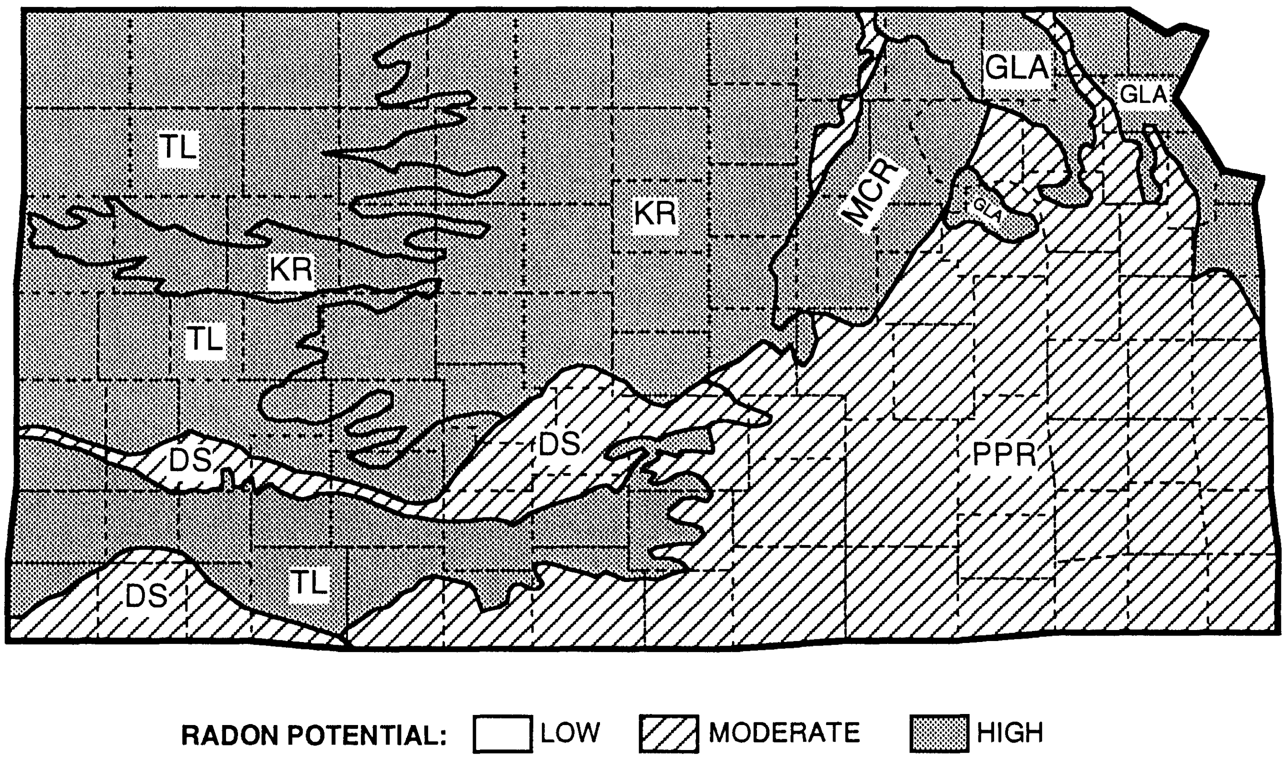


Figure 9. Geologic radon potential areas of Kansas. See Table 2 and text for descriptions and rankings of areas.

REFERENCES USED IN THIS REPORT
AND GENERAL REFERENCES PERTAINING TO RADON IN KANSAS

Bainum, D., Barton, J., Miller, D., To, D. and Trupp, R., 1989, Radon concentration in houses in the vicinity of Topeka, Kansas: Transactions of the Kansas Academy of Science, v. 92, p. 63-69.

Berendsen, P., and Hathaway, L.R., 1981, Uranium in unconsolidated aquifers of western Kansas: Kansas Geological Survey Mineral Resource Series 9, 43 p.

Berendsen, P., and Blair, K.P., 1986, Subsurface structural maps over the Central North American rift system (CNARS), central Kansas, with discussion: Kansas Geological Survey Subsurface Geology Series 8, 16 p., 7 plates.

Berendsen, P., Hathaway, L.R. and Macfarlane, P.A., 1988, Radionuclide distributions in the natural environment in Kansasa review of existing data, *in* M.A. Marikos and R.H. Hansman (eds), Geologic causes of natural radionuclide anomalies: Proceedings of GEORAD conference, St. Louis, MO, Apr. 21-22, 1987, Missouri Department of Natural Resources Special Publication 4, p. 65-74.

Berendsen, P., Newell, K.D., and Blair, K.P., 1989, Structural aspects of the mid-content rift system in Kansas: American Association of Petroleum Geologists Bulletin, v. 73, p. 1043.

Bidwell, O.W., and McBee, C.W., compilers, 1973, Soils of Kansas: Kansas Agricultural Experiment Station, Department of Agronomy Contribution No, 1359, scale 1:1,125,000.

Brookins, D.G., 1970, The kimberlites of Riley County, Kansas: Kansas Geological Survey Bulletin 200, p. 3-32.

Carey, S.J., Frye, J.C., Plummer, N., and Swineford, A., 1952, Kansas volcanic ash resources: Kansas Geological Survey Bulletin 96, 68 p.

Carmichael, R.S., 1989, Practical Handbook of physical properties of rocks and minerals: Boca Raton, Fla., CRC Press, 741 p.

Coveney, R.M., Jr., Hilpman, P.L., Allen, A.V., and Glascock, M.D., 1988, Radionuclides in Pennsylvanian black shales of the midwestern United States, *in* M.A. Marikos and R.H. Hansman (eds), Geologic causes of natural radionuclide anomalies: Proceedings of GEORAD conference, St. Louis, MO, Apr. 21-22, 1987, Missouri Department of Natural Resources Special Publication 4, p. 25-42.

Cullers, R.L., Ramakrishnan, S., Berendesn, P., and Griffin, T., 1985, Geochemistry and petrogenesis of lamproites, Late Cretaceous age, Woodson County, Kansas, USA: Geochimica et Cosmochimica Acta, v. 49, p. 1383-1402.

Dort, Wakefield, Jr., 1987, Salient aspects of the terminal zone of continental glaciation in Kansas, *in* Johnson, W.C., ed., Quaternary environments of Kansas: Kansas Geological Survey Guidebook Series no. 5, p. 55-66.

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

Gundersen, L.C.S., 1991, Radon in sheared metamorphic and igneous rocks, *in* Gundersen, L.C.S., and Wanty, R.B. (eds), Field studies of radon in rocks, soils, and water: U.S. Geological Survey Bulletin 1971, p. 39-50.

James, G.W., 1977, Uranium and thorium in volcanic ash deposits of Kansas: Implications for uranium exploration in the Central Great Plains, *in* Waldron, G.A., ed, Short Papers on Research in 1977: Kansas Geological Survey Bulletin 211, part 4, p. 1-3.

Landis, E.R., 1959, Radioactivity and uranium content, Sharon Springs Member of the Pierre Shale, Kansas and Colorado: U.S. Geological Survey Bulletin 1046-L, p. 299-319.

Macfarlane, P.A., 1981, Distribution of radium-226 in the lower Paleozoic aquifers of southeast Kansas and adjacent areas, *in* Hemphill, D.D., (ed), Trace substances in environmental health XIV, a symposium: Columbia, Missouri, University of Missouri, p. 78-85.

Olson, J.W., 1974, Using soils of Kansas for waste disposal: Kansas Geological Survey Bulletin 208, 51 p.

Ross, Jorgina A., compiler, 1991, Geologic map of Kansas: Kansas Geological Survey, scale 1:500,000.

Schumann, R.R., Owen, D.E., and Asher-Bolinder, S., 1989, Weather factors affecting soil-gas radon concentrations at a single site in the semiarid western U.S., *in* Osborne, M.C., and Harrison, J., Symposium Cochairmen., Proceedings of the 1988 EPA Symposium on Radon and Radon Reduction Technology, v. 2, EPA Publication EPA/600/9-89/006B, p. 3-1 to 3-13.

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

Steeples, D.W., and Buchanan, Rex, 1983, Kansas geomaps: Kansas Geological Survey Educational Series 4, 30 p.

Wagner, H.C., 1954, Geology of the Fredonia quadrangle, Kansas: U.S. Geological Survey Map GO-49.

Welch, J.E., and Hale, J.M., 1987, Pleistocene loess in Kansasstatus, present problems, and future considerations, *in* Johnson, W.C., ed., Quaternary environments of Kansas: Kansas Geological Survey Guidebook Series no. 5, p. 67-84.

Wilson, Frank, 1984, Landscapes: A geologic diary, *in* Buchanan, Rex, ed., Kansas geology: Lawrence, Kansas, University of Kansas Press, p. 9-39.

Wilson, F.W., 1979, A study of the regional tectonics and seismicity of eastern Kansas—summary of project activities and results to the end of the second year, or September 30, 1978: U.S. Nuclear Regulatory Commission report NUREG/CR-0666, 68 p.

Zeller, E.J., Dreschhoff, G., Angino, E., Holdoway, K., Hakes, W., Jayaprakash, G., Crisler, K., and Saunders, D.F., 1976, Potential uranium host rocks and structures in the central Great Plains: Kansas Geological Survey Geology Series 2, 59 p.

Zielinski, R.A., 1983, Tuffaceous sediments as source rocks for uranium—A case study of the White River Formation, Wyoming: Journal of Geochemical Exploration, v. 18, p. 285-306.

PRELIMINARY GEOLOGIC RADON POTENTIAL ASSESSMENT OF MISSOURI

by
James K. Otton
U.S. Geological Survey

INTRODUCTION

This assessment of the radon potential of Missouri is largely dependent on geologic information derived from publications of the Missouri Department of Natural Resources, Division of Geology and Land Survey, and from publications of the U.S. Geological Survey. Also, an analysis of data gathered during a radon survey in the winter of 1987-1988 by U.S. EPA and the Missouri Department of Health is included in this report. Much information in the geographic setting section is derived from The National Atlas of the United States of America (U.S. Geological Survey, 1974).

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

GEOGRAPHIC SETTING

Missouri lies within the continental interior of the United States and extends from the northern edge of the Gulf Coastal Plain northward to the southern edge of the glaciated plains. The Mississippi River runs along the eastern edge of the state and the Missouri River crosses north-central Missouri. The state can be subdivided into three major physiographic provinces (fig. 1)—the Central Lowlands, the Ozark Plateaus and the Coastal Plain or southeastern lowlands.

The Central Lowlands Province is divisible into two subprovinces (fig 1): the dissected till plains north of the Missouri River (IB) and the Osage Plains in the west-central part of the state south of the Missouri River (IA). The dissected till plains generally have 100-300 feet of relief but include areas of smooth plains, irregular plains, and open low hills (fig. 2). In the smooth plains more than 80 percent of the area is characterized by gentle slopes. In the irregular plains 50-80 percent of the area is characterized by gentle slopes, whereas in the low hills 20-50 percent of the area is underlain by gentle slopes. Bluffs along the Mississippi River north of St. Louis have 300-500 feet of local relief. In these areas, 20-50 percent of the area is underlain by gentle slopes. The Osage Plains are marked by smooth plains and irregular plains with 100-300 feet of local relief. More than 80 percent of the smooth plains are gently sloping, whereas 50-80 percent of the irregular plains are gently sloping.

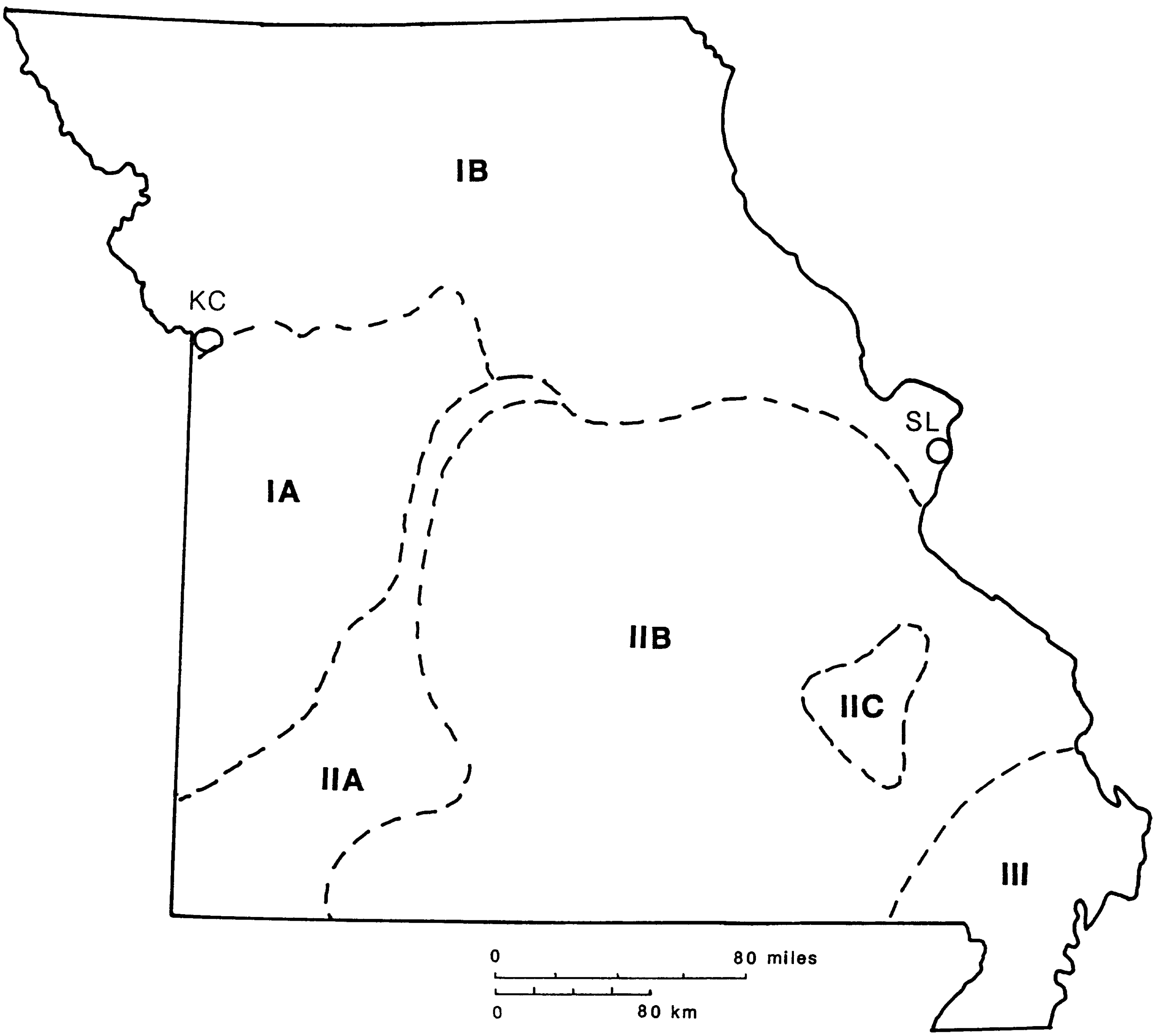


Fig. 1- Physiographic provinces of Missouri. I- Central Lowland Province: IA- Osage Plains, IB- Dissected till plains. II- Ozark Plateaus Province: IIA- Springfield Plateau, IIB- Salem Plateau, IIC- St. Francois Mountains. III- Southeastern lowlands or the Coastal Plains Province. KC- Kansas City; SL- Saint Louis. Modified from Duley, 1983.

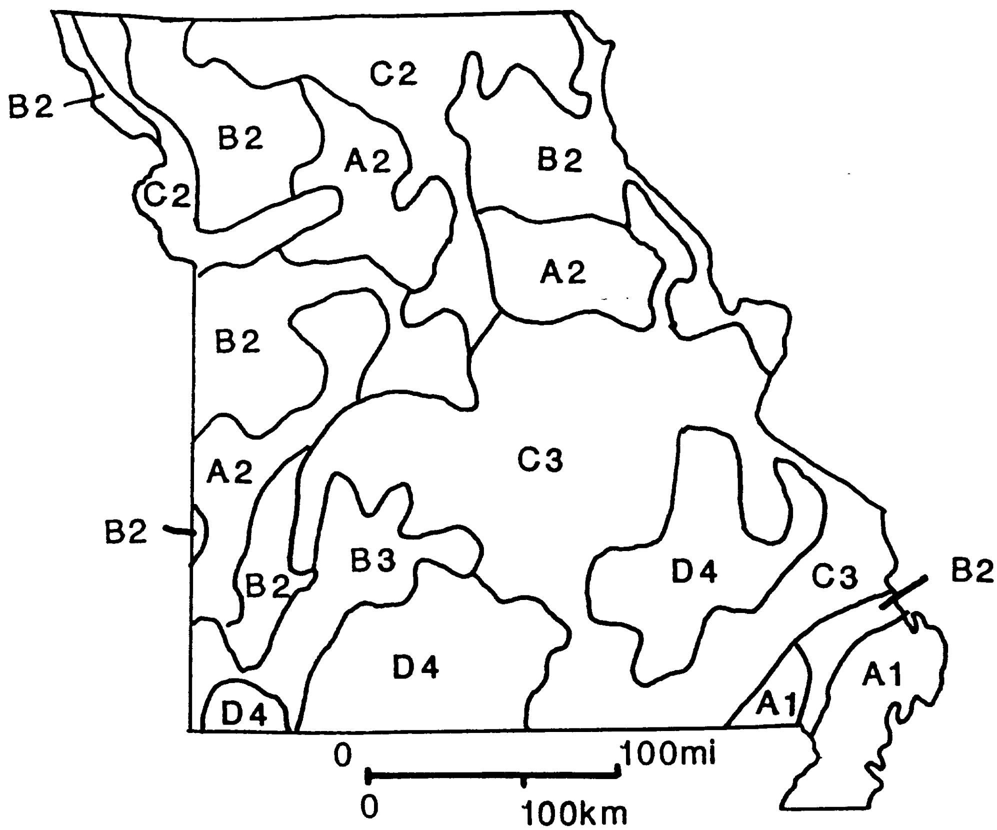


Fig. 2- Land surface map of Missouri. A1- Flat plains, >80% of the land surface is gently sloping, local relief 0-100 feet. A2- Smooth plains, >80% of the land surface is gently sloping, local relief 100-300 feet. B2- Irregular plains, 50-80% of the land's surface is gently sloping, local relief 100-300 feet. B3- Tablelands, 50-80% of the land's surface is gently sloping, local relief 300-500 feet. C2- Open low hills, 20-50% of the land's surface is gently sloping, local relief 100-300 feet. C3- Open hills, 20-50% of the land's surface is gently sloping, local relief 300-500 feet. D4- High hills, <20% of the land's surface is gently sloping, local relief 500-1000 feet. Map modified from The National Atlas of the United States of America.

The Ozark Plateaus Province includes the Springfield Plateau (IIA), the Salem Plateau (IIB), and the St. Francois Mountains (IIC) (fig. 1). This area includes tablelands and open hills of moderate relief (300-500 feet) and high hills with 500-1000 feet of relief (fig. 2). In the tablelands, which lie mostly along the western edge of the area, about 50-80 percent of the surface consists of gentle slopes that mostly occur in upland areas. The open hills have 20-50 percent of the surface underlain by gentle slopes as compared to the high hills where less than 20 percent of the area is gently sloping.

The Coastal Plain Province (III, fig. 1) is mostly underlain by flat plains with relief less than 100 feet, except for a northeast-trending ridge with relief 100-300 feet that traverses the province (fig. 2). On the flat plains, more than 80 percent of the area is gently sloping. On the ridge, 50-80 percent of the area is gently sloping.

Annual precipitation across the state decreases gradually from about 48 inches in the southeast corner to about 32 inches in the northwest corner. May and June, the wettest months of the year, have a mean monthly rainfall of four inches across most of the state. December, January, and February are the driest months with mean monthly precipitation ranging from about 1 inch in the northwest to nearly 4 inches in the southeast.

About half of the population of the state lives in the St. Louis and Kansas City metropolitan areas (fig. 1). The rest of the population is fairly evenly distributed throughout the rest of the state (fig. 3) in small cities and towns, except in the Ozark Plateau (IIA, IIB, IIC, fig. 1) and the dissected till plains (IB, fig. 1) where the population density is lower.

The Central Lowlands (IA, IB, fig. 1) are used primarily as cropland; lesser uses include grazing land, pasture, woodland, and forest. The Ozark Plateau (IIA, IIB, IIC, fig. 1) includes mostly woodland and forest with lesser areas of cropland and pasture. The Coastal Plain (III, fig 1) is dominantly cropland.

GEOLOGIC SETTING

Missouri lies within the stable midcontinent area of the United States. The dominant geologic feature is the Ozark uplift in the southeastern part of the state which forms the Ozark Plateau Province. Precambrian crystalline rocks core the uplift and crop out along its eastern side (fig. 4). Paleozoic sedimentary rocks dip away from this core in all directions. To the north, northwest, and west of the uplift these sedimentary sequences are folded into broad arches and sags. The Forest City basin occupies the northwest corner of the state. Along the northeastern edge of the state, the sedimentary sequences dip eastward into the Illinois basin. A broad arch, cored by Ordovician rocks, lies parallel to and just west of the Mississippi River from St. Louis northward.

The northernmost part of the Mississippi Embayment underlies the southeastern corner of the State and forms the Coastal Plain Province (III, fig. 1), or southeastern lowlands. Cretaceous and younger marine sediments were deposited in this structural sag, but the present-day surface exposures consist mostly of Tertiary and Quaternary alluvium.

The Precambrian core of the Ozark uplift is primarily granite and rhyolite (fig. 4). Much of this rock is slightly enriched in uranium (2.5-5.0 ppm). The Precambrian core is surrounded by Cambrian and Ordovician sandstone, dolostone, shale, cherty dolostone, chert, and limestone. Pennsylvanian sandstone, shale and clay crop out in the north-central part of the uplift. To the north and west of the uplift, Mississippian and Pennsylvanian shale, limestone, sandstone, clay, coal, and fire clay occur. Silurian and Devonian sedimentary rocks crop out in central Missouri

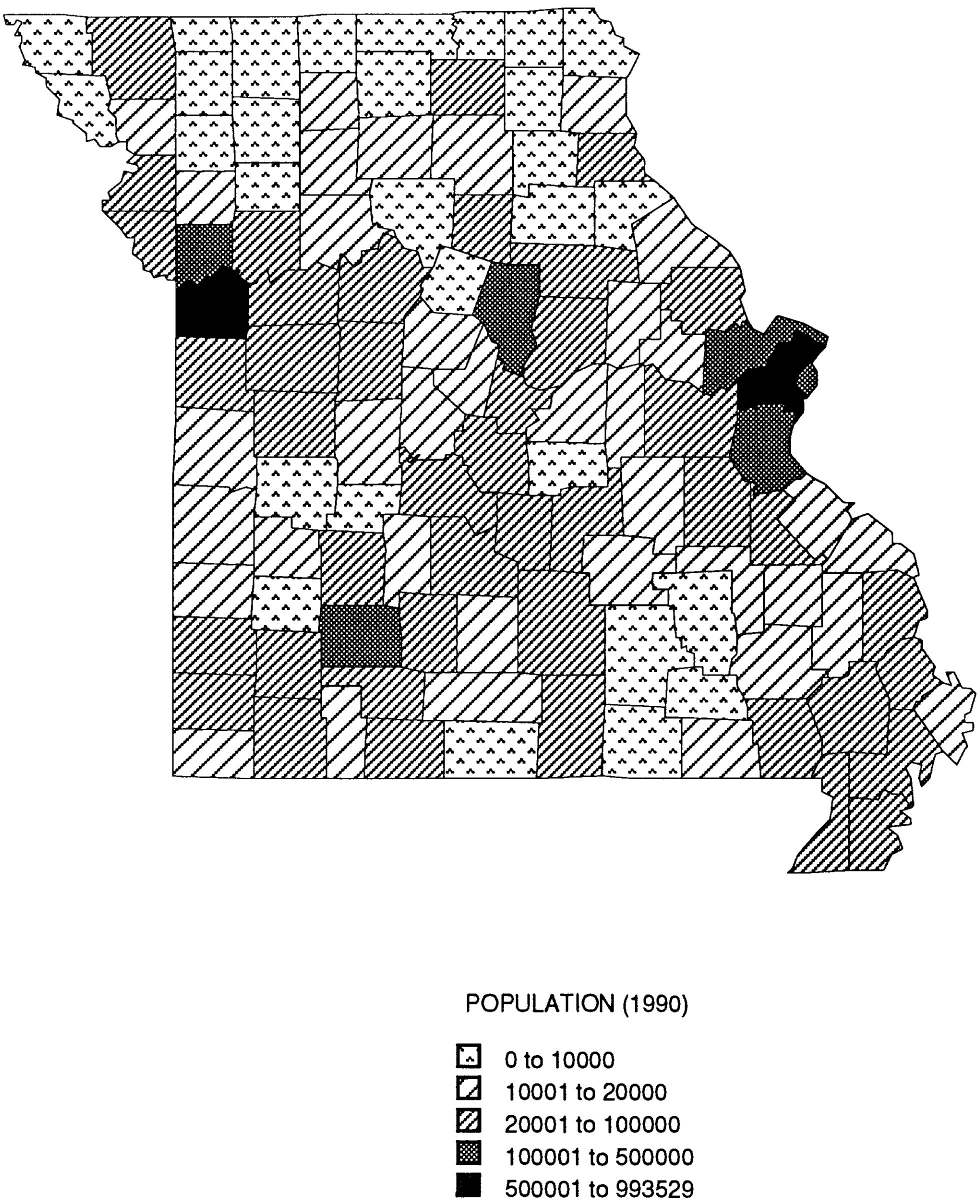


Figure 3. Population of counties in Missouri (1990 U.S. Census data).

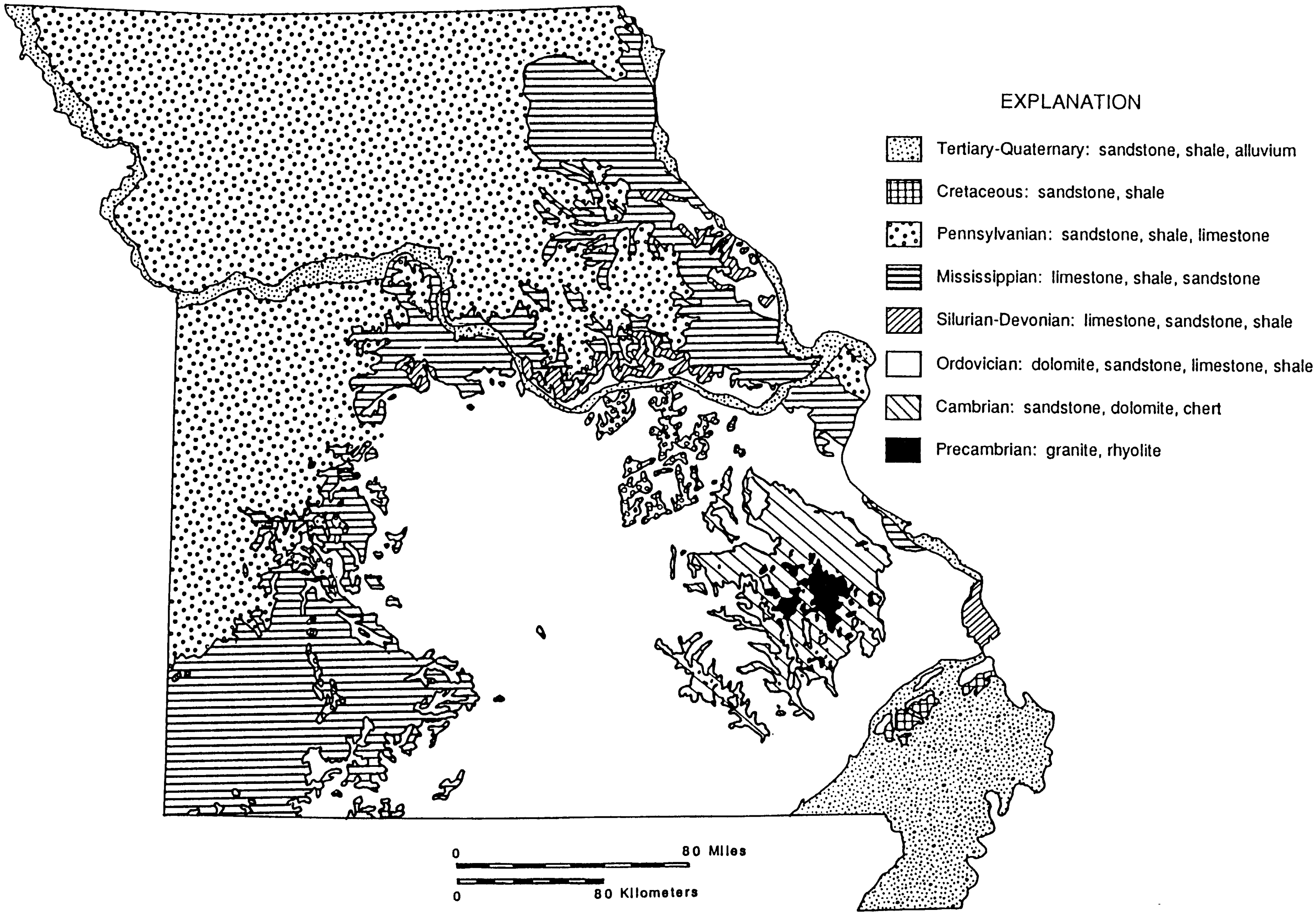


Figure 4- Generalized geologic map of Missouri. Modified from Howe, 1984.

along the Missouri River and along the Mississippi River northeast of St. Louis and in Cape Girardeau and Perry Counties south of St. Louis (figs. 4 and 5).

Several very thin, uranium-bearing (as much as 180 ppm; Nuelle, 1987), black, phosphatic shales occur in the Devonian and Pennsylvanian sedimentary rock sequence. They crop out principally in west-central Missouri in Jackson, Lafayette, Cass, Johnson, Bates, Henry, Vernon, and Barton Counties (figs. 4 and 5). North of the Missouri River these black shales are mostly covered by glacial deposits, but they are exposed at the surface in some areas, especially in Randolph, Macon, and Boone Counties.

Land subsidence related to old mine workings occurs in some areas of the Ozark Plateau. Such subsidence may locally affect soil and subsoil permeability and foundation integrity. Uranium-bearing granite has been quarried in Iron County for dimension stone (M. Marikos, written commun., 1986) and used locally for construction of buildings.

The surficial geology north of the Missouri River (fig. 6) is dominated by glacial deposits covered by a thin veneer of loess (fine-grained wind blown sediment); however, several areas of residual soils developed on underlying sedimentary rocks occur in the eastern and western parts of this region. Residual soils are those soils formed by weathering of the material beneath the soil. These surficial deposits (both glacial deposits and residuum) are generally 50-200 feet thick, but they locally exceed 200 feet along the northern border of the state.

Residuum developed on sedimentary rocks dominates the area south of the Missouri River. Here, the surficial materials are generally less than 50 feet thick, except in the eastern part of the Ozark Plateau where residuum is typically 50-200 feet thick and locally exceeds 200 feet. In the southeastern corner of the state, thick residuum exceeding 50 feet, and locally exceeding 200 feet, has developed on the sedimentary rocks and the younger alluvium exposed there.

Alluvial deposits (silt, sand, and gravel) are the primary surficial deposits along the Missouri and Mississippi River valley floor. Loess deposits occur on the flanks on the river valleys in several areas and are especially widespread in Platte, Buchanan, Holt, and Atchison Counties along the Missouri River north of Kansas City.

Broad karst areas have formed by dissolution of carbonate rocks in the central and western Ozark Plateau and the southern Osage Plains areas, and along the Mississippi River from Cape Girardeau County to Ralls County (fig. 7). Karst is a type of topography characterized by closed depressions or sinkholes, caves, and underground drainage. The permeability of soils and subsoils in karst areas has been enhanced by solution openings in and near carbonate pinnacles and by zones of solution collapse. Where soils developed on such carbonate rocks are thin, foundations may encounter open bedrock fractures or solution cavities in the limestone.

The aeroradiometric survey of the State shows two distinctive areas (fig. 8). One, north of the Missouri River, is a broad area with gradual changes in equivalent uranium (eU) that range from 1.0-2.0 ppm in the north-central part of the area to as much as 3.0 ppm in the southeastern part of that area. The change in values likely reflects changes in the composition of the parent material of the glacial deposits. Areas of elevated eU (defined as >2.5 ppm in this report) may contain a higher proportion of uraniferous black shale fragments in the glacial deposits. Loess and alluvium along the Missouri River upstream from Kansas City ranges from 2.0 to 3.0 ppm eU.

South of the Missouri River, changes in the aeroradiometric signature appear more abrupt. Residuum developed on the rhyolites and granites comprising the core of the Ozark uplift contain as much as 4.0 ppm eU (fig. 8). These rhyolites and granites contain modest amounts of uranium in fresh samples; for example, six of eight sampled granites averaged greater than 3 ppm U

Figure 5. Missouri Counties.

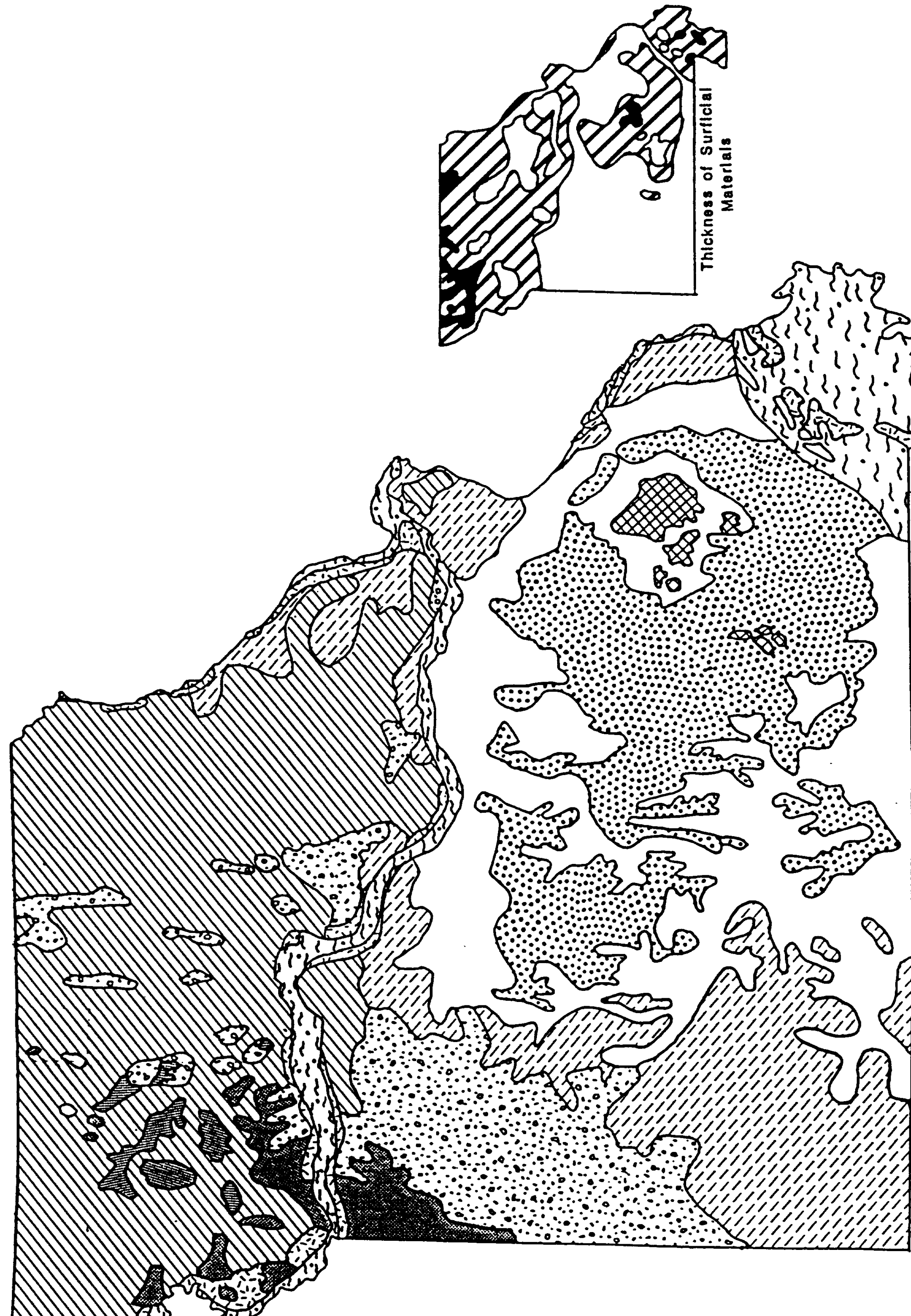


Figure 6- Surficial materials map of Missouri. Modified from Missouri Geologic Survey, 1983.

EXPLANATION FOR THE SURFICIAL MATERIALS MAP OF MISSOURI

- Alluvium - silt, sand, and gravel
- Loess - silt and clayey silt
- Glacial deposits - usually overlain by loess
- Residuum from limestone and shale
- Residuum from shale, limestone, and sandstone
- Residuum from cherty limestone
- Residuum from cherty dolomite
- Residuum from cherty sandstone and dolomite
- Residuum from igneous rocks

Thickness of Surficial Materials:

- < 50 feet
- 50 - 200 feet
- > 200 feet

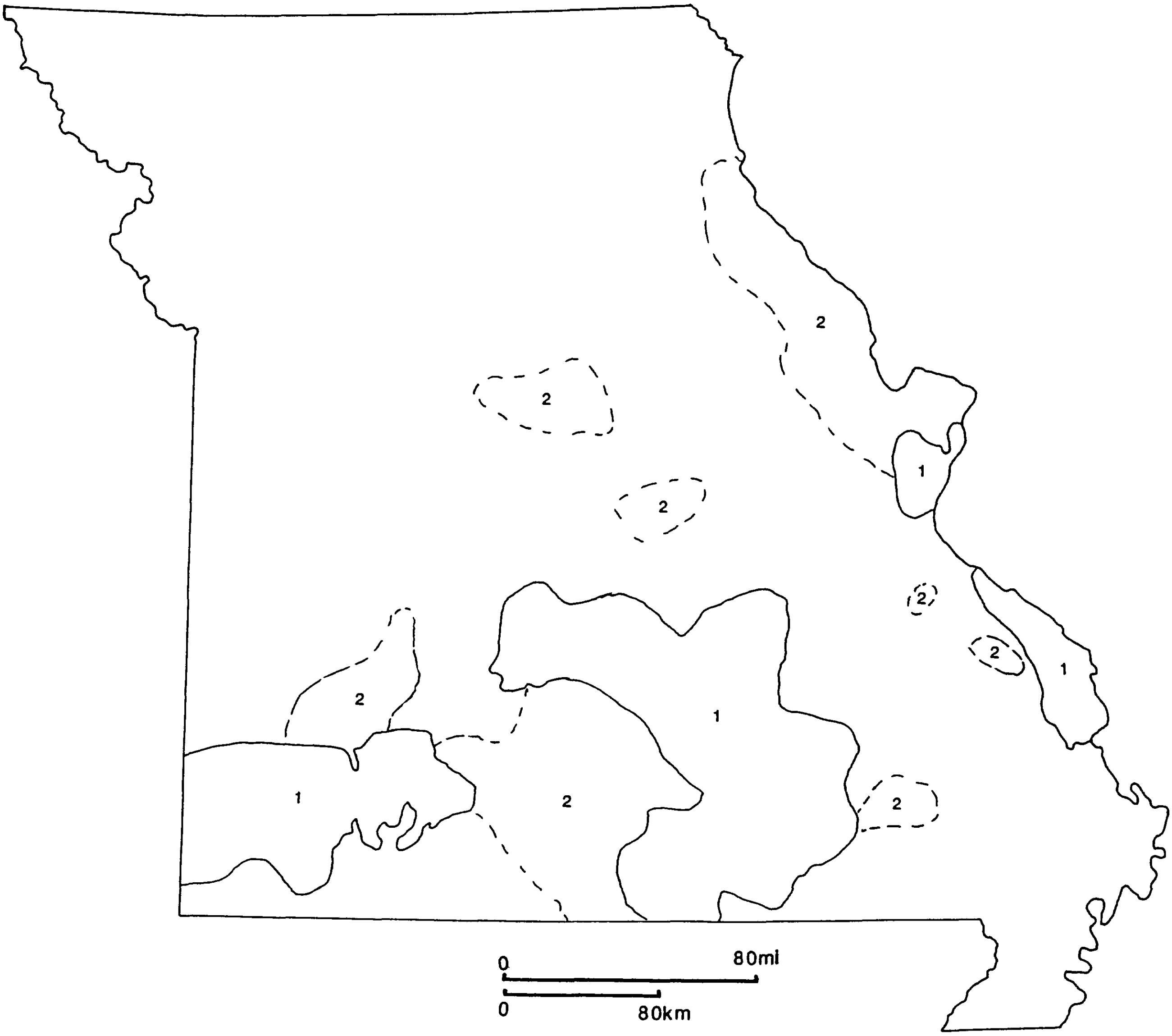


Fig. 7- Map showing areas of karst in Missouri. 1- Areas of substantial karst development. 2- Areas of moderate karst development. Modified from Duley (1983).

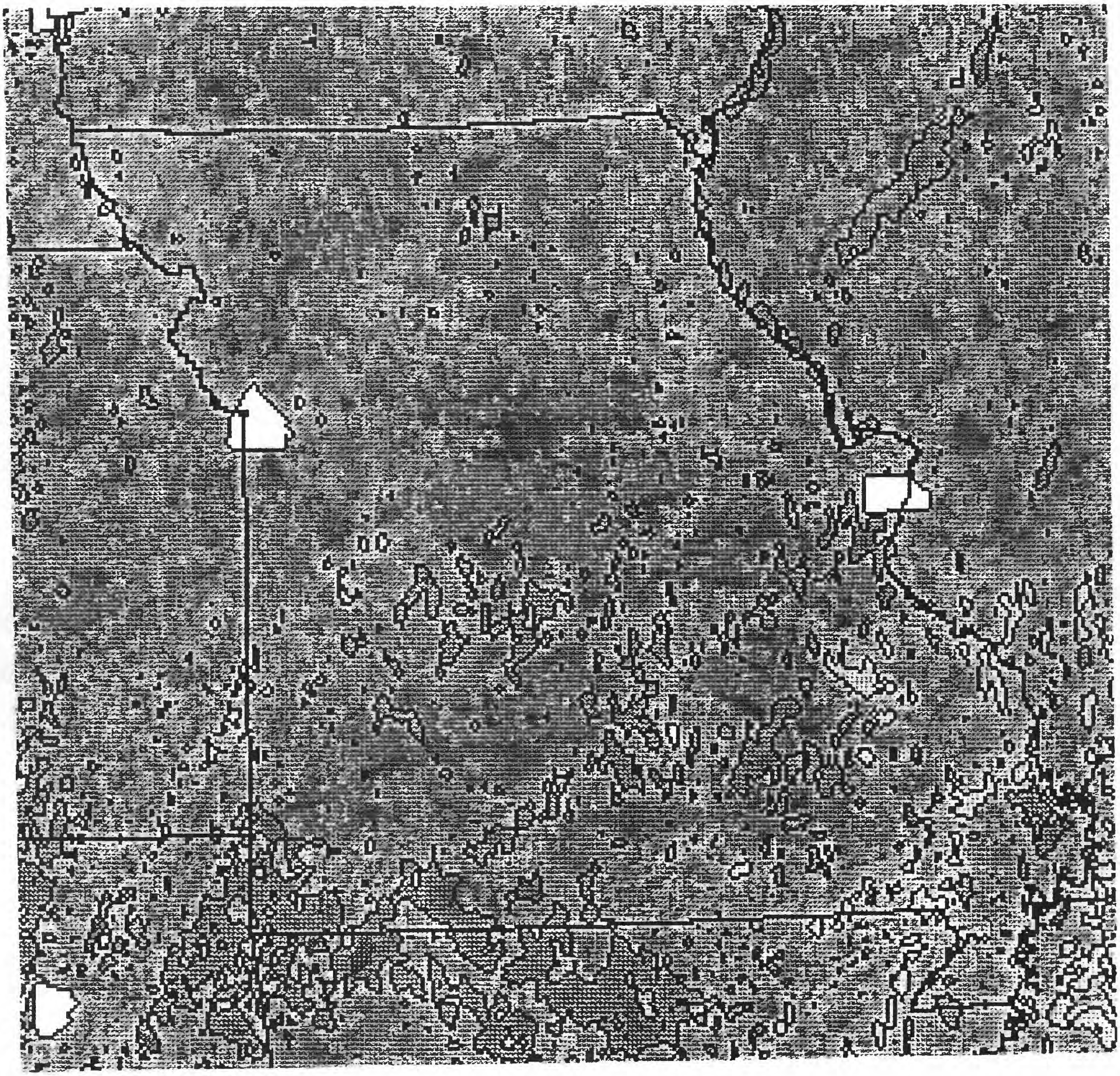


Fig. 8- Aerial radiometric map of Missouri (after Duval and others, 1989). Contour lines at 1.5 and 2.5 ppm equivalent uranium (eU). Pixels shaded from 0 to 6.0 ppm eU at 0.5 ppm eU increments; darker pixels have lower eU values; white indicates no data.

(the average for granites worldwide) and they ranged from 3 to 34 ppm U in various data sets (Nuelle, 1987). Structures sited directly on thin soils developed over such uranium-bearing bedrock or on deep residuum in which uranium has been retained in the soil profile are likely to have elevated indoor radon. Deep residuum developed on the Cambrian, Ordovician, and Mississippian sedimentary rocks of the rest of the Ozark Plateau and the southern part of the Osage Plain ranges from 0.5 ppm to 3.5 ppm eU (fig. 8). The parts of this area with elevated eU values probably represent residuum developed on carbonate rocks in which uranium has been retained in the soil profile. In Pennsylvania, residuum on carbonate rocks of this age may contain as much as 8 ppm uranium (Greeman and others, 1990). Although the original limestone or dolostone may have less than 1 ppm uranium, uranium is often retained in the soil profile by clays and iron oxyhydroxides during dissolution of the carbonate bedrock; thus the soil becomes enriched in uranium. Houses sited on such residuum often have elevated indoor radon readings. Elevated eU readings (2.5-3.5 ppm) occur in Ordovician and Mississippian-age rocks in Perry, Cape Girardeau, Bollinger, Carter, Ripley, Oregon, Howell, Texas, Barry, and Lawrence Counties (figs. 5 and 8).

The region underlain by residuum developed on Pennsylvanian sedimentary rocks in western Missouri has a broad northeast-trending band of elevated eU with as much as 4.0 ppm in Henry County. This corresponds to an outcrop belt of uranium-bearing Pennsylvanian black shales (fig. 4), notably the Mecca Quarry and Excello Shale Members of the Carbondale Formation, the Little Osage Shale Member of the Fort Scott Limestone, and the Anna Shale Member of the Fort Pawnee Formation (Coveney and others, 1987). These black shale beds are typically very thin (a few tens to several tens of centimeters) but contain significant amounts of uranium (20-170 ppm; Coveney, and others, 1987; Nuelle, 1987); the phosphatic black shales tend to be the most uraniferous. Such shales are also well jointed and thus have relatively high permeability to gases. The shales are typically separated from one another by thick intervals of coal, fire clay, gray shale, sandstone, and limestone. Detailed geologic maps are necessary for determining where such shales occur in outcrop. Other black shales occur throughout northwesternmost and north-central Missouri but are largely covered by glacial deposits. Where such shales are overlain by glacial deposits, they may be incorporated in those deposits and cause an increase in the uranium content of such deposits. Several thin black shale intervals have been identified in the Kansas City metropolitan area (Coveney and others, 1987). Where the foundation of a structure cuts through one of these black shale intervals, the indoor radon levels may be high. Locations where overlying residuum is thin and black shale bedrock is near the surface, such as on hillslopes adjacent to stream valleys, are places where radon potential is likely to be high.

The uranium-bearing, Late Devonian and Early Mississippian-age, Chattanooga Shale occurs in McDonald, Newton, and Barry Counties in southwestern Missouri and in Marion, Ralls, Pike, and Lincoln Counties in northeastern Missouri (Nuelle, 1987; M. Marikos, written commun., 1986). Uranium analyses of this unit are sparse in Missouri, however. In McDonald, Newton, and Barry Counties, the Chattanooga crops out near the base of bluffs or underlies alluvium in stream valleys. Homes sited in stream valleys in these areas may have elevated radon levels.

Uranium minerals and radioactive carbonaceous material occur in fire clay pits near Owensville in southern Gasconade County and near Fulton in Callaway County (Muilenburg, 1957). Uranium minerals occur in a limestone quarry near Ste. Genevieve in Ste. Genevieve County and in chert and limestone near Creighton in Cass County (Muilenburg, 1957). Uraniferous asphaltic or bituminous material occurs in dolomitic rocks near Ava in Douglas

County, in cherty residuum near West Plains and Willow Springs in Howell County, in siliceous residuum and sandstone near Bardley in Oregon County, and in vugs in the Bonneterre Dolomite (Upper Cambrian) near Fredericktown in Madison County (Muilenburg, 1957). Such uranium occurrences may cause indoor radon problems if the foundations of structures are sited in rocks and soils where they occur. Predicting the specific location of such uranium occurrences is not possible with present information and individual site inspections may be necessary due to the localized nature of such deposits.

SOILS

Most of Missouri lies in the mesic udic soil moisture-temperature regime (Rose and others, 1990); however, the southeastern corner of the state and the westernmost edge of the state south of Kansas City is thermic udic. Mesic udic soils are very moist (56-96 percent pore saturation in sandy loams, and 74-99 percent saturation in a silty clay loam) in the winter and are moderately moist (44-56 percent saturation in sandy loams, and 58-74 percent in a silty clay loam) in the summer. Thermic udic soils are very moist in the winter (56-96 percent pore saturation in sandy loams, and 74-99 percent saturation in a silty clay loam) and are slightly moist in the summer (24-44 percent pore saturation in sandy loams, and 39-58 percent pore saturation in silty clay loams).

In places where soils are moderately moist to very moist, soil moisture will tend to inhibit radon migration by diffusion and flow. However, soils in which the water drains rapidly from the soil profile because of elevated intrinsic permeability, or steep slopes, or both, may be areas where radon may migrate more readily and the radon potential of that area is increased. Conversely, soils in which the water drains away slowly because of low intrinsic permeability, low slopes, or both, may be areas where radon migrates very slowly, and the area's radon potential is lowered.

Excessively drained soils (soils with high internal permeability or steep slope) are uncommon in Missouri, but they do form parts of some mapped soil associations (fig. 9). Somewhat excessively drained soils are more common and form parts of several mapped soil associations, principally in the Ozark Plateau and along the valley of the Missouri River.

Very slowly permeable and somewhat poorly to very poorly drained soils are also common in Missouri, and they form varying percentages of various mapped soil associations, largely in the eastern part of the central lowland (fig. 10), the lower Osage plain, along the lower Missouri and Mississippi River valley floors, and in the southeastern lowland. Broad areas in which the entire soil association is composed of very slowly permeable and somewhat poorly to poorly drained soils occur in the eastern part of the central lowland.

INDOOR RADON DATA

The Missouri Department of Health and the U.S. EPA conducted a population-based screening survey of indoor radon levels in Missouri (Table 1, fig. 11). Geologic interpretations of population-based data must be made with caution because the measured houses are typically only from a relatively few population centers in a given county and thus do not necessarily characterize the entire county's area. For example, a county may have a relatively high radon potential on well-drained, uranium-bearing soils on hillslopes that occur over a widespread area, but if housing is generally located on poorly drained, low-uranium soils on the valley floor, a population-based survey for that area will have relatively low radon values.

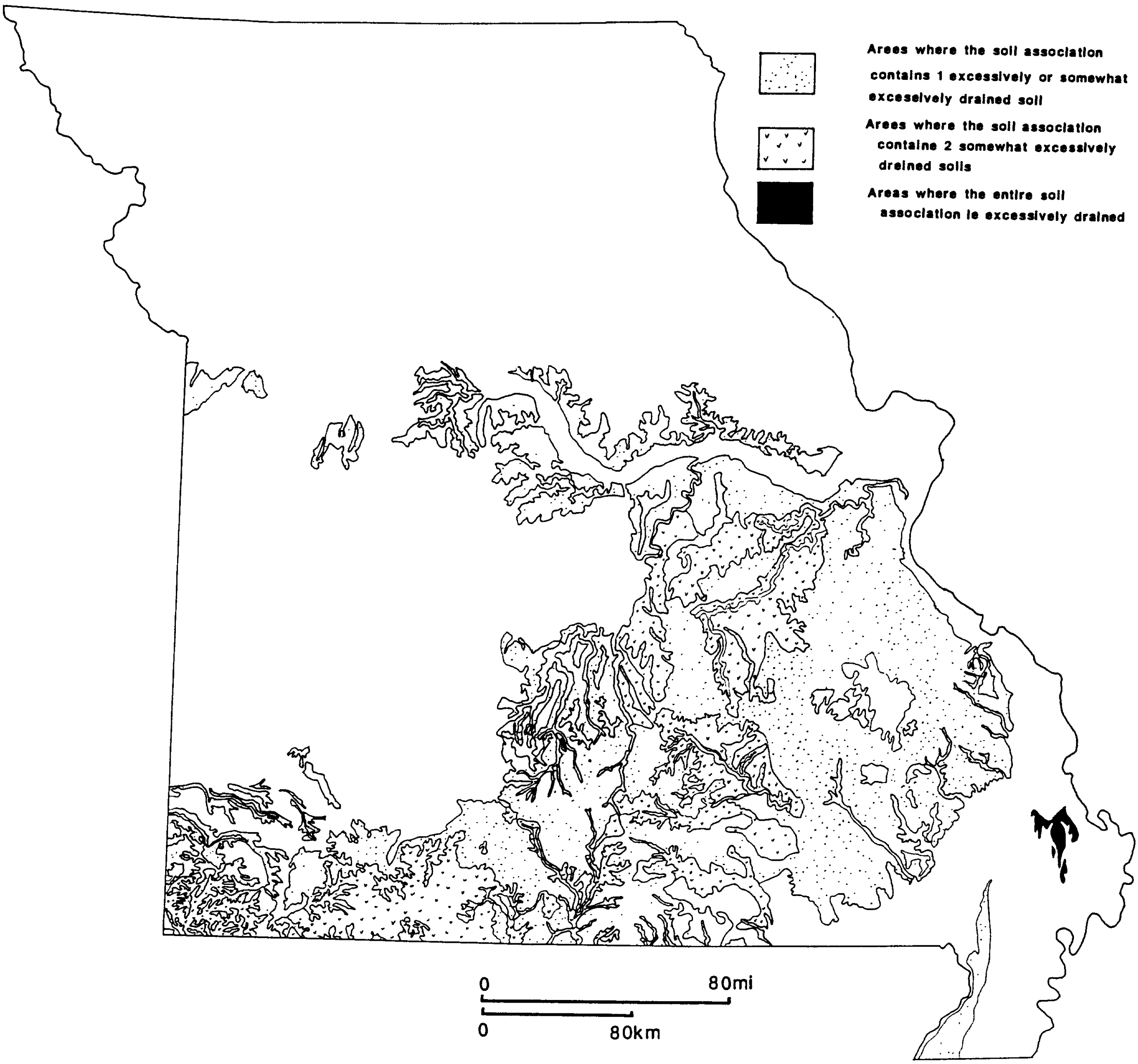


Fig. 9- Map showing soil associations in Missouri where one or more mapped soils are excessively or somewhat excessively drained. Map derived from maps and data in Soil Conservation Service (1979).

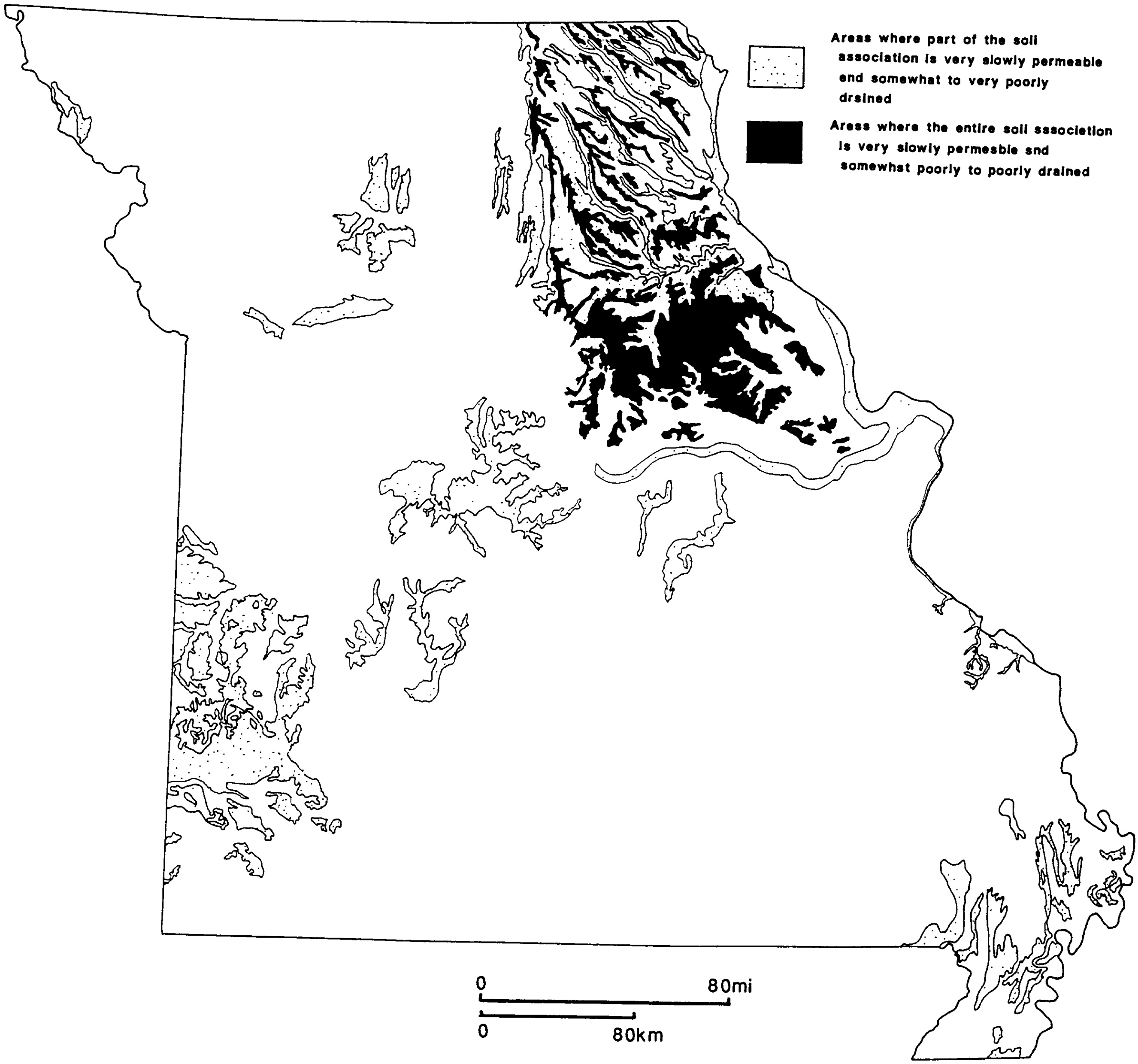
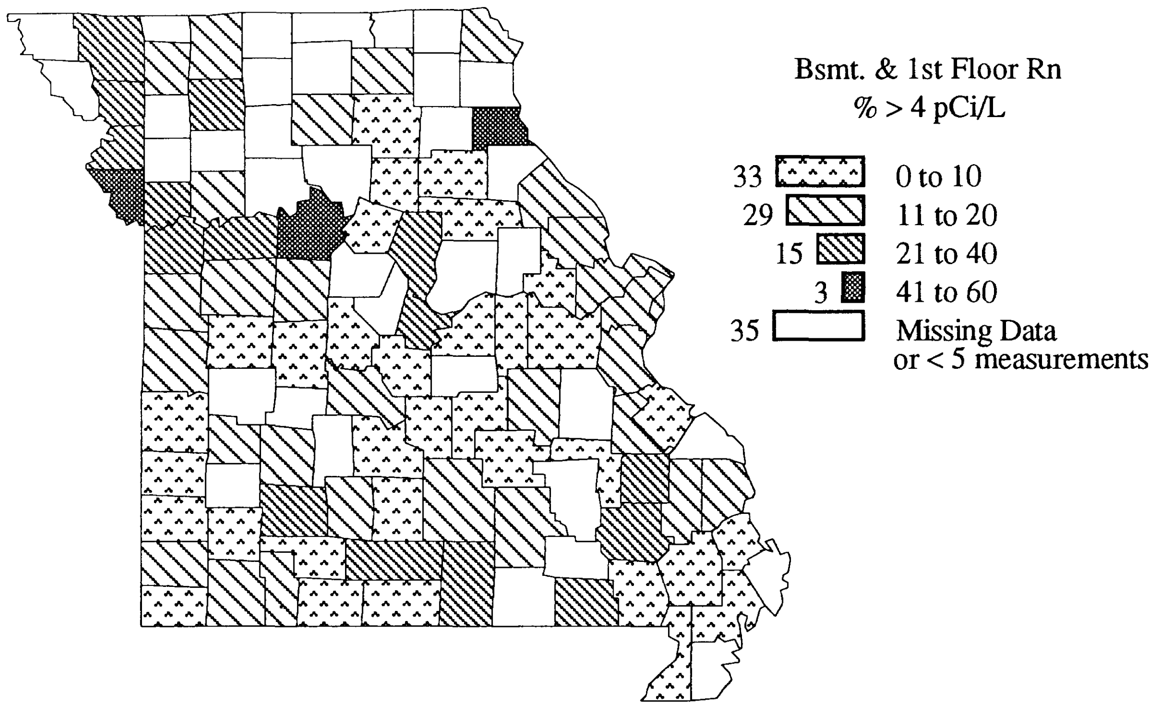


Fig. 10- Map showing soil associations in Missouri where one or more mapped soils are very slowly permeable and somewhat to very poorly drained. Map derived from maps and data in Soil Conservation Service (1979).



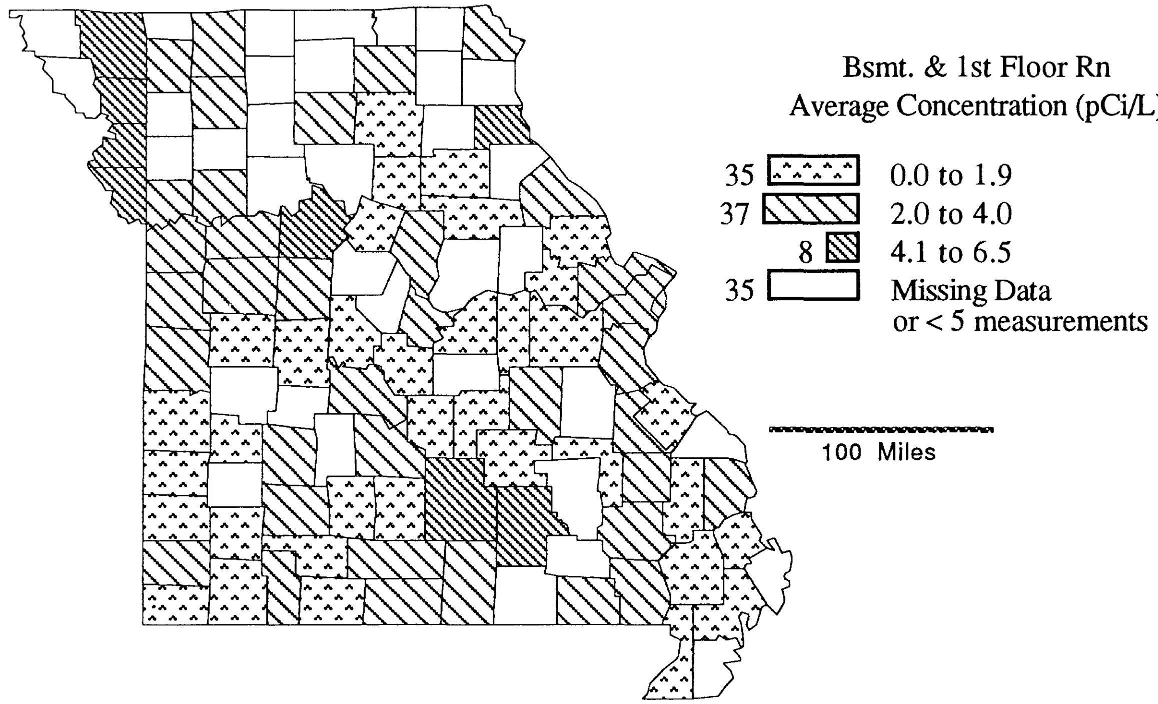


Figure11. Screening indoor radon data from the EPA/State Residential Radon Survey of Missouri, 1987-1988, for counties with 5 or more measurements. Data are from 2-7 day charcoal canister tests. Histograms in map legends show the number of counties in each category. The number of samples in each county (See Table 1) may not be sufficient to statistically characterize the radon levels of the counties, but they do suggest general trends. Unequal category intervals were chosen to provide reference to decision and action levels.

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

COUNTY	NO. OF MEAS.	MEAN	GEOM. MEAN	MEDIAN	STD. DEV.	MAXIMUM	%>4 pCi/L	%>20 pCi/L
ADAIR	6	2.4	1.9	2.2	1.7	5.6	17	0
ANDREW	6	6.5	2.6	1.9	10.7	28.0	33	17
ATCHISON	4	10.8	8.2	9.5	8.2	22.0	75	25
AUDRAIN	6	0.9	0.5	0.5	0.8	1.9	0	0
BARRY	10	1.9	1.5	1.6	1.4	4.5	20	0
BARTON	10	1.1	0.8	0.7	1.1	3.4	0	0
BATES	11	2.8	2.0	2.3	2.2	7.0	18	0
BENTON	7	0.9	0.6	0.9	0.6	1.7	0	0
BOLLINGER	10	1.8	1.3	1.4	1.6	5.1	20	0
BOONE	13	3.0	2.0	1.9	3.1	11.9	23	0
BUCHANAN	39	4.5	3.1	3.3	3.8	19.9	38	0
BUTLER	12	2.4	1.0	1.0	3.9	14.4	8	0
CALDWELL	3	2.3	2.1	2.5	1.3	3.5	0	0
CALLAWAY	3	2.1	1.5	2.3	1.6	3.5	0	0
CAMDEN	24	3.3	1.8	1.7	4.8	22.8	17	4
CAPE GIRARDEAU	10	3.1	2.4	2.0	2.9	10.2	20	0
CARROLL	4	3.2	2.8	3.3	1.8	4.9	50	0
CARTER	2	2.5	2.4	2.5	0.1	2.5	0	0
CASS	57	2.1	1.6	1.5	2.0	10.2	14	0
CEDAR	8	1.3	0.9	0.8	1.6	5.2	13	0
CHARITON	4	1.6	1.3	1.7	1.0	2.8	0	0
CHRISTIAN	7	1.1	0.9	0.9	0.6	2.0	0	0
CLARK	5	2.0	1.7	2.0	1.3	4.1	20	0
CLAY	94	3.8	2.5	2.4	4.5	25.3	29	3
CLINTON	4	2.6	2.0	1.6	2.4	6.2	25	0
COLE	34	2.4	1.6	1.8	2.0	8.8	21	0
COOPER	4	3.1	2.2	2.3	2.7	6.9	25	0
CRAWFORD	7	2.5	1.0	0.9	3.4	9.7	14	0
DADE	1	2.7	2.7	2.7	0.0	2.7	0	0
DALLAS	4	1.1	1.0	1.1	0.5	1.6	0	0
DAVIESS	7	2.0	1.3	1.2	1.7	4.6	29	0
DE KALB	4	1.6	0.8	1.7	1.5	3.1	0	0
DENT	6	0.8	0.5	0.6	0.7	1.6	0	0
DOUGLAS	8	2.9	1.4	1.1	3.8	10.7	25	0
DUNKLIN	12	1.5	1.1	1.1	1.3	4.9	8	0
FRANKLIN	40	1.8	1.4	1.5	1.5	6.9	8	0
GASCONADE	7	0.6	0.4	0.5	0.4	1.2	0	0
GENTRY	5	2.2	1.6	1.1	2.2	6.0	20	0
GREENE	42	3.8	2.2	2.1	7.8	51.8	24	2
GRUNDY	4	1.3	1.2	1.3	0.4	1.7	0	0
HARRISON	6	3.3	2.6	2.0	3.2	9.7	17	0

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

COUNTY	NO. OF MEAS.	MEAN	GEOM. MEAN	MEDIAN	STD. DEV.	MAXIMUM	%>4 pCi/L	%>20 pCi/L
HENRY	28	1.6	1.3	1.3	1.1	4.1	4	0
HICKORY	2	0.6	0.5	0.6	0.1	0.6	0	0
HOLT	2	1.8	1.0	1.8	2.1	3.3	0	0
HOWARD	10	1.8	1.4	1.6	1.2	3.8	0	0
HOWELL	15	3.6	2.3	2.1	3.6	12.5	33	0
IRON	7	0.8	0.6	0.6	0.5	1.5	0	0
JACKSON	271	3.9	2.7	2.8	4.1	29.9	30	1
JASPER	40	1.5	1.0	1.1	1.4	7.8	5	0
JEFFERSON	49	2.8	1.8	1.8	3.2	17.0	16	0
JOHNSON	32	2.3	1.6	1.7	2.4	11.2	19	0
KNOX	3	1.2	0.7	1.6	0.9	1.8	0	0
LACLEDE	12	2.0	0.9	0.9	3.4	12.3	8	0
LAFAYETTE	34	3.5	2.8	3.1	2.3	8.8	38	0
LAWRENCE	11	1.5	1.1	1.1	1.0	2.9	0	0
LEWIS	1	0.4	0.4	0.4	0.0	0.4	0	0
LINCOLN	6	1.3	0.8	0.9	1.6	4.5	17	0
LINN	5	2.2	2.0	2.1	1.3	4.2	20	0
LIVINGSTON	2	3.5	3.0	3.5	2.3	5.1	50	0
MACON	5	1.2	1.0	1.2	0.6	2.0	0	0
MADISON	7	3.1	2.1	1.7	3.0	8.0	29	0
MARIES	2	0.4	0.2	0.4	0.4	0.6	0	0
MARION	8	5.5	3.0	3.7	6.4	19.6	50	0
MCDONALD	5	1.0	0.4	0.5	1.4	3.4	0	0
MERCER	2	1.1	1.1	1.1	0.3	1.3	0	0
MILLER	10	1.2	0.9	1.0	1.0	3.0	0	0
MISSISSIPPI	3	0.4	0.3	0.2	0.3	0.8	0	0
MONITEAU	4	0.8	0.6	0.7	0.7	1.8	0	0
MONROE	7	0.6	0.5	0.7	0.3	1.0	0	0
MONTGOMERY	2	2.8	1.6	2.8	3.3	5.1	50	0
MORGAN	8	0.9	0.7	0.8	0.8	2.7	0	0
NEW MADRID	7	1.2	0.8	0.8	1.3	3.8	0	0
NEWTON	11	3.0	1.5	1.4	4.1	12.0	18	0
NODAWAY	8	4.1	2.9	2.4	4.3	14.2	38	0
OREGON	3	3.6	3.4	3.1	1.4	5.2	33	0
OSAGE	6	1.3	0.9	0.8	1.3	3.8	0	0
OZARK	5	2.0	1.9	2.1	0.5	2.4	0	0
PEMISCOT	1	2.7	2.7	2.7	0.0	2.7	0	0
PERRY	4	6.4	3.3	5.7	6.4	13.4	50	0
PETTIS	18	2.5	1.6	1.7	2.8	12.4	11	0
PHELPS	14	1.0	0.8	0.8	1.0	4.1	7	0
PIKE	9	2.2	1.5	1.5	2.2	7.2	11	0
PLATTE	25	5.6	3.6	4.2	5.5	21.3	52	4
POLK	15	2.2	1.3	1.3	2.9	11.6	13	0

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

COUNTY	NO. OF MEAS.	MEAN	GEOM. MEAN	MEDIAN	STD. DEV.	MAXIMUM	%>4 pCi/L	%>20 pCi/L
PULASKI	12	0.7	0.6	0.6	0.5	2.2	0	0
PUTNAM	3	0.7	0.6	0.7	0.3	0.9	0	0
RALLS	1	0.9	0.9	0.9	0.0	0.9	0	0
RANDOLPH	6	1.3	1.1	1.3	0.6	2.1	0	0
RAY	17	2.7	1.8	1.6	3.1	10.8	12	0
REYNOLDS	1	2.7	2.7	2.7	0.0	2.7	0	0
RIPLEY	11	3.1	1.9	1.4	3.0	8.3	27	0
SALINE	9	4.7	3.4	3.8	3.8	12.5	44	0
SCHUYLER	1	2.3	2.3	2.3	0.0	2.3	0	0
SCOTLAND	4	1.1	0.7	1.0	0.9	2.2	0	0
SCOTT	13	1.3	0.9	1.0	1.0	3.4	0	0
SHANNON	6	5.0	2.6	2.2	7.5	20.3	17	17
SHELBY	3	3.2	2.3	1.4	3.1	6.8	33	0
ST. CHARLES	50	2.5	1.7	1.7	2.8	13.9	16	0
ST. CLAIR	3	2.9	2.5	3.3	1.6	4.2	33	0
ST. FRANCOIS	48	2.5	1.6	1.6	2.8	15.8	17	0
ST. LOUIS	91	2.3	1.7	1.6	2.6	17.8	13	0
ST. LOUIS CITY	207	2.3	1.6	1.6	3.1	37.5	13	0
STE. GENEVIEVE	11	1.4	0.8	1.2	1.4	5.2	9	0
STODDARD	9	1.3	0.9	0.9	1.0	3.1	0	0
STONE	9	2.3	1.5	2.4	2.1	7.0	11	0
SULLIVAN	2	1.4	1.3	1.4	0.2	1.5	0	0
TANEY	10	1.8	1.5	1.4	1.1	3.7	0	0
TEXAS	8	5.0	0.9	0.6	11.8	34.0	13	13
VERNON	13	1.1	0.9	0.7	0.8	2.9	0	0
WARREN	6	1.3	1.1	1.0	0.8	2.6	0	0
WASHINGTON	4	0.9	0.8	0.7	0.6	1.7	0	0
WAYNE	8	2.5	1.4	1.2	2.8	8.2	25	0
WEBSTER	15	1.8	1.0	0.9	2.3	8.0	13	0
WORTH	2	1.0	0.9	1.0	0.1	1.0	0	0
WRIGHT	7	1.1	0.9	0.8	0.8	2.7	0	0

Some persistent patterns are present in the survey data. Elevated (> 4 pCi/L) screening indoor radon levels occur along the upper Missouri River drainage in an area extending from Atchison County to Lafayette County. This area is underlain by river alluvium, loess, and residuum developed on limestone and shale. The loess deposits along the river north of Kansas City are somewhat elevated in uranium and some residual soils developed on limestone and shale in southern Jackson County are somewhat excessively drained.

A broad area of counties with elevated indoor radon levels occurs in the southern, eastern, and western part of the Ozark Plateau Province. This is an area of locally moderately elevated eU values, somewhat excessively drained soils, and karst.

Elevated eU values are associated with granite and rhyolite exposed in Washington, Iron, St. Francois, and Madison Counties, yet only Madison and St. Francois Counties have elevated averge indoor radon levels (fig. 11). Sampled houses in Washington and Iron Counties simply may not be located on soils developed on the granite and rhyolite. Elevated eU values are associated with basal Cretaceous sedimentary rocks of the Mississippi Embayment underlying northern Scott and Stoddard Counties and southeastern Butler County, yet elevated indoor radon levels are not present in Scott and Stoddard Counties. Again, sampling demographics may play a role. However, this part of the State is also characterized by high rainfall and elevated soil moisture, so radon migration may be inhibited.

GEOLOGIC RADON POTENTIAL

Elevated indoor radon levels can be expected in several geologic settings in Missouri. Uranium-bearing granites and rhyolites and residuum developed on carbonate rocks in the Ozark Plateau Province are likely to have significant percentages of homes with indoor radon levels exceeding 4 pCi/L. The most likely areas are those in which elevated eU values occur (fig. 8). Where structures are sited on somewhat excessively drained soils in this area (fig. 9) the radon potential is further increased. Extreme indoor radon levels may occur where structures are sited on uranium occurrences and where the disturbed zone around a foundation is connected to solution openings in carbonate rocks or to open zones in soil and bedrock caused by mine subsidence. Karst underlies parts of the City and County of St. Louis and may locally cause elevated indoor radon levels. Elevated eU and significant karst development occur in Perry and Cape Girardeau Counties. Structures sited on locally highly permeable karst soils with elevated eU in these two counties will likely have elevated indoor radon levels.

Elevated indoor radon levels may occur where the foundations of structures intercept the thin Pennsylvanian black shales or the Chattanooga Shale in the southwestern part of the State from Kansas City south to McDonald and Barry Counties and in north-central Missouri in Boone, Randolph and Macon Counties, or where they intercept well-drained alluvium derived from these rocks. Because these uranium-bearing shales are so thin, such circumstances are likely to be very site- or tract-specific, so detailed geologic and soil mapping will be necessary to outline areas of potential problems. Where these shales are jointed or fractured or soils formed on them are somewhat excessively drained on hillslopes, the radon potential is further increased. Indoor radon levels exceeding 100 pCi/L have been reported for homes sited on the Ohio Shale (Upper Devonian) in the Columbus, Ohio metropolitan area (Michael Hansen, oral commun., 1987). Residuum developed on limestones associated with these uranium-bearing shales may also have elevated uranium levels and have significant geologic radon potential.

Alluvium and loess along the upper Missouri River Valley upstream from Kansas City seem to be producing elevated indoor radon levels that may be related to the somewhat elevated uranium content of these materials and, possibly, to increased radon emanation and diffusive transport associated with well-drained loess deposits. Detailed studies of indoor radon data in this area would be necessary to determine more closely the origin of elevated indoor radon levels. Thin, somewhat excessively drained soils developed on limestone that occur as part of one soil association in the southern suburbs of Kansas City may also be related to elevated indoor radon levels in Jackson County. Information on the equivalent uranium content of these soils is not available as aeroradiometric data were not gathered over this area.

A multi-county area in northeastern Missouri would seem to have relatively low radon potential, which is probably related to very poorly drained soils developed on loess and glacial deposits. However, a single 6.8 pCi/L basement radon measurement in Shelby County remains unexplained, so some caution should be exercised in evaluating this area.

The geologic radon potential also seems low in the southeastern lowland area. Only one indoor radon value exceeding 4 pCi/L is reported for a six-county area, and very poorly drained soils are widespread (fig. 10). However, some aeroradiometric anomalies occur in this area (fig. 8), and some excessively drained soils occur locally (fig. 9). Elevated indoor radon levels may be associated with these locales. Some site-specific sampling is needed in these areas.

SUMMARY

There are seven areas in Missouri for which geologic radon potential may be evaluated (fig. 12). 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). These areas are evaluated in Table 2.

The northwestern part of Missouri has high overall radon potential. This area includes alluvium with elevated uranium contents along the upper Missouri River Valley, adajacent areas of thick loess just east of the valley, and areas underlain by Pennsylvanian black shales near Kansas City.

The dissected till plain of northern Missouri has moderate overall radon potential, but this assessment has moderate confidence. Except for counties along the Missouri River, the indoor radon data for the counties in the dissected till plain are sparse and appear to be biased on the low side. The eastern half of this area has soils of low permeability, but moderate uranium contents.

The unglaciated part of the Osage Plain province has a moderate overall radon potential; however, areas of very slowly permeable soils have lower radon potential, and areas of thin soils underlain by the uranium-bearing shales in this province have high radon potential, with locally extreme values possible.

The Ozark Plateau Province has a moderate overall geologic radon potential. Several areas of somewhat excessively drained soils, scattered uranium occurrences, carbonate soils in which uranium has been concentrated, and areas of karst all contribute to the moderate radon potential of this area. The indoor radon data support this conclusion but far more data need to be gathered to increase the confidence level.

The carbonate region has moderate geologic radon potential. Intense karst development, elevated uranium in residual soils developed on carbonate, and large areas of somewhat excessively drained to excessively drained soils contribute to this evaluation.

The St. Francois Mountains have high geologic radon potential owing to elevated levels of uranium in soils developed on granitic and volcanic rocks throughout these mountains and to substantial areas of somewhat excessively to excessively drained soils.

The Coastal Plain Province has a low geologic radon potential overall. Although elevated eU occurs over some of the sedimentary rocks in this province, the high soil moisture, very poorly drained soils, and the low indoor radon values all point towards low radon potential. Elevated eU over similar rocks in the coastal plain of Alabama did not produce elevated indoor radon levels there.

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) for geologic radon potential areas of Missouri. See figure 12 for locations of areas. See the introductory chapter for discussion of RI and CI.

FACTOR	Dissected till plain RI	Dissected till plain CI	Unglaciated Osage plain RI	Unglaciated Osage plain CI	Ozark Plateau RI	Ozark Plateau CI	Coastal Plain RI	Coastal Plain CI
INDOOR RADON	2	2	2	3	1	3	1	2
RADIOACTIVITY	2	2	2	3	1	3	2	3
GEOLOGY	2	2	2	3	3	3	1	2
SOIL PERMEABILITY	2	3	2	3	3	3	2	3
ARCHITECTURE	3	-	3	-	3	-	1	-
GFE POINTS	0	-	0	-	0	-	-2	-
TOTAL	11	9	11	12	11	12	5	10
RANKING	Mod	Mod	Mod	High	Mod	High	Low	High

FACTOR	Carbonate region RI	Carbonate region CI	St. Francois Mountains RI	St. Francois Mountains CI	Northwestern Missouri RI	Northwestern Missouri CI
INDOOR RADON	2	3	2	3	3	3
RADIOACTIVITY	2	3	3	3	2	3
GEOLOGY	2	3	3	3	3	3
SOIL PERMEABILITY	2	3	2	3	2	3
ARCHITECTURE	3	-	3	-	3	-
GFE POINTS	0	-	0	-	0	-
TOTAL	11	12	13	12	13	12
RANKING	Mod	High	High	High	High	High

RADON INDEX SCORING:

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

Possible range of points = 3 to 17

CONFIDENCE INDEX SCORING:

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

Possible range of points = 4 to 12

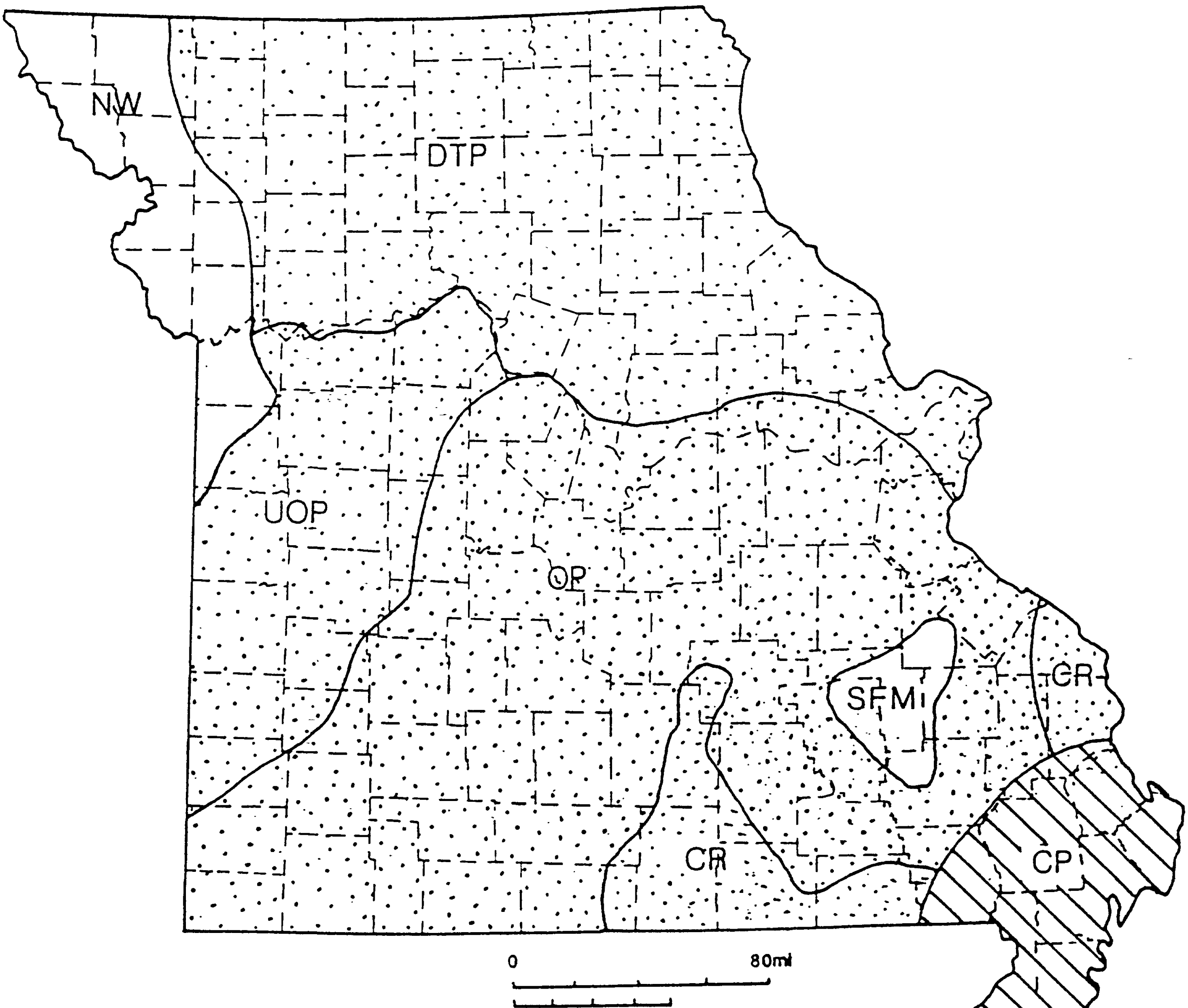


Fig. 12- Radon potential areas in Missouri. DTP- Dissected till plain; NW- Northwest Missouri; UOP- Unglaciated Osage Plain; OP- Ozark Plateau; CR- Carbonate region; SFM- St. Francois Mountains; CP- Coastal Plain. Radon potential: Cross-hatched- low; stippled- moderate; blank- high.

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

Coveney, R. M., Jr., 1981, Thin black Pennsylvanian-age shales of the Mid-continent U.S.; a neglected metallic resource?: Geological Society of America Abstracts with Programs, v.13, n.7, p. 432.

Coveney, Raymond M., Jr., Hilpman, Paul L., Allen, Ashley V., and Glascock, Michael D., 1987, Radionuclides in Pennsylvanian black shales of the midwestern United States, *in* Marikos, Mark Alan and Hansman, Robert H., eds., Geologic causes of natural radionuclide anomalies, Proceedings of the GEORAD conference, St. Louis, MO, April 21-22, 1987: Missouri Department of Natural Resources Special Publication 4, p. 25-42.

Coveney, Raymond M., Jr., Leventhal, Joel S., and Glascock, Michael D., 1987, Origins of metals and organic matter in the Mecca Quarry Shale Member and stratigraphically equivalent beds across the Midwest: Economic Geology, v.82, no. 4, p. 915-933.

Duley, J.W., 1983, Geologic aspects of individual home liquid-waste disposal in Missouri: Missouri Division of Geology and Land Survey Engineering Geology Report No. 7, 78 p.

Duval, Joseph S. and Jones, William J., 1988, Regional aerial gamma-ray maps for Illinois and parts of Wisconsin, Iowa, Michigan, Indiana, Missouri, and Kentucky, *in* Marikos, Mark Alan and Hansman, Robert H., eds., Geologic causes of natural radionuclide anomalies, Proceedings of the GEORAD conference, St. Louis, MO, Apr. 21-22, 1987: Missouri Department of Natural Resources Special Publication 4, p. 157-166.

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

Erickson, R. L. and Pratt, W. P., 1981, Coastal plain-type uranium deposits, *in* Pratt, W. P., ed., Metallic mineral-resource potential of the Rolla 1° x 2° quadrangle, Missouri, as appraised in September 1980: U.S. Geological Survey Open-File Report 81-518, 50 p.

Greeman, D.J., Rose, A.W., and Jester, W.A., 1990, Form and behavior of radium, uranium, and thorium in central Pennsylvania soils derived from dolomite: Geophysical Research Letters, v.17, no.6, p. 833-836.

Howe, W.B.,1984, Generalized geologic map of Missouri: Rolla, MO, Geology and Land Survey, Department of Natural Resources. 1 p.

Johnson, V. C. and Dubyk, W. S., 1977, Preliminary study of the geology and uranium favorability of the Forest City Basin in Kansas, Missouri, Iowa, and Nebraska: U.S. Department of Energy Report No. GJBX-83(77), 18 p.

Kisvarsanyi, E. B., 1981, Uranium and thorium in Precambrian rocks, *in* Pratt, W. P., ed., Metallic mineral-resource potential of the Rolla 1° x 2° quadrangle, Missouri, as appraised in September 1980: United States Geological Survey Open-File Report 81-518, 50 p.

Kisvarsanyi, E. B., 1987, Radioactive HHP (high heat production) granites in the Precambrian terrane of southeastern Missouri, *in* Marikos, Mark Alan and Hansman, Robert H., eds., Geologic causes of natural radionuclide anomalies, Proceedings of the GEORAD conference, St. Louis, MO, Apr. 21-22, 1987: Missouri Department of Natural Resources Special Publication 4, p. 5-16.

Marikos, M. A., 1981, Distribution and possible causes of radionuclides in groundwaters of Missouri, *in* Hemphill, D. D., ed., Proceedings of University of Missouri's 15th annual conference on trace substances in environmental health, Columbia, MO, June 1-4, 1981: Trace Substances in Environmental Health, v.15, 86 p.

Missouri Geological Survey, 1983, Surficial materials map of Missouri: Rolla, MO, Missorui Geological Survey, Missouri Department of Natural Resources, 1 p.

Muilenburg, G.A., Notes on uranium, revised edition: Missouri Division of Geological Survey and Water Resources Information Circular No. 5, 22 p.

Nuelle, Laurence M., 1987, Distribution of radionuclides in Missouri geologic terranes: a summary of available data and the need for more data, *in* Marikos, Mark Alan and Hansman, Robert H., eds., Geologic causes of natural radionuclide anomalies, Proceedings of the GEORAD conference, St. Louis, MO, Apr. 21-22, 1987: Missouri Department of Natural Resources Special Publication 4, p. 75-90.

Odland, S. K.; Millard, H. T., Jr., 1979, Uranium and thorium content of some sedimentary and igneous rocks from the Rolla 1° x 2° quadrangle, Missouri: U. S. Geological Survey Open-File Report 79-1080, 17 p.

Pratt, W. P., 1981, Uranium in Paleozoic sedimentary rocks, *in* Pratt, W. P., ed., Metallic mineral-resource potential of the Rolla 1° x 2° quadrangle, Missouri, as appraised in September 1980: United States Geological Survey Open-File Report 81-0518, 50 p.

Proctor, P. D. and O'Brien, W. P., 1980, Radiometric signature and petrochemistry of the Graniteville Granite, St. Francois Mountains, Southeast Missouri: Geological Society of America Abstract with Programs, v.12, n.5, p. 254.

Proctor, P. D., O'Brien, W. and Grant, S. K., 1981, Graniteville Granite, Missouri; a possible Bokan Mountain, Alaska, analog?: Geological Society of America Abstracts with Programs, v.13, no.7, p. 533.

Rose, A.W., Ciolkosz, E.J., and Washington, J.W., 1990, Effects of regional and seasonal variations in soil moisture and temperature on soil gas radon, *in* U.S. Environmental Protection Agency, The 1990 international symposium on radon and radon reduction technology: Volume III. Preprints, unpaginated.

Sauer, Herbert I. and Mirielli, Edward J., Jr., 1987, Associations of natural radiation and radon with the risk of dying, *in* Hemphill, D. D., ed., Proceedings of University of Missouri's 15th annual conference on trace substances in environmental health, Columbia, MO, June 1-4, 1981: Trace Substances in Environmental Health, v. 15, p. 195-202.

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

Sims, Paul K., Schulz, Klaus J. and Kisvarsanyi, Eva B., 1990, Proterozoic anorogenic granite-rhyolite terranes in the Midcontinental United States; possible hosts for Cu-, Au-, Ag-, U-, and rare-earth element-bearing iron oxide deposits similar to the Olympic Dam orebody, *in* Pratt, Walden P. and Goldhaber, Martin B., eds., U.S. Geological Survey-Missouri Geological Survey symposium; Mineral-resource potential of the Midcontinent; program and abstracts, St. Louis, Missouri, April 11-12, 1989: U.S. Geological Survey Circular 1043, p. 33-34.

Steele, K. F. and Fay, W. M., 1982, Orientation study of St. Francois Mountain and Decaturville Precambrian areas, Missouri; hydrogeochemical and stream sediment reconnaissance: U.S. Dept. of Energy Report No. GJBX-200(82), 72 p.

Steele, S. R., Hood, W. C. and Sexton, J. L., 1982, Radon emanation in the New Madrid seismic zone, *in* McKeown, F. A. and Pakiser, L. C., eds., Investigations of the New Madrid, Missouri, earthquake region: U. S. Geological Survey Professional Paper 1236, p. 191-201.

Szabo, B. J., 1979, Extreme fractionation of $^{234}U/^{238}U$ isotopes within a Missouri aquifer: U.S. Geological Survey Professional Paper 1150, 188 p.

Szabo, B. J., 1980, Extreme $^{234}U/^{238}U$ and $^{230}Th/^{234}U$ activity ratios in Missouri groundwaters and spring deposits; dating organic sand samples and fossil bones by the uranium-series method: Geological Society of America Abstracts with Programs, v.12, no.7, p. 532.

Szabo, B. J., 1982, Extreme fractionation of $^{234}U/^{238}U$ and $^{230}Th/^{234}U$ in spring waters, sediments, and fossils at the Pomme de Terre Valley, southwestern Missouri: Geochimica et Cosmochimica Acta, v. 46, no. 9, p. 1675-1679.

Unfer, L., Jr. and Tibbs, N. H., 1980, Radioactivity in the Cretaceous and Tertiary sediments of Crowleys Ridge, Southeast Missouri: Geological Society of America Abstract with Programs, v. 12, no. 5, p. 258-259.

U.S. Geological Survey, 1974, The National Atlas of the United States of America.

PRELIMINARY GEOLOGIC RADON POTENTIAL ASSESSMENT OF NEBRASKA

by
R. Randall Schumann
U.S. Geological Survey

INTRODUCTION

Many of the rocks and soils in Nebraska have the potential to generate levels of indoor radon exceeding the U.S. Environmental Protection Agency's guideline of 4 pCi/L. In a survey of 2027 homes conducted during the winter of 1989-90 by the State of Nebraska and the EPA, 54 percent of the homes had indoor radon levels exceeding this value. Areas of Nebraska have geologic radon potentials ranging from low to high.

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

PHYSIOGRAPHIC AND GEOGRAPHIC SETTING

Most of Nebraska (the western four-fifths of the State) is part of the Great Plains physiographic province, characterized primarily by flat and dissected plains. The eastern one-fifth of Nebraska (east of the glacial limit) is part of the Central Lowlands Province, consisting of rolling hills. Nebraska's topography comprises several types of land surfaces (fig. 1). Most of western and central Nebraska are characterized by plains, regions of relatively flat uplands, and dissected plains, regions of hilly land that have been eroded by water and wind, resulting in moderate to steep slopes, sharp ridge crests, and remnants of the original plain (Nebraska Conservation and Survey Division, 1986). Rolling hills occupy the eastern part of the State and a small area in the northwestern corner of Nebraska (fig. 1). In eastern Nebraska they consist of ridges and valleys formed by glaciers and modified by subsequent erosion and deposition. Most of the hills are covered by windblown silt, called loess. The Sand Hills are a region of low- to high-relief sand dunes, most of which have been stabilized by vegetation. Valleys are regions of low relief along major drainages. Some of the valleys are bordered by rugged bluffs and escarpments with steep and irregular slopes, and the broader valleys in western and northwestern Nebraska have recognizable valley side slopes between the bluffs and valley floors (fig. 1) (Nebraska Conservation and Survey Division, 1986).

Nebraska is divided into 93 counties (fig. 2). The population density is generally low; most counties have less than 10,000 inhabitants (fig. 3). Counties with populations greater than 100,000 include Douglas and Lancaster Counties, representing the Omaha and Lincoln areas, respectively (fig. 3).

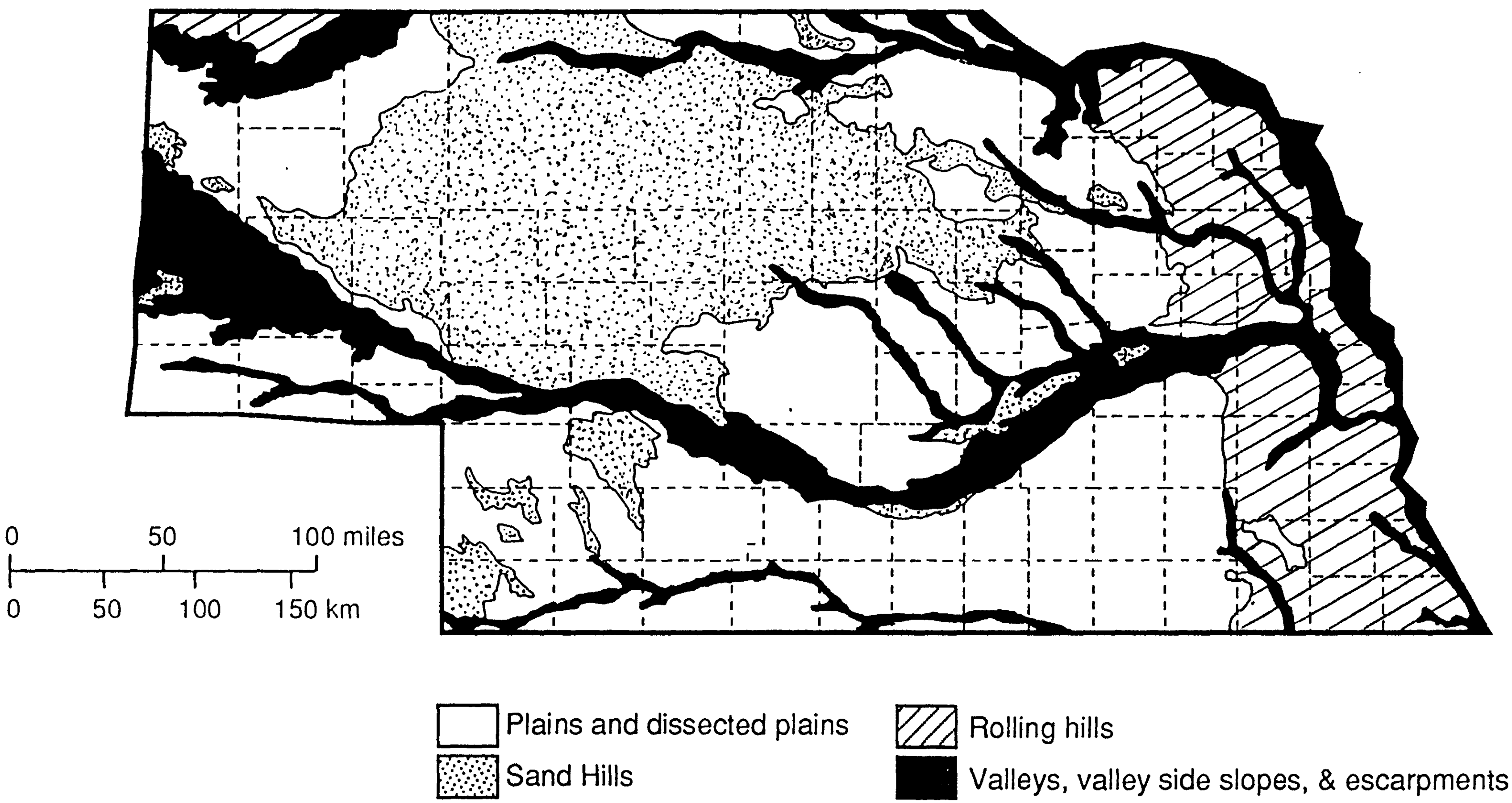


Figure 1. Generalized map showing topographic regions of Nebraska (after Nebraska Geological Survey, 1963).

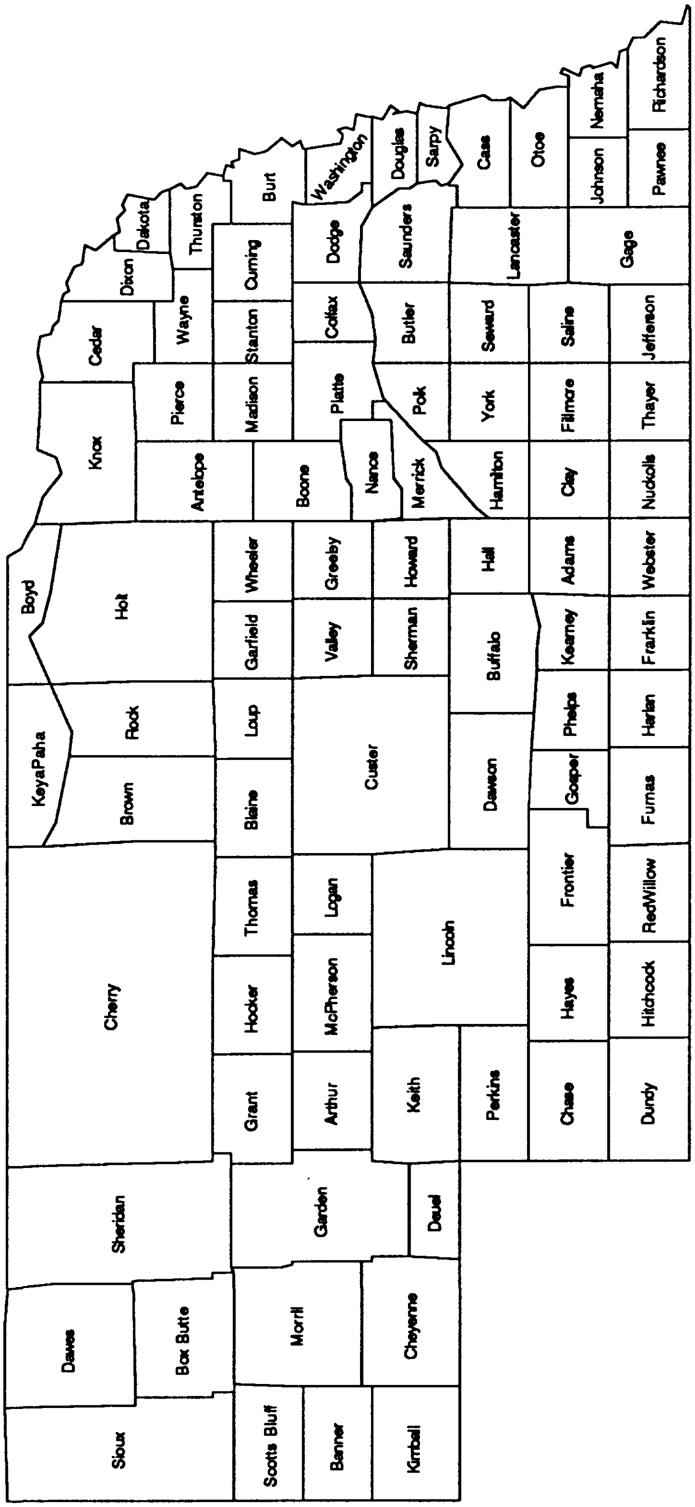


Figure 2. Nebraska counties.

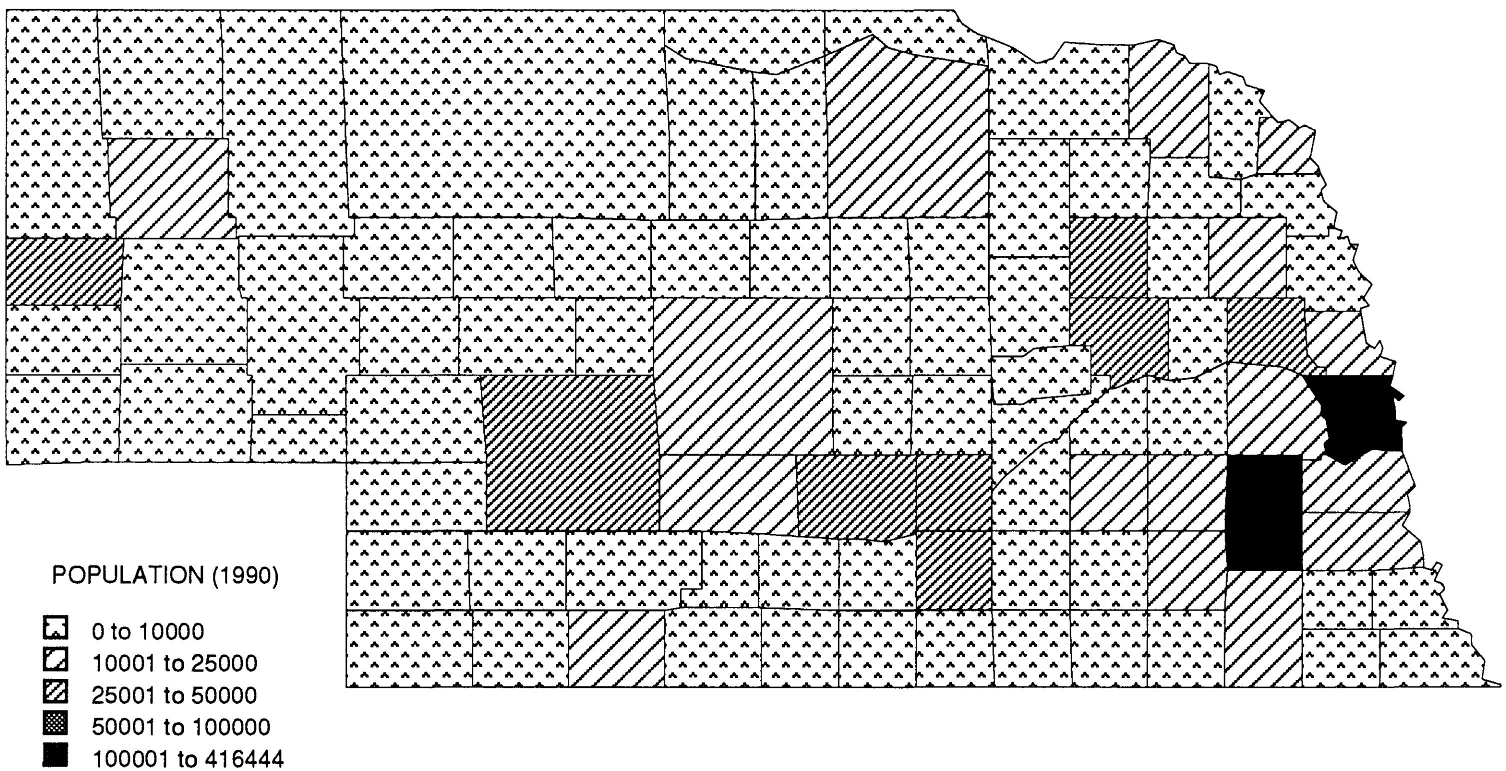


Figure 3. Population of counties in Nebraska (1990 U.S. Census data).

GEOLOGY

Bedrock geology: Rocks ranging in age from Pennsylvanian to Quaternary are exposed in Nebraska. Pennsylvanian rocks are exposed in southeastern Nebraska (fig. 4) and include limestones, shales, and sandstones. Only some of the Upper Pennsylvanian strata are exposed in Nebraska; these rocks are a repeated sequence of marine shales and limestones alternating with nonmarine sandstones and shales (Burchett, 1979). Several thin coal seams occur within the exposed Pennsylvanian strata in Cass, Otoe, Johnson, Nemaha, Pawnee, and Richardson Counties. Pennsylvanian shales include gray, greenish-gray, red (iron-rich), and black (organic-rich) shales (Burchett, 1979). Only the lower portion of the Permian series is exposed in Nebraska. Exposed Permian rocks consist of green, gray, and red shales, limestone, and gypsum (Burchett, 1983). Exposures of Pennsylvanian and Permian rocks are generally limited to valley sides along streams because much of the eastern part of the State is mantled with Pleistocene glacial deposits and loess.

Cretaceous rocks are exposed in much of eastern Nebraska, in parts of northern and northwestern Nebraska, and along the Republican River Valley (fig. 4). Lower Cretaceous rocks are represented by the Dakota Group, which consists of sandstones, shales, and thin coals. Upper Cretaceous rocks include the Colorado and Montana Groups (Condra and Reed, 1959; Burchett, 1986). The Colorado Group includes the Graneros Shale, Greenhorn Limestone, Carlile Shale, and Niobrara Formation (consisting of the Smoky Hill Chalk and Fort Hays Limestone). The Montana Group overlies the Colorado Group and includes the Pierre Shale, Fox Hills Sandstone, and Lance Formation. The Pierre Shale consists of gray, brown, and black shales, with thin layers of bentonite, chalk, limestone, and sandstone (Condra and Reed, 1959). The stratigraphically lowest unit in the Pierre Shale is the Sharon Springs Member, a black shale of widespread occurrence in Nebraska, South Dakota, Kansas, and Colorado. The Lance Formation consists of continental sandstone, shale, and thin coals.

Tertiary rocks have the most widespread exposure in the State. The White River Group consists of mudstone, siltstone, sandstone, and thin layers of volcanic ash. White River rocks are exposed in the North Platte and South Platte valleys and in northwestern Nebraska (fig. 4). The Arikaree Group overlies the White River Group and consists of siltstone and sandstone (Swinehart and others, 1985). The Tertiary Ogallala Group covers about two-thirds of the State (fig. 4). It consists of sandstone, siltstone, gravel, sand, silt, clay, and thin volcanic ash layers. The Ogallala is covered by the Sand Hills in the north-central part of Nebraska. Pre-Sand Hills sediments of Pliocene and Quaternary age also overlie portions of the Ogallala in this area (Swinehart and Diffendal, 1990).

Glacial geology: Pleistocene glacial deposits of Pre-Illinoian age (Richmond and others, 1991) cover approximately the eastern one-fifth of Nebraska (fig. 5). The glacial deposits generally consist of a clay, silt, or sand matrix with pebbles and cobbles of limestone, igneous rocks, and quartzite (Reed and Dreeszen, 1965). Most of the tills are calcareous (containing layers, nodules, or cements of calcium carbonate, $CaCO_3$) and many contain layers or grain coatings of iron oxides. Source material for the glacial deposits includes locally-derived Permian and Pennsylvanian limestone and shale and Cretaceous sandstone and shale, as well as lesser amounts of sandstone, limestone, shale, and igneous and metamorphic rocks from bedrock sources to the north and northeast. Loess (windblown silt of glacial, periglacial, and non-glacial

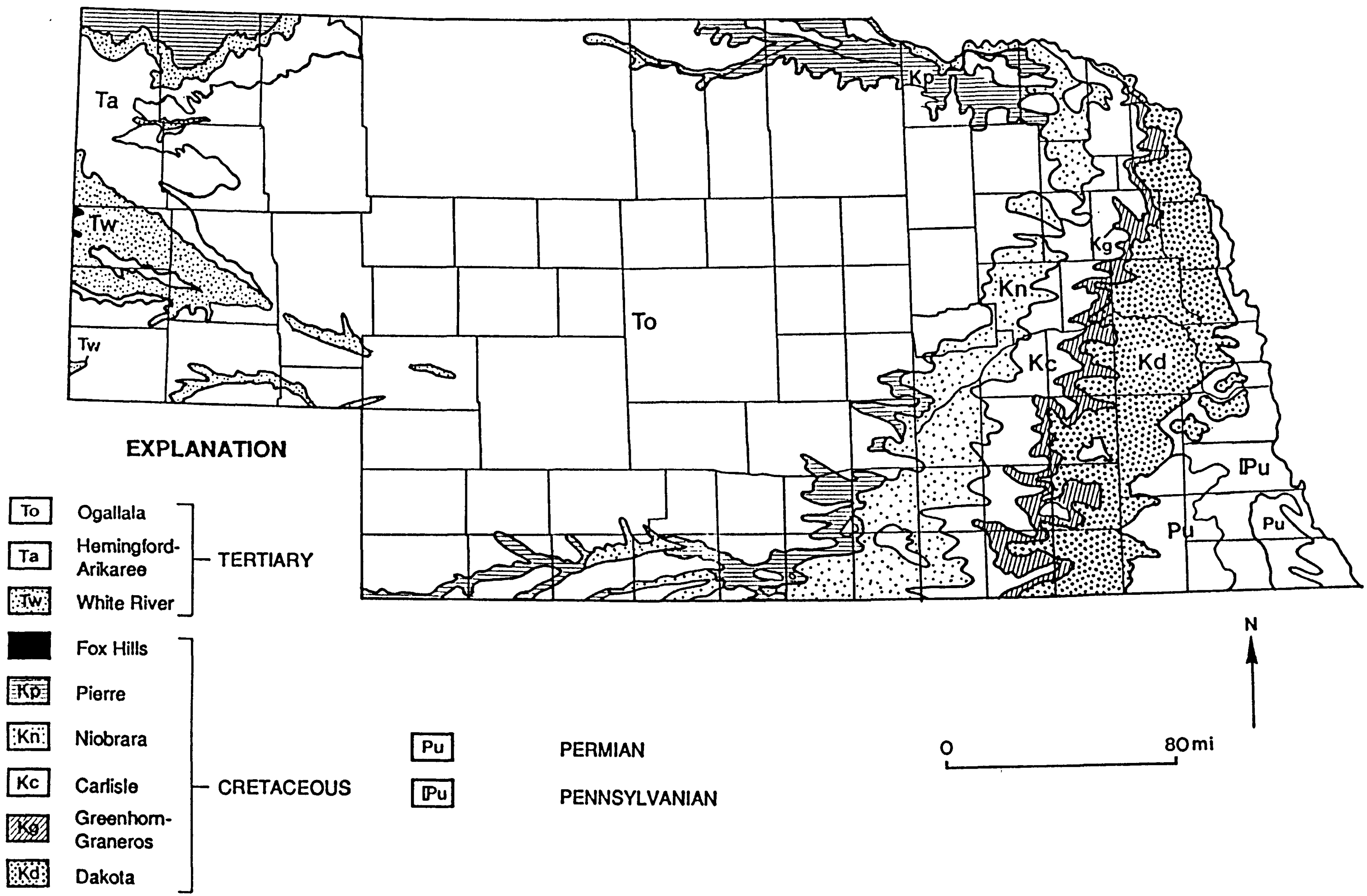


Figure 4. Generalized bedrock geologic map of Nebraska (after Burchett and Pabian, 1991).

Era	Period	Epoch	Ages in millions of years[1]	Group or Formation	Lithology
Cenozoic	Quaternary	Holocene			Sand, silt, gravel and clay
			0.01		
		Pleistocene			
			~2.0		
	Tertiary	Pliocene			Sand, gravel and silt
			5		
		Miocene		Ogallala	Sand, sandstone, siltstone and some gravel
			24		
		Oligocene		Arikaree	Sandstone and siltstone
				White River	Siltstone, sandstone and clay in lower part
			37		
		Eocene		Rocks of this age are not identified in Nebraska.	
			58		
		Paleocene			
			67		
Mesozoic	Cretaceous	Late Cretaceous		Lance	Sandstone and siltstone
				Fox Hills	
				Pierre	Shale, some sandstone in west
				Niobrara	Shaly chalk and limestone
				Carlile	Shale; in some areas, contains sandstones in upper part
				Greenhorn-Graneros	Limestone and shale
			98		
		Early Cretaceous		Dakota	Sandstone and shale
			144		
	Jurassic				Siltstone, some sandstone
			208		
	Triassic				Siltstone
			245		
Paleozoic	Permian				Limestones, dolomites, shales and sandstones
			286		
	Pennsylvanian				
			320		
	Mississippian				
			360		
	Devonian				
			408		
	Silurian				
			438		
	Ordovician				
			505		
	Cambrian				
			570		
Precambrian					

[1]Estimated ages of time boundaries from the Geological Society of America, 1983 Geologic Time Scale

Figure 4 (continued) DESCRIPTION OF GEOLOGIC UNITS IN NEBRASKA (modified from Nebraska Conservation and Survey Division, 1986).

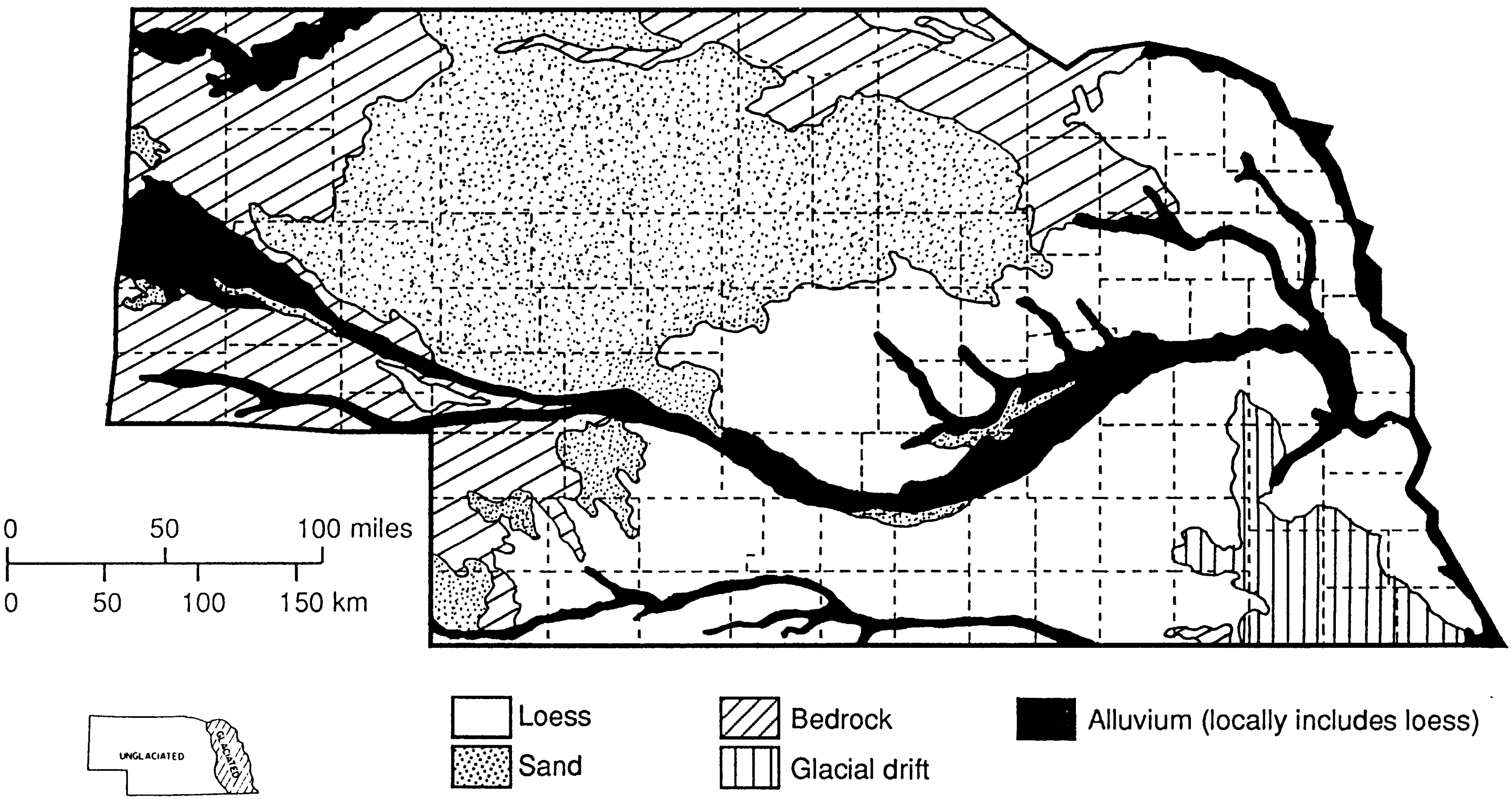


Figure 5. Generalized map showing surficial geology of Nebraska (after Elder, 1969).

origin) covers most of the glacial deposits in eastern Nebraska as well as bedrock in the south-central part of the State (fig. 5).

Uranium geology: Uranium in commercial, as well as significant but non-commercial grades, occurs in Nebraska in rocks and sediments of Tertiary, Cretaceous, and Pennsylvanian age, and in Pleistocene glacial deposits derived from these rocks. Uranium in concentrations as high as 3 percent (Gjelsteen and Collings, 1988) occurs in the White River Group in Dawes County. Uranium is currently being solution mined from a subsurface deposit in the Chadron Formation of the White River Group at Crow Butte near Crawford (Collings and Knode, 1984). A sample of the Brule Formation (upper part of the White River Group) from Noddings Ridge, north of Chadron, was found to contain as much as 0.43 percent (4300 ppm) uranium (Dunham, 1955; Dickinson, 1991). Overall, the White River Group is estimated to contain an average of 7.7 ppm uranium (Gjelsteen and Collings, 1988). The sources of the uranium in the Tertiary deposits is thought to be the volcanic ash layers (Zielinski, 1983) and volcanic glass in the bulk sediments, especially in the White River and Arikaree Groups. The Arikaree Group is also known to host local uranium occurrences in western South Dakota (Denson and Gill, 1956). The Tertiary Ogallala Group is considered favorable for uranium, and higher-than-average uranium concentrations have been found in groundwater samples taken from the Ogallala aquifer in eastern Colorado (Nelson-Moore and others, 1978).

Several shales in the State also contain above-average amounts of uranium (average crustal abundance of uranium is about 2.5 ppm (Carmichael, 1989) and non-organic-rich shales generally contain 1-4 ppm uranium). The Sharon Springs Member of the Pierre Shale, an organic-rich black shale, locally contains as much as 100 ppm uranium (Tourtelot, 1956), with an average uranium content of about 15 ppm (Kepferle, 1959). The Sharon Springs Member is exposed to the northeast and southeast of the Sand Hills (part of the areas labeled Pierre Shale on figure 4). Altered shales in the Cretaceous Niobrara Formation have anomalous concentrations of uranium where they are directly overlain by the Chadron Formation of the White River Group. Samples of altered Niobrara Formation in southwestern South Dakota yielded 300 ppm uranium (Tourtelot, 1956). Many of the Pennsylvanian black shales underlying the glacial deposits in the southeastern corner of Nebraska contain significant amounts of uranium. The black shale beds are generally thin and scattered throughout the Pennsylvanian sequence. About 20 of the Pennsylvanian black shale beds contain more than 30 ppm uranium; several contain about 100 ppm uranium; and a few thin black shales locally contain as much as 170 ppm uranium (Swanson, 1956). Many of the Pennsylvanian black shales contain small, irregularly distributed phosphatic nodules or concretions that comprise approximately 5 percent of the shale unit. The phosphate nodules typically contain 150-200 ppm uranium, and a few contain as much as 1000 ppm uranium (Swanson, 1956).

SOILS

Soils of the Entisol and Mollisol orders occur in Nebraska. Approximately the eastern one-sixth of Nebraska is covered by Udolls, moist silt loam to silty clay loam soils with black, organic-rich surface horizons and subsurface horizons that have been leached of calcium carbonate (U.S. Soil Conservation Service, 1987). These soils have low to moderate permeability (fig. 6). The remainder of the State exclusive of the Sand Hills is covered by Ustolls, drier soils with subsurface accumulations of salts or carbonates. These soils are mostly silt loams, silty clay loams, and loams developed on loess and a combination of loess and eolian sand on sandstone residuum (Elder, 1969). These soils have mostly moderate permeability (fig. 6).

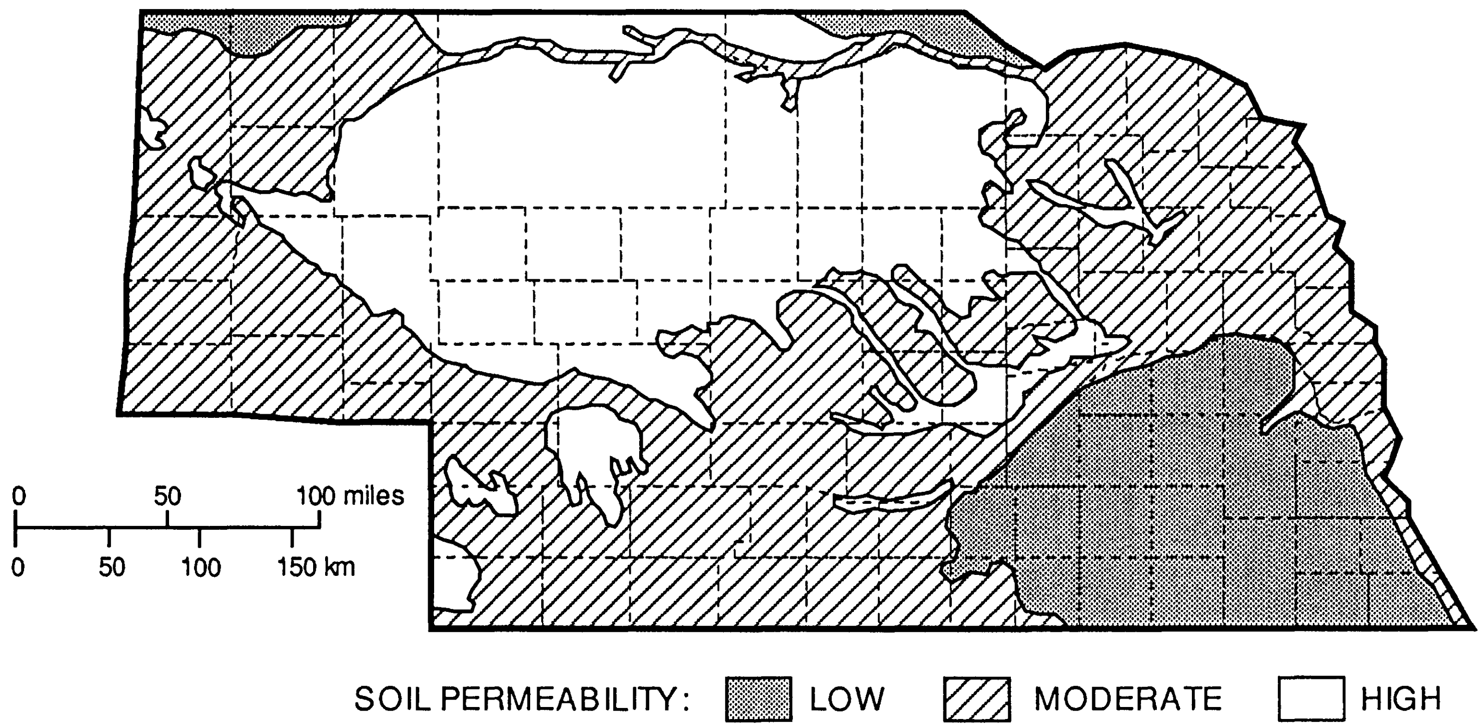


Figure 6. Generalized soil permeability map of Nebraska (data from Elder, 1969).

Soils in the Sand Hills region are classified as Entisols, soils with little or no development of pedogenic horizons. The soils are sands or sandy loams with high permeability (fig. 6) that absorb precipitation rapidly; there is very little runoff (Kuzila, 1990).

INDOOR RADON DATA

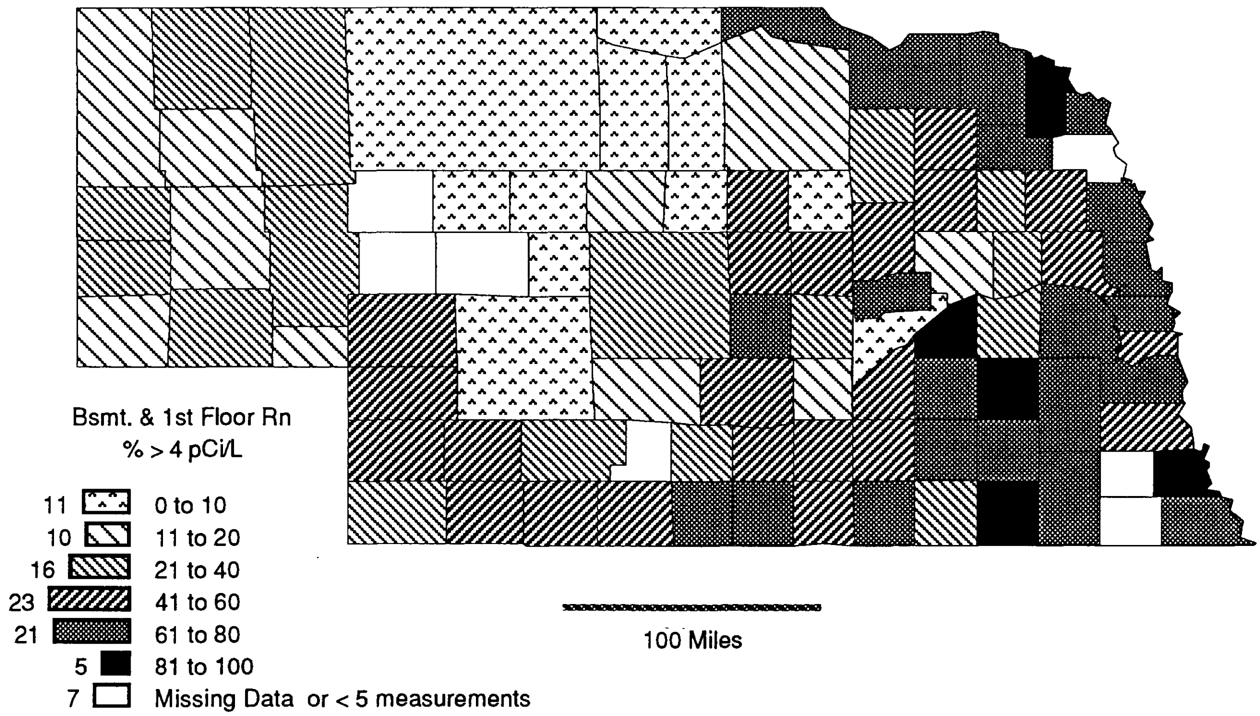
Indoor radon data from 2027 homes sampled in the State/EPA Residential Radon Survey conducted in Nebraska during the winter of 1989-90 are shown in figure 7 and listed in Table 1. The data are derived from short-term (2-7 day) screening measurements using charcoal canister radon detectors placed in the lowest level of the home (in Nebraska, usually the basement). Data are only displayed in figure 7 for those counties with 5 or more data values. The maximum value recorded in the survey was 123.4 pCi/L in Dakota County (Table 1). Average indoor radon concentrations exceed 4 pCi/L in most counties in eastern and southern Nebraska (fig. 7). Merrick County, which is underlain almost entirely by alluvium (fig. 5), has a low radon average (1.9 pCi/L). Counties underlain by the Sand Hills have low (<2.0 pCi/L) to moderate (2-4 pCi/L) indoor radon averages (fig. 7). Counties in the panhandle have mostly moderate to locally high indoor radon averages (fig. 7). The percentage of homes sampled in each county with indoor radon concentrations exceeding 4 pCi/L generally follows the same trend as the averages (fig. 7). A high percentage of homes have indoor radon levels exceeding 4 pCi/L in eastern Nebraska, a moderate to high proportion of homes exceed 4 pCi/L in southern Nebraska, generally low proportions of homes exceed 4 pCi/L in the Sand Hills, and a moderate proportion of homes exceed 4 pCi/L in the panhandle (fig. 7).

GEOLOGIC RADON POTENTIAL

A comparison of bedrock and surficial geology (figs. 4, 5) with aerial gamma radioactivity (fig. 8) and indoor radon distributions (fig. 7) indicates areas and lithologies with differing radon potentials. Three primary types of bedrock or surficial deposits are likely to generate moderate to high amounts of radon in Nebraska: (1) Tertiary sandstones; (2) shales, especially organic-rich black shales; and (3) glacial deposits and loess. The Tertiary Ogallala, Arikaree, and White River Groups all have high surface radioactivity (for purposes of this evaluation, high radioactivity is defined as greater than 2.5 ppm eU) and are known to host uranium deposits. Soils developed on the Tertiary units have moderate permeability (fig. 6) and generate moderate to locally high indoor radon. The White River and Arikaree Groups have significant amounts of uranium-bearing volcanic glass and may be somewhat more likely to generate elevated indoor radon concentrations.

Outcrops of the Pierre Shale in the northwestern corner of Nebraska have the highest surface radioactivity in the State, averaging 3.0-3.5 ppm eU (fig. 8) and displaying several prominent anomalies in the 6.0 ppm or greater range (Duval and others, 1989). Although the permeability of soils developed on the Pierre Shale is listed as low (fig. 6), the shales contain numerous fractures and partings and are likely to have sufficient permeability for radon transport during dry periods. The Sharon Springs Member of the Pierre Shale is exposed along the Niobrara and Missouri Rivers from Keya Paha to Cedar Counties and along the Republican River in southern Nebraska (fig. 4). Black shales of Pennsylvanian age underlie glacial deposits in southeastern Nebraska and may constitute a significant radon source where the shales are a source component of the tills.

Eastern Nebraska and southern Nebraska south of the Platte River are underlain by Permian through Tertiary rocks mantled with glacial deposits and loess. These deposits have a



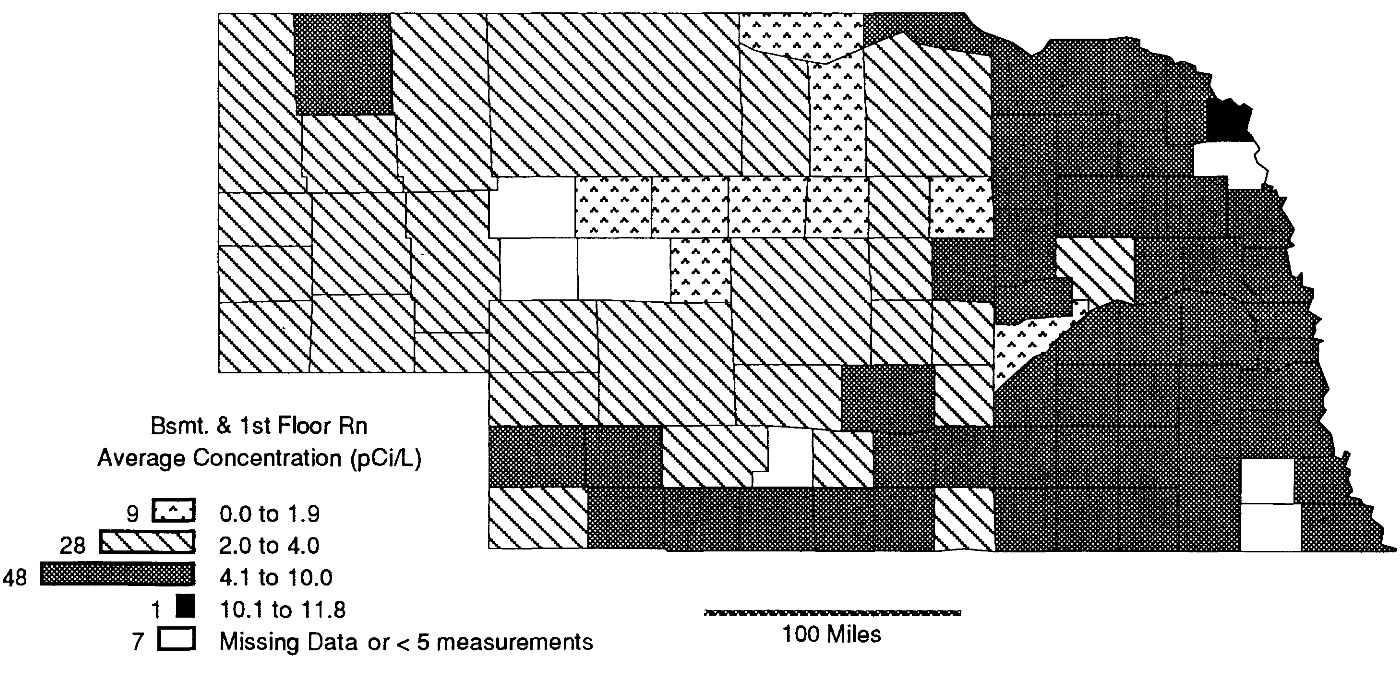


Figure 7. Screening indoor radon data from the EPA/State Residential Radon Survey of Nebraska, 1989-90, for counties with 5 or more measurements. Data are from 2-7 day charcoal canister tests. Histograms in map legends show the number of counties in each category. The number of samples in each county (See Table 1) may not be sufficient to statistically characterize the radon levels of the counties, but they do suggest general trends. Unequal category intervals were chosen to provide reference to decision and action levels.

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

COUNTY	NO. OF MEAS.	MEAN	GEOM. MEAN	MEDIAN	STD. DEV.	MAXIMUM	%>4 pCi/L	%>20 pCi/L
ADAMS	75	4.7	3.7	4.2	3.4	19.7	52	0
ANTELOPE	20	4.8	3.3	3.8	3.4	12.6	40	0
ARTHUR	4	1.0	0.8	1.0	0.7	1.9	0	0
BANNER	6	3.4	2.7	2.2	2.6	8.2	33	0
BLAINE	5	1.5	0.7	0.4	2.3	5.5	20	0
BOONE	17	6.1	5.0	5.7	3.6	14.8	59	0
BOX BUTTE	37	2.8	2.2	2.2	1.8	9.3	19	0
BOYD	11	7.2	5.0	4.2	7.2	26.2	64	9
BROWN	6	2.3	2.0	2.5	1.2	3.6	0	0
BUFFALO	81	4.8	3.4	4.2	3.8	24.4	54	1
BURT	13	9.5	7.7	8.6	5.6	19.3	77	0
BUTLER	9	4.2	3.1	2.8	3.8	12.7	33	0
CASS	10	8.2	6.7	7.6	5.1	15.9	70	0
CEDAR	32	9.0	6.3	7.8	6.4	24.5	72	9
CHASE	15	4.2	3.3	4.6	1.9	9.1	60	0
CHERRY	40	2.0	1.4	1.8	1.6	9.8	5	0
CHEYENNE	45	3.5	3.0	2.8	2.2	12.7	24	0
CLAY	14	7.0	5.3	5.4	5.4	20.0	57	0
COLFAX	10	5.0	3.0	2.6	4.7	14.4	40	0
CUMING	26	6.3	4.7	4.6	5.5	24.6	58	4
CUSTER	40	3.6	3.0	3.2	2.2	11.5	28	0
DAKOTA	27	11.8	5.6	5.9	23.3	123.4	63	15
DAWES	34	4.3	3.3	3.6	3.0	13.9	38	0
DAWSON	40	2.6	2.1	2.3	1.8	8.4	13	0
DEUEL	5	3.1	2.1	3.6	2.4	6.3	20	0
DIXON	17	8.8	7.0	9.4	5.5	19.4	82	0
DODGE	16	5.4	4.2	4.6	4.0	16.2	50	0
DOUGLAS	148	6.4	4.9	5.3	5.9	51.7	65	4
DUNDY	7	2.6	2.3	2.1	1.5	4.8	29	0
FILLMORE	6	7.7	5.7	5.4	6.7	20.1	67	17
FRANKLIN	14	6.1	5.1	5.3	3.7	13.3	64	0
FRONTIER	8	2.9	1.9	3.6	1.8	4.9	25	0
FURNAS	12	4.5	3.0	4.3	2.6	8.8	58	0
GAGE	10	6.0	5.0	5.7	3.5	12.3	70	0
GARDEN	28	3.0	1.6	1.7	3.8	16.9	21	0
GARFIELD	9	3.5	2.5	3.5	1.6	5.6	44	0
GOSPER	4	4.9	3.9	5.0	3.1	8.2	50	0
GRANT	2	0.6	0.3	0.6	0.6	1.0	0	0
GREELEY	18	7.2	4.6	3.9	9.5	42.8	44	6
HALL	109	2.5	2.0	2.5	1.6	9.0	12	0
HAMILTON	18	5.4	4.3	4.1	4.0	17.0	50	0

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

COUNTY	NO. OF MEAS.	MEAN	GEOM. MEAN	MEDIAN	STD. DEV.	MAXIMUM	%>4 pCi/L	%>20 pCi/L
HARLAN	8	5.2	4.5	5.3	2.7	9.4	63	0
HAYES	8	4.4	3.4	4.0	3.2	11.0	50	0
HITCHCOCK	10	4.2	2.9	4.4	2.7	9.6	60	0
HOLT	34	2.4	1.3	1.8	2.1	8.4	18	0
HOOKER	15	1.3	1.1	1.3	0.8	2.9	0	0
HOWARD	13	2.8	2.0	1.9	2.0	6.0	23	0
JEFFERSON	7	6.2	6.0	6.2	1.8	9.9	100	0
JOHNSON	1	21.0	21.0	21.0	0.0	21.0	100	100
KEARNEY	17	4.3	3.5	3.8	2.5	10.1	47	0
KEITH	31	3.9	3.0	3.5	2.9	15.0	42	0
KEYA PAHA	6	1.3	0.8	1.1	1.0	3.1	0	0
KIMBALL	17	2.8	2.1	2.3	2.8	12.7	12	0
KNOX	25	7.9	5.0	5.0	8.7	40.9	64	8
LANCASTER	74	6.0	4.9	5.6	3.2	15.2	72	0
LINCOLN	77	2.2	1.6	1.7	1.7	10.7	10	0
LOGAN	11	1.7	1.0	1.6	1.3	4.0	0	0
LOUP	6	1.5	0.9	0.9	1.4	3.6	0	0
MADISON	89	6.4	4.3	5.5	5.3	31.2	60	2
MCPHERSON	4	1.7	0.9	1.3	1.7	3.8	0	0
MERRICK	21	1.9	1.3	1.4	2.1	10.0	10	0
MORRILL	26	2.2	1.3	2.0	1.9	7.7	15	0
NANCE	16	5.4	4.1	5.0	3.6	13.7	63	0
NEMAHA	7	7.8	6.3	4.6	5.3	16.2	86	0
NUCKOLLS	19	7.6	6.3	7.6	4.0	15.2	79	0
OTOE	7	5.2	4.7	5.1	2.5	9.3	57	0
PAWNEE	2	3.5	3.5	3.5	0.0	3.5	0	0
PERKINS	9	3.3	1.6	3.6	2.7	8.5	44	0
PHELPS	24	3.0	2.4	2.8	1.7	6.5	21	0
PIERCE	14	7.4	3.7	4.8	7.4	22.9	57	7
PLATTE	11	3.3	2.6	2.6	2.6	9.1	18	0
POLK	6	6.2	5.5	5.3	3.6	13.2	83	0
RED WILLOW	25	4.2	3.5	3.4	2.7	13.0	44	0
RICHARDSON	7	5.2	4.0	5.1	3.5	11.5	71	0
ROCK	15	0.8	0.5	0.7	0.8	3.3	0	0
SALINE	9	8.3	6.6	9.6	4.9	14.3	67	0
SARPY	33	5.6	4.5	4.0	4.4	24.2	48	3
SAUNDERS	8	6.9	6.2	6.5	3.3	10.9	63	0
SCOTTS BLUFF	113	3.5	2.8	2.9	2.5	17.3	28	0
SEWARD	7	5.1	4.9	4.9	1.3	6.8	86	0
SHERIDAN	33	3.8	2.6	2.9	3.6	18.4	30	0
SHERMAN	8	4.0	3.7	4.2	1.6	6.3	63	0
SIOUX	6	3.4	1.9	1.6	4.5	12.4	17	0
STANTON	11	4.9	2.4	3.1	4.9	13.8	36	0

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

COUNTY	NO. OF MEAS.	MEAN	GEOM. MEAN	MEDIAN	STD. DEV.	MAXIMUM	%>4 pCi/L	%>20 pCi/L
THAYER	6	4.2	3.4	3.6	2.9	9.0	33	0
THOMAS	10	1.5	1.2	1.1	1.3	5.0	10	0
THURSTON	4	8.3	7.7	9.7	3.1	10.2	75	0
VALLEY	13	4.0	3.5	4.2	1.9	7.0	54	0
WASHINGTON	8	8.3	5.2	4.6	12.0	37.9	63	13
WAYNE	18	9.3	7.1	7.2	6.4	20.2	72	6
WEBSTER	12	4.0	2.4	3.5	3.1	9.0	42	0
WHEELER	6	1.4	0.8	1.3	1.1	3.0	0	0
YORK	12	5.8	4.5	5.1	4.1	15.9	67	0

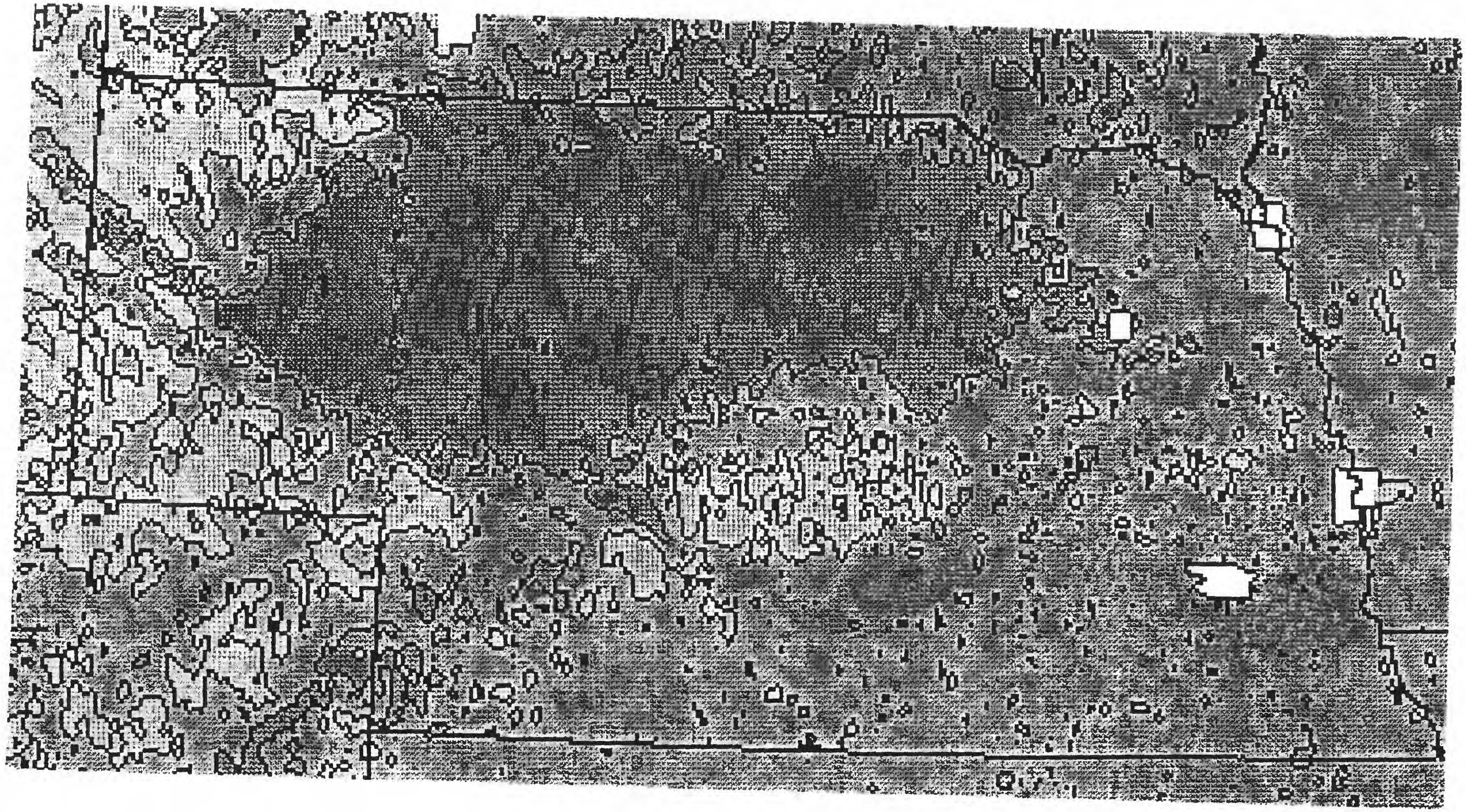


Figure 8. Aerial radiometric map of Nebraska (after Duval and others, 1989). Contour lines at 1.5 and 2.5 ppm equivalent uranium (eU). Pixels shaded from 0 to 6.0 ppm eU at 0.5 ppm eU increments; darker pixels have lower eU values; white indicates no data.

gamma radioactivity signature averaging between 2.0 and 2.5 ppm equivalent uranium (eU), with scattered areas less than 2.0 ppm and scattered anomalies greater than 3.0 ppm, locally as high as 6.0 ppm (fig. 8). Of the source rocks underlying the glacial deposits and those to the north and northeast, Cretaceous sandstones and shales, Pennsylvanian black shales, and Precambrian crystalline rocks all contain significant amounts of uranium-series radionuclides (uranium and(or) radium) to generate radon at elevated levels. In general, soils developed from glacial deposits are rapidly weathered, because crushing and grinding of the rocks by glacial action can enhance and speed up soil weathering processes (Jenny, 1935). Grinding of the rocks increases the mobility of uranium and radium in the soils by exposing them at grain surfaces, enhancing radionuclide mobility and radon emanation. In addition, poorly-sorted glacial drift may in many cases have higher permeability than the bedrock from which it is derived. Cracking of clayey glacial soils during dry periods can create sufficient permeability for convective radon transport to occur. Loess is a generally good radon source because it consists of silt and clay-sized particles, which are more likely to be associated with radionuclides and have higher emanation coefficients than larger sized particles (Megumi and Mamuro, 1974), and it typically has moderate permeability (fig. 6).

The area mapped as loess between the Platte River and the Sand Hills in the central part of the State (fig. 5) has surface radioactivity in the 2.5-3.0 ppm eU range (fig. 8), which is more similar to the surface radioactivity of the Tertiary bedrock in the Panhandle area than to other loess-covered areas in eastern and south-central Nebraska. The Sand Hills have low surface radioactivity (fig. 8) and generally low radon potential.

SUMMARY

For the purposes of this assessment, Nebraska is divided into five geologic radon potential areas (fig. 9) and each area assigned a Radon Index (RI) and Confidence Index (CI) score (Table 2). The Radon Index is a semiquantitative measure of radon potential based on geologic, soil, and indoor radon factors, and the Confidence Index is a measure of the relative confidence of the RI assessment based on the quality and quantity of data used to make the predictions (see the Introduction chapter to this booklet for more information on the methods and data used).

Area 1, the Sand Hills, has a low radon potential (RI=8) with high confidence (CI=12). Area 2 is underlain by Tertiary sedimentary bedrock in the Nebraska Panhandle and on the northeastern side of the Sand Hills (fig. 9). Area 2 has a moderate radon potential (RI=11) with high confidence (CI=12). Some homes in this area are likely to have high indoor radon levels, particularly those sited on uranium-bearing parts of the White River and Arikaree Groups in northwestern Nebraska. Area 3 is underlain by Tertiary bedrock covered by varying thicknesses of loess. Area 3 has a moderate radon potential (RI=11) with high confidence (CI=12). Homes sited on thicker loess along the north side of the Platte River in Dawson and Buffalo Counties may have locally high indoor radon levels. Area 4 is underlain by Cretaceous Pierre Shale bedrock, including the uranium-bearing Sharon Springs Member. The gray-shale units of the Pierre Shale, while not as uraniferous as the black shale units of the Sharon Springs Member, generally contain higher-than-average (i.e., >2.5 ppm) amounts of uranium and are correlated with elevated indoor radon levels in several areas. Area 4 has an overall high radon potential (RI=12) with high confidence (CI=12). Area 5 is underlain by loess-mantled glacial drift in eastern Nebraska and loess-mantled Tertiary and Cretaceous bedrock in south-central Nebraska. Average indoor radon levels are consistently greater than 4 pCi/L in areas underlain by loess-mantled glacial drift. The majority of homes in the area underlain by loess-mantled bedrock in the south-central part of the State also have radon levels exceeding 4 pCi/L, but indoor radon levels are likely to be more variable from house to house in south-central Nebraska, depending on the distribution, thickness, or weathering extent of the loess. Area 5 has an overall high radon potential (RI=13) with high confidence (CI=12).

This is a generalized assessment of Nebraska'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 Nebraska. See figure 9 for locations of areas.

RADON POTENTIAL AREAS

FACTOR	1-Sand Hills RI	1-Sand Hills CI	2-Tertiary Bedrock RI	2-Tertiary Bedrock CI	3-Loess over Tertiary RI	3-Loess over Tertiary CI	4-Pierre Shale RI	4-Pierre Shale CI	5-Glacial Drift & Loess RI	5-Glacial Drift & Loess CI
INDOOR RADON	1	3	2	3	2	3	3	3	3	3
RADIOACTIVITY	1	3	3	3	3	3	3	3	2	3
GEOLOGY	1	3	2	3	2	3	3	3	3	3
SOIL PERM.	3	3	2	3	2	3	1	3	2	3
ARCHITECTURE	2	--	2	--	2	--	2	--	3	--
GFE POINTS	0	--	0	--	0	--	0	--	0	--
TOTAL	8	12	11	12	11	12	12	12	13	12
RANKING	LOW	HIGH	MOD	HIGH	MOD	HIGH	HIGH	HIGH	HIGH	HIGH

RADON INDEX SCORING:

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

Possible range of points = 3 to 17

CONFIDENCE INDEX SCORING:

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

Possible range of points = 4 to 12

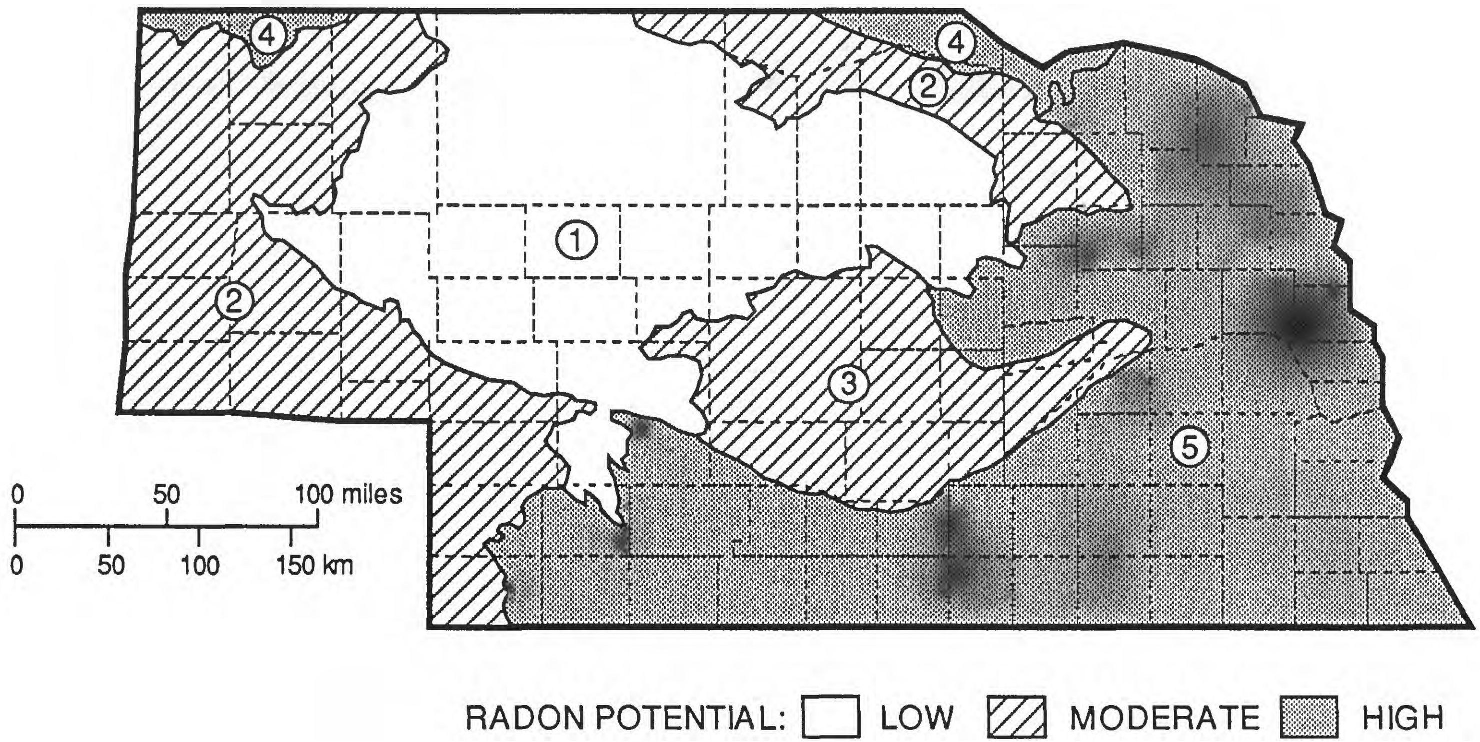


Figure 9. Geologic radon potential areas of Nebraska. See text for discussion of areas.

REFERENCES USED IN THIS REPORT
AND GENERAL REFERENCES PERTAINING TO RADON IN NEBRASKA

Burchett, R.R., 1979, The Mississippian and Pennsylvanian (Carboniferous) Systems in the United States—Nebraska: U.S. Geological Survey Professional Paper 1110-P, 15 p.

Burchett, R.R., 1983, Surface to subsurface correlation of Pennsylvanian and Lower Permian rocks across southern Nebraska: Nebraska Geological Survey Report of Investigations No. 8, 24 p.

Burchett, R.R., and Pabian, R.K., (compilers), 1991, Geologic bedrock map of Nebraska: Nebraska Geological Survey, scale 1:1,000,000.

Carmichael, R.S., 1989, Practical Handbook of physical properties of rocks and minerals: Boca Raton, Fla., CRC Press, 741 p.

Collings, S.P., and Knode, R.H., 1984, Geology and discovery of the Crow Butte uranium deposit, Dawes County, Nebraska, in Practical Hydromet '83: Proceedings of the 7th Annual Symposium on Uranium and Precious Metals, American Institute of Mining Engineers, p. 5-14.

Condra, G.E., and Reed, E.C., 1959, The geological section of Nebraska (with revisions by E.C. Reed): Nebraska Geological Survey Bulletin 14-A, 82 p.

Denson, N.M., and Gill, J.R., 1956, Uranium-bearing lignite and its relation to volcanic tuffs in eastern Montana and North and South Dakota, *in* Page. L.R., Stocking, H.E., and Smith, H.B. (eds), Contributions to the geology of uranium and thorium by the United States Geological Survey and Atomic Energy Commission for the United Nations international conference on peaceful uses of atomic energy, Geneva, Switzerland, 1955: U.S. Geological Survey Professional Paper 300, p. 413-418.

Dickinson, K.A., 1991, Uranium and diagenesis in evaporitic lacustrine mudstone of the Oligocene White River Group, Dawes County, Nebraska: U.S. Geological Survey Bulletin 1956, 25 p.

Dunham, R.J., 1955, Uranium minerals in the Oligocene gypsum near Chadron, Dawes County, Nebraska: U.S. Atomic Energy Commission report TEI-525, 31 p.

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

Elder, J.A., 1969, Soils of Nebraska: University of Nebraska Conservation and Survey Division Resource Report No. 2, 60 p.

Gjelsteen, T.W., and Collings, S.P., 1988, Relationship between groundwater flow and uranium mineralization in the Chadron Formation, northwest Nebraska: Wyoming Geological Association 39th Field Conference Guidebook, p. 271-284.

Kepferle, R.C., 1959, Uranium in Sharon Springs Member of Pierre Shale, South Dakota and northeastern Nebraska: U.S. Geological Survey Bulletin 1046-R, p. 577-604.

Kuzila, M., 1990, Soil Associations and Series, *in* Bleed, A. and Flowerday, C. (eds), An Atlas of the Sand Hills: Resource Atlas No. 5a, 2nd edition., Conservation and Survey Division, University of Nebraska-Lincoln, p. 58-66.

Megumi, K., and Mamuro, T., 1974, Emanation and exhalation of radon and thoron gases from soil particles: Journal of Geophysical Research, v. 79, p. 3357-3360.

Nebraska Conservation and Survey Division, 1986, Groundwater atlas of Nebraska: Nebraska Conservation and Survey Division Resource Atlas No. 4, 32 p.

Nelson-Moore, J.L, Collins, Donna Bishop, and Hornbaker, A.L., 1978, Radioactive mineral occurrences of Colorado and bibliography: Colorado Geological Survey Bulletin 40, 1054 p.

Reed, E.C., and Dreeszen, V.H., 1965, Revision of the classification of the Pleistocene deposits of Nebraska: Nebraska Geological Survey Bulletin 23, 65 p.

Richmond, G.M., Fullerton, D.S., and Christiansen, Ann Coe (editors), 1991, Quaternary geologic map of the Des Moines 4°x6° quadrangle, United States: U.S. Geological Survey Miscellaneous Investigations Map I-1420, sheet NK-15, scale 1:1,000,000.

Struempler, A.W., 1989, Radon in outside air, buildings, water, and soil in northwestern Nebraska, *in* A. Zechmann (ed), Proceedings of Nebraska Academy of Sciences, 99th annual meeting Lincoln, NE, Apr. 14-15, 1989, p. 55.

Swanson, V.E., 1956, Uranium in marine black shales of the United States, *in* Page. L.R., Stocking, H.E., and Smith, H.B. (eds), Contributions to the geology of uranium and thorium by the United States Geological Survey and Atomic Energy Commission for the United Nations international conference on peaceful uses of atomic energy, Geneva, Switzerland, 1955: U.S. Geological Survey Professional Paper 300, p. 451-456.

Swinehart, J.B., Souders, V.L., DeGraw, H.D., and Diffendal, R.F., Jr., 1985, Cenozoic paleogeography of western Nebraska, *in* Flores, R.M. and Kaplan, S.S. (eds), Cenozoic Paleogeography of west-central United States: Rocky Mountain Section, Society of Economic Paleontologists and Mineralogists, Denver Colorado, p. 209-229.

Swinehart, J.B. and Diffendal, R.F., Jr., 1990, Geology of the pre-dune strata, *in* Bleed, A. and Flowerday, C. (eds), An Atlas of the Sand Hills: Resource Atlas No. 5a, 2nd edition., Conservation and Survey Division, University of Nebraska-Lincoln, 29-42.

Tourtelot, H.A., 1956, Radioactivity and uranium content of some Cretaceous shales, central Great Plains: Bulletin of the American Association of Petroleum Geologists, v. 40, p. 62-83.

U.S. Soil Conservation Service, 1987, Soils: U.S. Geological Survey National Atlas sheet 38077-BE-NA-07M-00, scale 1:7,500,000.

Zielinski, R.A., 1983, Tuffaceous sediments as source rocks for uranium—A case study of the White River Formation, Wyoming: Journal of Geochemical Exploration, v. 18, p. 285-306.