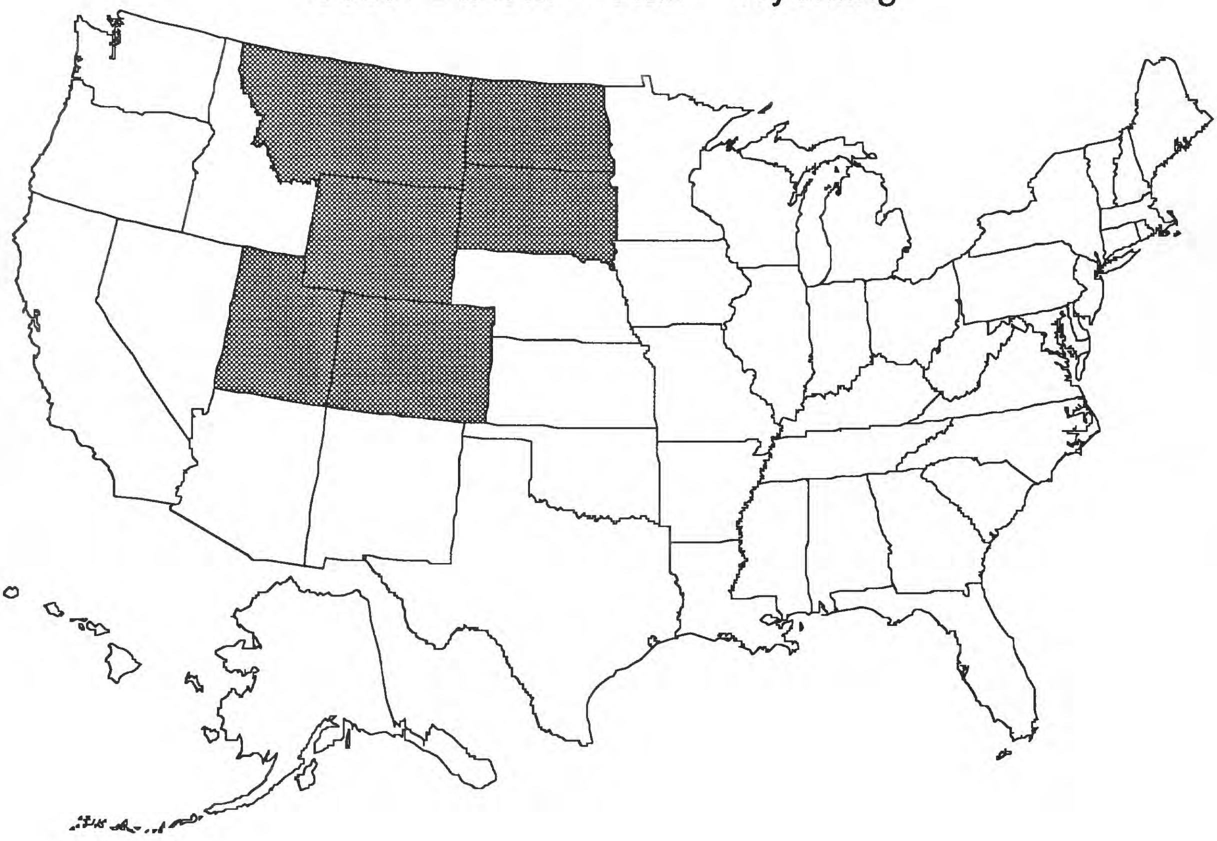
U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

GEOLOGIC RADON POTENTIAL OF EPA REGION 8

Colorado Montana North Dakota
South Dakota Utah Wyoming



OPEN-FILE REPORT 93-292-H

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

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Colorado, Montana, North Dakota, South Dakota, Utah, and Wyoming

R. Randall Schumann
EDITOR

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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

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THE USGS/EPA RADON POTENTIAL ASSESSMENTS: AN INTRODUCTION

by
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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

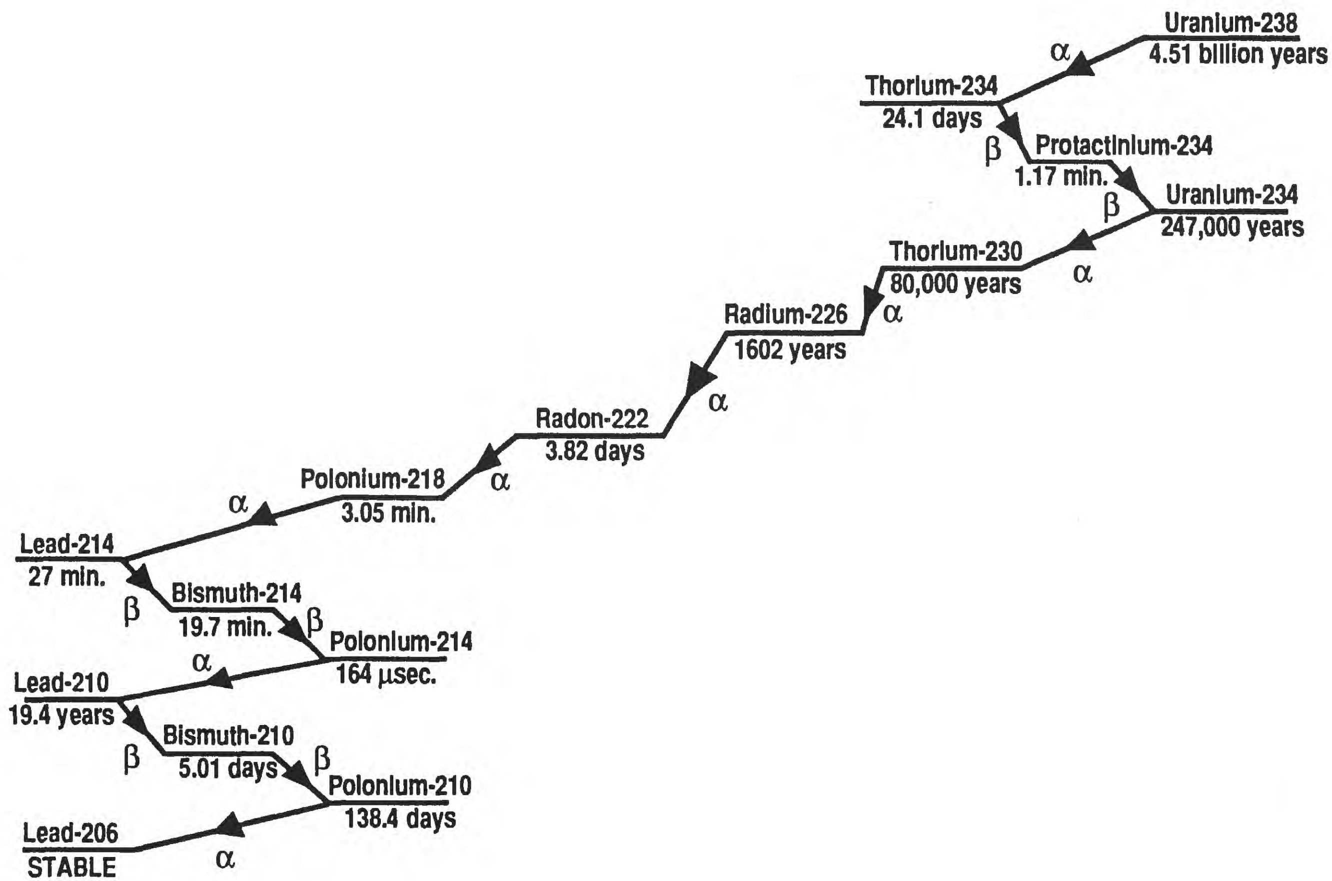

Figure 1. The uranium-238 decay series, showing the half-lives of elements and their modes of decay (after Wanty and Schoen, 1991). α denotes alpha decay, β denotes beta decay.

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 $2x10^{-6}$ 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.

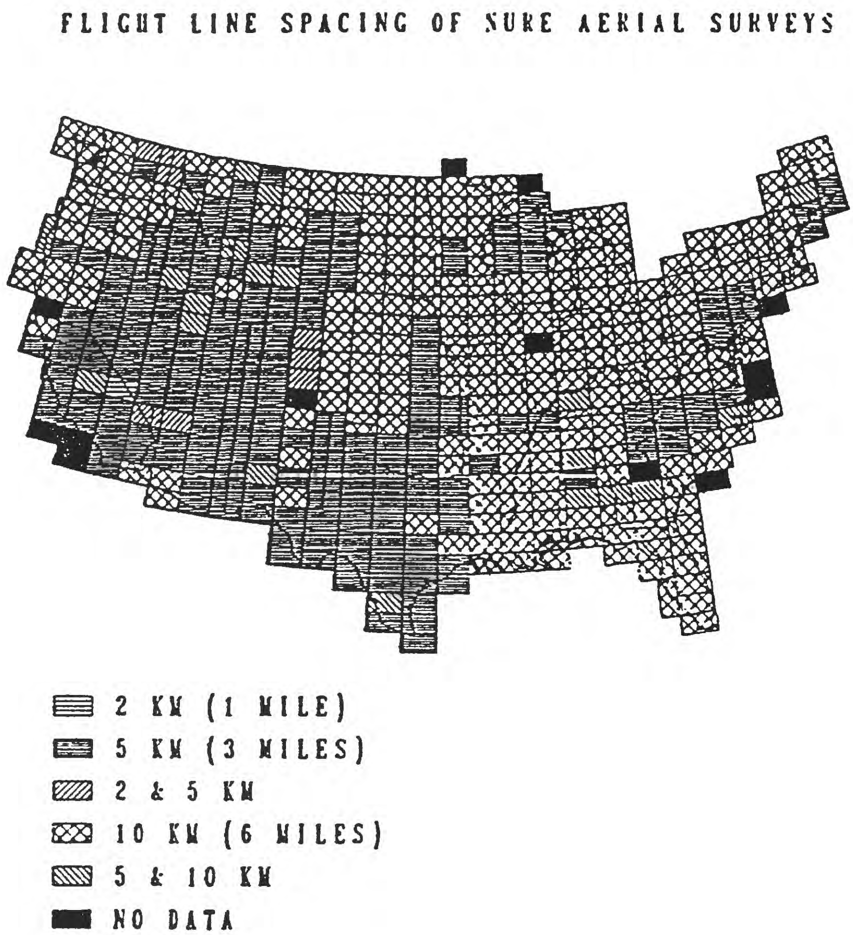

Figure 2. Nominal flightline spacings for NURE aerial gamma-ray surveys covering the contiguous United States (from Duval and others, 1990). Rectangles represent 1°x2° quadrangles.

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

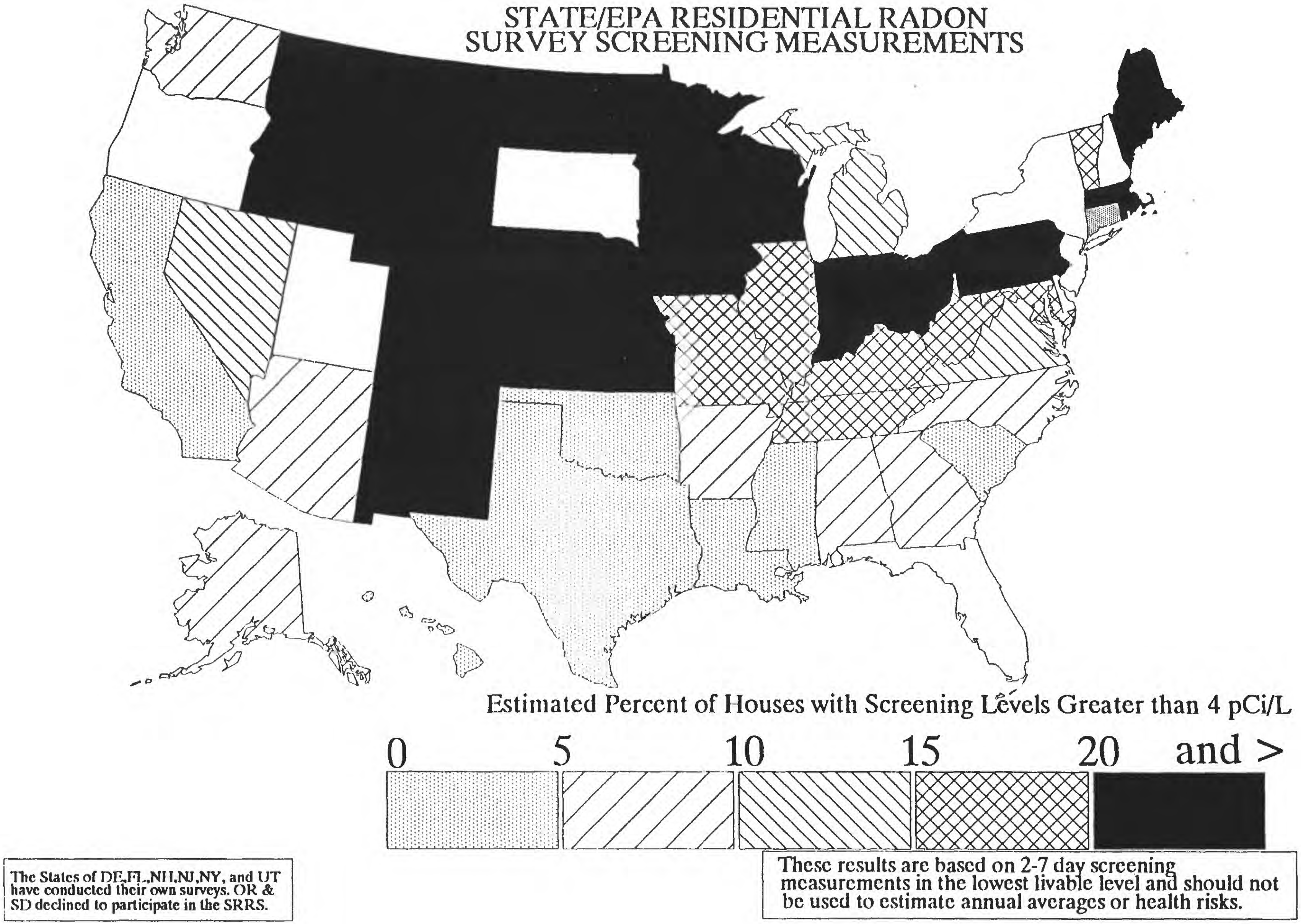

Figure 3. Percent of homes tested in the State/EPA Residential Radon Survey with screening indoor radon levels exceeding 4 pCi/L.

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.

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APPENDIX A
GEOLOGIC TIME SCALE

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

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

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

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

[4] Informal time term without specific rank.

APPENDIX B
GLOSSARY OF TERMS

Units of measure

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

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

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

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

Geologic terms and terms related to the study of radon

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

eolian Pertaining to sediments deposited by the wind.

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

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

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

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

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

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

formation A mappable body of rock having similar characteristics.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

placer deposit See heavy minerals

residual Formed by weathering of a material in place.

residuum Deposit of residual material.

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

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

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

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

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

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

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

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

shrink-swell clay See clay mineral.

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

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

slope An inclined part of the earth's surface.

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

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

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

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

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

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

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

uraniferous Containing uranium, usually more than 2 ppm.

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

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

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

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

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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
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EPA REGION 8 GEOLOGIC RADON POTENTIAL SUMMARY

by

R. Randall Schumann, Douglass E. Owen, Russell F. Dubiel, and Sandra L. Szarzi

U.S. Geological Survey

EPA Region 8 includes the states of Colorado, Montana, North Dakota, South Dakota, Utah, and Wyoming. For each state, geologic radon potential areas were delineated and ranked on the basis of geologic, soils, housing construction, and other factors. Areas in which the *average screening indoor radon level of all homes within the area* is estimated to be greater than 4 pCi/L were ranked high. Areas in which the average screening indoor radon level of all homes within the area is estimated to be between 2 and 4 pCi/L were ranked moderate/variable, and areas in which the average screening indoor radon level of all homes within the area is estimated to be less than 2 pCi/L were ranked low. Information on the data used and on the radon potential ranking scheme is given in the introduction to this volume. More detailed information on the geology and radon potential of each state in Region 8 is given in the individual state chapters. The individual chapters describing the geology and radon potential of the six states in EPA Region 8, though much more detailed than this summary, still are generalized assessments and there is no substitute for having a home tested. Within any radon potential area homes with indoor radon levels both above and below the predicted average likely will be found.

Figure 1 shows a generalized map of the physiographic provinces in EPA Region 8. The following summary of radon potential in Region 8 is based on these provinces. Figure 2 shows average screening indoor radon levels by county. The data for South Dakota are from the EPA/Indian Health Service Residential Radon Survey and from The Radon Project of the University of Pittsburgh; data for Utah are from an indoor radon survey conducted in 1988 by the Utah Bureau of Radiation Control; data for Colorado, Montana, North Dakota, and Wyoming are from the State/EPA Residential Radon Survey. Figure 3 shows the geologic radon potential areas in Region 8, combined and summarized from the individual state chapters. Rocks and soils in EPA Region 8 contain ample radon source material (uranium and radium) and have soil permeabilities sufficient to produce moderate or high radon levels in homes. At the scale of this evaluation, all areas in EPA Region 8 have either moderate or high geologic radon potential, except for an area in southern South Dakota corresponding to the northern part of the Nebraska Sand Hills, which has low radon potential.

The limit of continental glaciation is of great significance in Montana, North Dakota, and South Dakota (fig. 1). The glaciated portions of the Great Plains and the Central Lowland generally have a higher radon potential than their counterparts to the south because glacial action crushes and grinds up rocks as it forms till and other glacial deposits. This crushing and grinding enhances weathering and increases the surface area from which radon may emanate; further, it exposes more uranium and radium at grain surfaces where they are more easily leached. Leached uranium and radium may be transported downward in the soil below the depth at which it may be detected by a gamma-ray spectrometer (approximately 30 cm), giving these areas a relatively low surface or aerial radiometric signature. However, the uranium and radium still are present at depths shallow enough to allow generated radon to migrate into a home.

The Central Lowland Province is a vast plain that lies between 500 and 2,000 feet above sea level and forms the agricultural heart of the United States. In Region 8, it covers the eastern part of North Dakota and South Dakota. The Central Lowland in Region 8 has experienced the effects of continental glaciation and also contains silt and clay deposits from a number of glacial

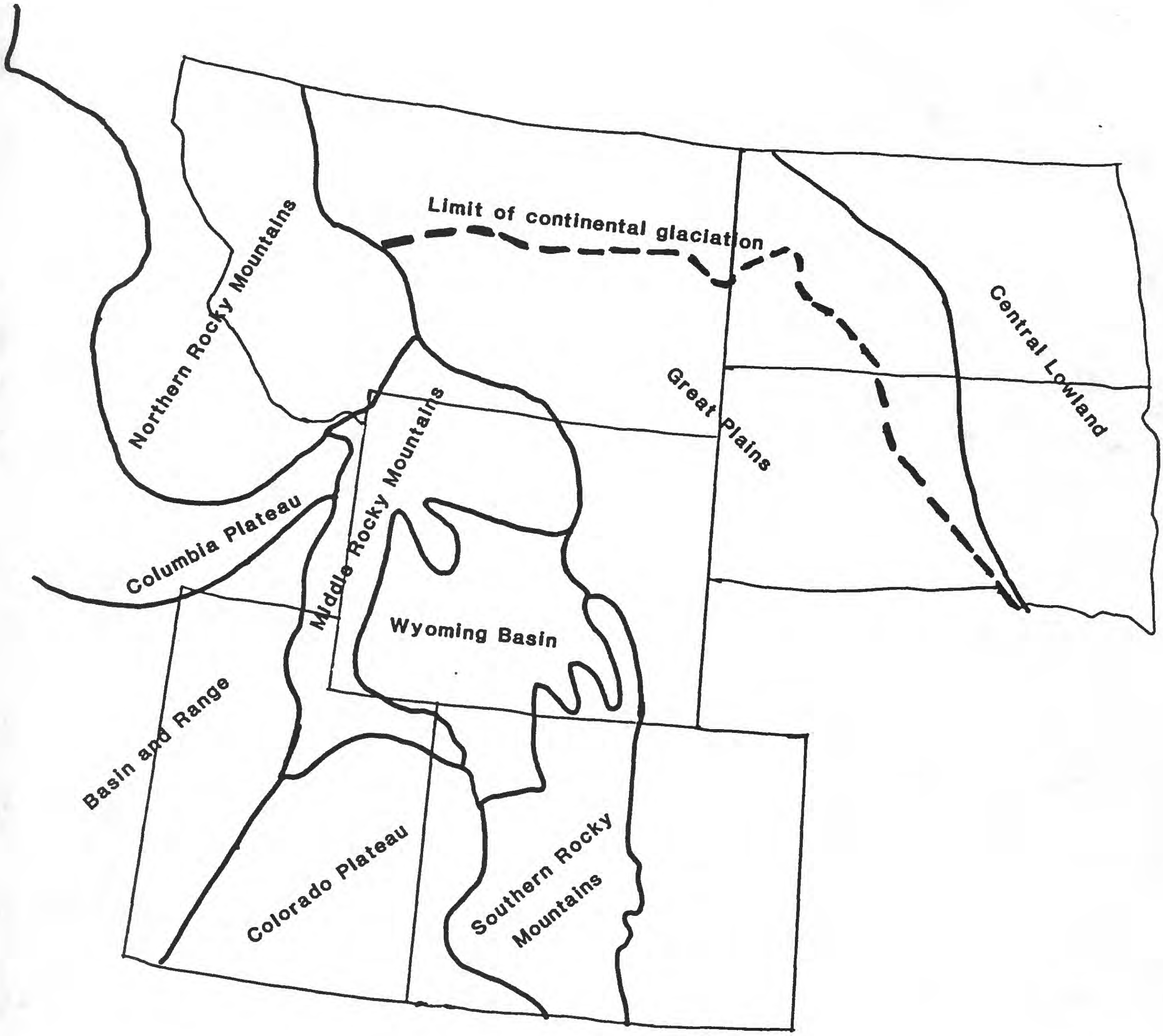

Figure 1. Physiographic provinces in EPA Region 8 (after Hunt, C.W., 1967, Physiography of the United States: Freeman and Co., p. 8-9.)

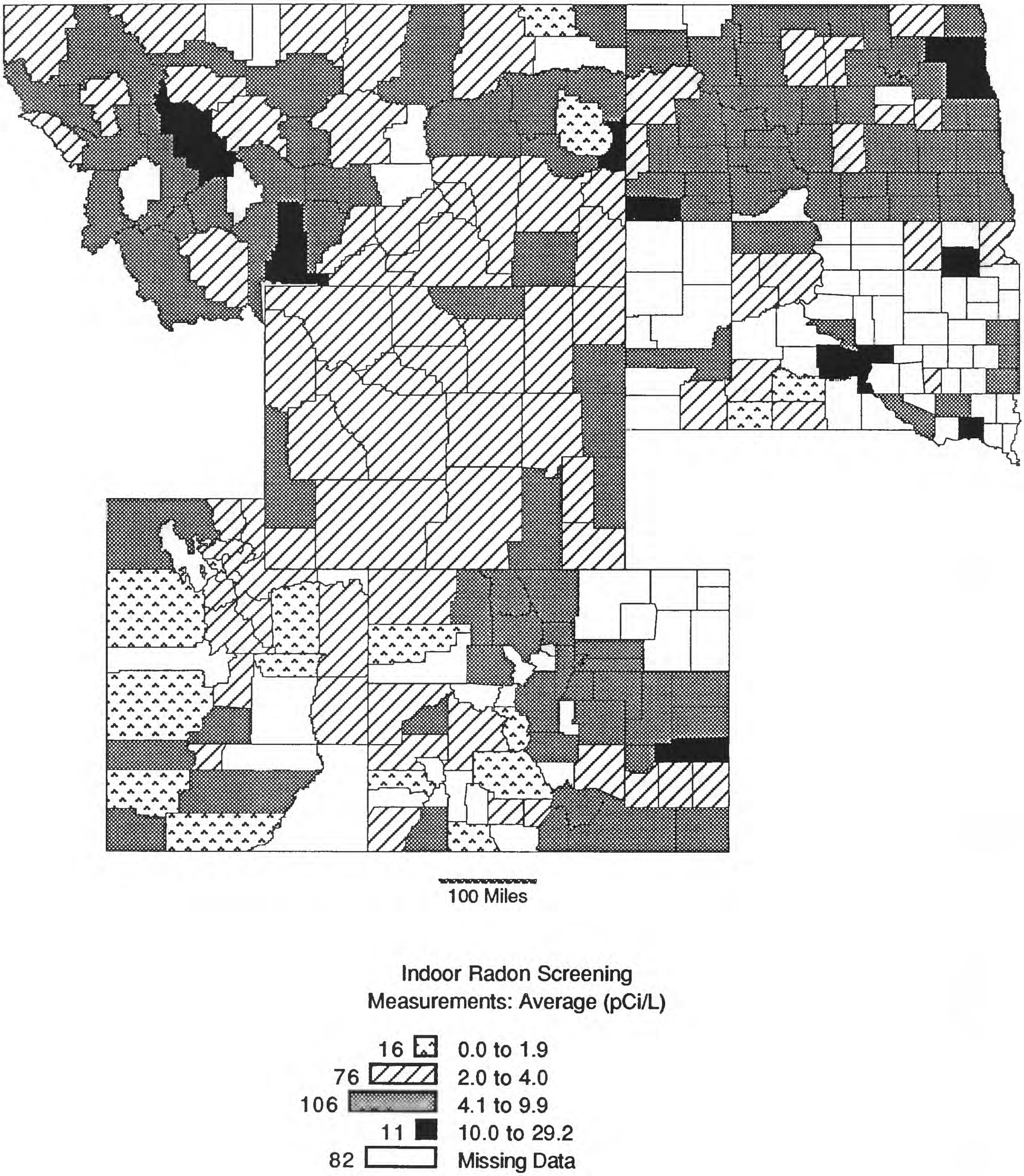

Figure 2. Average screening indoor radon levels by county for EPA Region 8. Data for CO, MT, ND, and WY from the EPA/State Residential Radon Survey; data for UT from the Utah Bureau of Radiation Control indoor radon survey; data for SD from the EPA/IHS Indoor Radon Survey and from The Radon Project. Histograms in map legend indicate the number of counties in each measurement category.

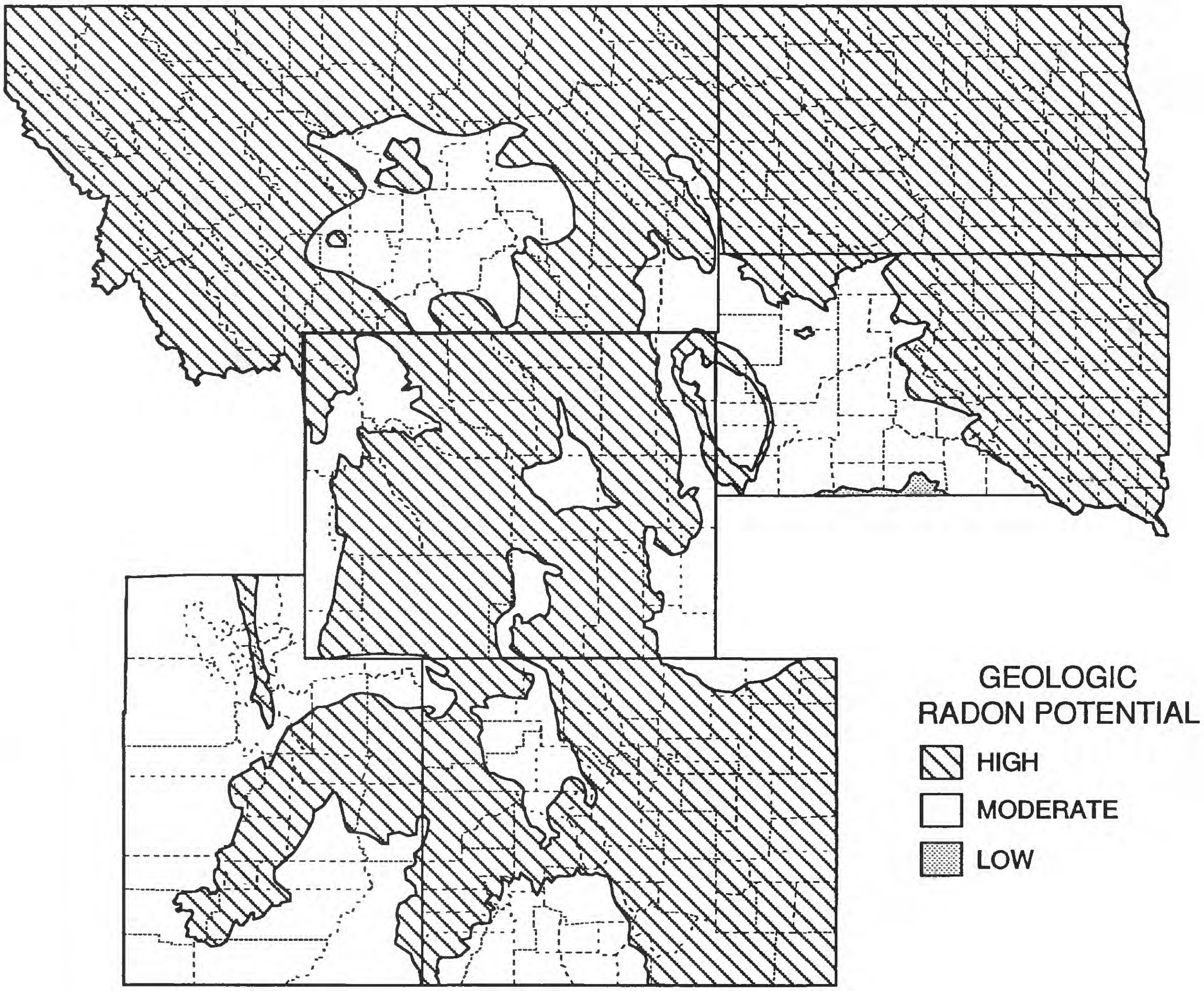

Figure 3. Geologic radon potential of EPA Region 8.

lakes. Many of the glacial deposits are derived from or contain components of the uranium-bearing Pierre Shale. Although many of the soils derived from glacial deposits in the Dakotas contain significant amounts of clay, the soils can have permeabilities that are higher than indicated by standard water percolation tests due to shrinkage cracks when dry. In addition, clays tend to have high radon emanation coefficients because clay particles have a high surface-area-to-volume ratio compared to larger and(or) more spherical soil grains. These two factors make areas underlain by glacial deposits derived from the Pierre Shale, and areas underlain by glacial lake deposits, such as the Red River Valley, highly susceptible to indoor radon problems. Average indoor radon levels in this province generally are greater than 4 pCi/L (fig. 2). The Central Lowland in Region 8 has high radon potential.

The Great Plains Province is an extension of the Central Lowlands that rises from 2,000 feet in the east to 5,000 feet above sea level in the west. In Region 8, it covers the western part of North and South Dakota and the eastern portions of Montana, Wyoming, and Colorado. The northern part of the Great Plains has been glaciated (fig. 1) and previous comments about continental glaciation apply. The Great Plains are largely underlain by Cretaceous and Tertiary sedimentary rocks. In general, the Cretaceous and Tertiary rocks in the southern part of the Great Plains in Region 8 have a moderate to high radon potential. The Cretaceous Inyan Kara Group, which surrounds the Black Hills in southwestern South Dakota and northeastern Wyoming, locally hosts uranium deposits. There are a number of uranium occurrences in Tertiary sedimentary rocks in the northern part of the Great Plains, such as in the Powder River Basin. The northwestern part of the Great Plains contains numerous discontinuous uplifts (mountainous areas) that generally have high radon potential. A few, such as the Black Hills, have uranium districts associated with them. Average indoor radon levels in this province are greater than 2 pCi/L, with a significant number of counties having average indoor radon concentrations exceeding 4 pCi/L (fig. 2).

The Northern Rocky Mountains Province (fig. 1) has high radon potential. Generally, the igneous and metamorphic rocks of this province have elevated uranium contents. The soils developed on these rocks typically have moderate or high permeability. Coarse-grained glacial flood deposits composed of sand, gravel, and boulders, which are found in many of the valleys in the province, also have high permeability. A number of uranium occurrences are found in granite and chalcedony in the Boulder Batholith; in veins or pegmatite dikes in igneous and metamorphic rocks near Clancy in Jefferson County, near Saltese in Mineral County, and in the Bitterroot and Beartooth Mountains, all in Montana. Uranium also occurs in Tertiary volcanic rocks about 20 miles east of Helena, and in the Mississippian-age Madison Limestone in the Pryor Mountains. County average indoor radon levels generally exceed 4 pCi/L in the province (fig. 2).

The Wyoming Basin Province lies dominantly in Wyoming, but also includes an area of Tertiary sedimentary rocks in northern Colorado (fig. 1). The Wyoming Basin consists of a number of elevated semiarid basins separated by small mountain ranges. In general the rocks and soils have uranium contents greater than 2.5 ppm and host a number of uranium occurrences as well, particularly in the Tertiary Fort Union and Wasatch Formations. Average indoor radon levels for homes tested in this area generally are greater than 3 pCi/L (fig. 2). The Wyoming Basin has a high radon potential.

The Middle Rocky Mountains Province (fig. 1) has both moderate and high radon potential areas (fig. 3). The southern part of the Middle Rocky Mountains province contains the Wasatch Range in Utah, which has high radon potential, and the Uinta Mountains and the Overthrust Belt in Utah and Wyoming, both of which have moderate radon potential. The northern part of the province contains the Yellowstone Plateau, which is underlain by volcanic rocks containing relatively high uranium concentrations. Mountain ranges such as the Grand Tetons and Big Horn Mountains, which are underlain by granitic and metamorphic rocks that generally contain more than 2.5 ppm uranium, also occur in this province. County average indoor radon levels are mostly in the 2-4 pCi/L range (fig. 2). The Yellowstone Plateau, Grand Tetons, and Big Horn Mountains all have high geologic radon potential.

The Southern Rocky Mountains Province lies dominantly in Colorado (fig. 1). Much of the province is underlain by igneous and metamorphic rocks with uranium contents generally exceeding the upper continental crustal average of 2.5 ppm. The Front Range Mineral Belt west of Denver hosts a number of uranium occurrences and inactive uranium mines. County indoor radon averages generally are greater than 4 pCi/L, except in the San Juan Mountains in south-central Colorado, where the county radon averages range from 1 to 4 pCi/L (fig. 3). The Southern Rocky Mountains generally have high radon potential, with the main exception being the volcanic rocks of the San Juan volcanic field (located in the southwestern part of the province) which have moderate radon potential.

The part of the Colorado Plateau Province in Region 8 has a band of high radon potential and a core of moderate radon potential (figs. 1, 3). The band of high radon potential consists largely of: (1) the Uravan Mineral Belt, a uranium mining district, on the east; (2) the Uinta Basin, which contains uranium-bearing Tertiary rocks, on the north; and (3) Tertiary volcanic rocks, which have a high aeroradiometric signature, on the west. The moderate radon potential zone in the interior part of the province is underlain primarily by sedimentary rocks, including sandstone, limestone, and shale, which have a low aeroradiometric signature. County average screening indoor radon levels in the Colorado Plateau are mostly greater than 2 pCi/L (fig. 3).

The part of the Basin and Range Province lying in EPA Region 8 has moderate geologic radon potential. The part of the province which is in Region 8 is actually a part of the Great Basin Section of the Basin and Range Province. The entire province is laced with numerous faults, and large displacements along the faults are common. Many of the faulted mountain ranges have high aeroradiometric signatures, whereas the intervening valleys or basins often have low aeroradiometric signatures. Because of the numerous faults and igneous intrusions, the geology is highly variable and complex. Indoor radon levels are similarly variable, with county averages ranging from less than 1 pCi/L to more than 4 pCi/L (fig. 3).

PRELIMINARY GEOLOGIC RADON POTENTIAL ASSESSMENT OF COLORADO

by
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U.S. Geological Survey

INTRODUCTION

Colorado is the birthplace of the uranium mining industry in the United States, which began with the discovery of pitchblende in 1871 in the mine tailings of the Wood mine in the Central City district of Gilpin County (Chenoweth, 1980). The subsequent development of the uranium mining industry in Colorado reflects the relative importance and abundance of three metals: radium, vanadium, and uranium. In 1980 Colorado ranked fourth in domestic uranium production behind New Mexico, Wyoming, and Utah (Chenoweth, 1980). Although uranium mining is not presently economically viable, uranium deposits occur in rocks of many geologic ages and lithologies in Colorado. Because the uranium- and radium-bearing bedrock and the soils and alluvium developed from those rocks are widespread in Colorado, and because radon is a daughter product of uranium decay, many areas in the state have the potential to generate and transport radon in sufficient concentrations to be of concern in indoor air.

This is a generalized assessment of geologic radon potential of rocks, soils, and surficial deposits of Colorado. 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

The physiography of Colorado (fig. 1) is in part a reflection of the underlying bedrock geology (fig. 2) (Mallory, 1972). The southern Rocky Mountains form a distinct physiographic province that extends in a broad north-south belt through Colorado from southeastern Wyoming to north-central New Mexico. The Rockies rise to more than 14,000 ft, and many of the ranges are anticlinal, with Precambrian igneous cores flanked by steeply dipping hogbacks of Paleozoic and Mesozoic sedimentary strata. Large intermontane basins, or parks, separate many of the ranges. The intermontane basins are generally filled by Tertiary and Quaternary deposits. In extreme northern Colorado, the Wyoming Basin province is transitional to the southern Rocky Mountains. The southern Rocky Mountains separate the Great Plains province in the eastern half of the state from the part of the Colorado Plateau province that occupies the southwestern corner of the state. The Great Plains in Colorado are generally underlain by Mesozoic and Cenozoic sedimentary rocks and rise to about 5,500 ft adjacent to the Rocky Mountains. That part of the Great Plains adjacent to the Front Range is known as the Colorado Piedmont or the High Plains. The Colorado Plateau

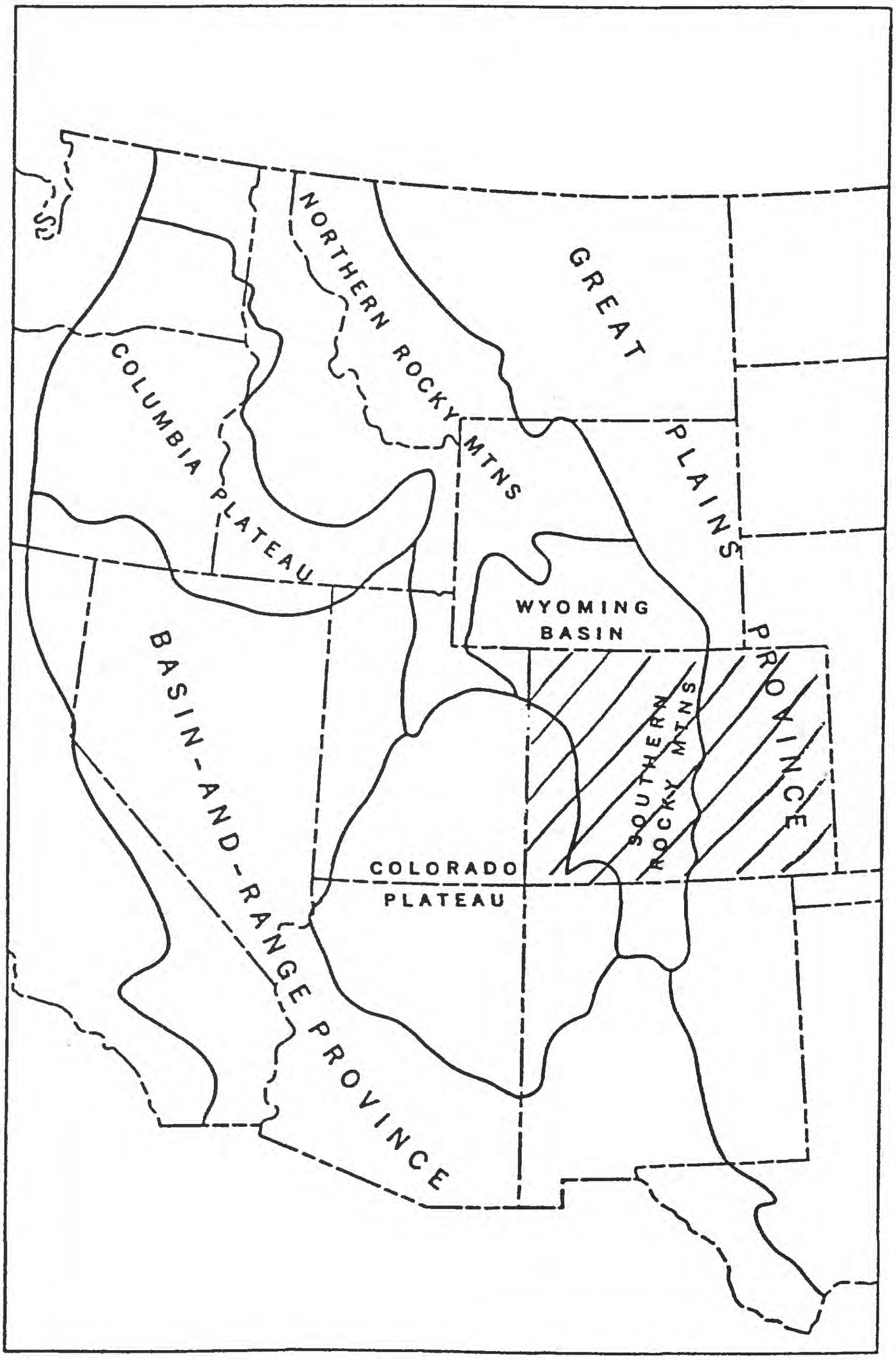


Figure 1. Major physiographic provinces of the western United States (modified from Mallory, 1972).

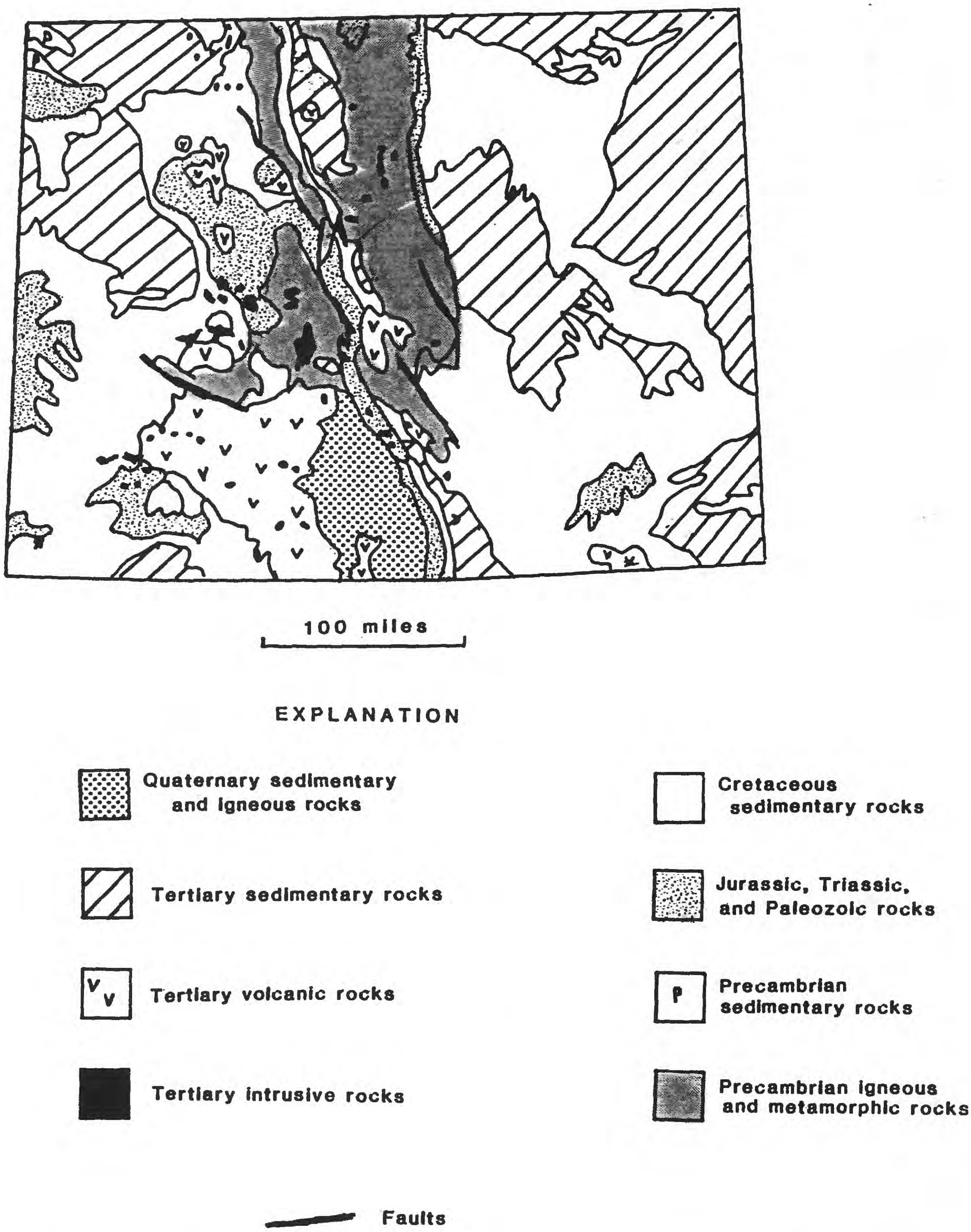


Figure 2. Map showing generalized geology of Colorado (modified from Mallory, 1972).

is a roughly circular area centered about the Four Corners region of Colorado, Utah, Arizona, and New Mexico, and it extends into southwestern Colorado. The Colorado Plateau consists of highly dissected plateaus and mesas ranging in elevation from about 5,000 to 11,000 ft, except in the deepest river canyons. The San Juan Mountains in southwestern Colorado form an isolated range at the transition between the Colorado Plateau and the southern Rocky Mountains and are composed primarily of Tertiary volcanic rocks.

Population distribution (fig. 3A, B) and land use in Colorado reflect in part the geology, topography, and climate of the state (Erickson and Smith, 1985). In 1990, the census indicated approximately 3.3 million persons residing within Colorado's 103,766 square miles. Thus, the population density (fig. 3A) is approximately 31 persons per square mile, substantially below the national average of 65 persons per square mile. Within Colorado, the population is very unevenly distributed (fig. 3B): some mountainous tracts have virtually no residents, and only a few ranching and farming families can be found over large areas of both the Great Plains and the Colorado Plateau provinces. Urban areas are concentrated along the Front Range on the eastern edge of the Rocky Mountains, extending from Pueblo on the south through Colorado Springs and Denver to Fort Collins on the north. This distribution reflects Colorado's early history and the rich mineral deposits of the Rocky Mountains. Mineral wealth provided the major impetus for settlement in Colorado (Erickson and Smith, 1985), and Denver, Colorado Springs, Golden, Boulder, and other towns along the Front Range were established at the mountain front as supply, transportation, and smelting centers for the mining industry in the Rocky Mountains. Other cities such as Grand Junction, Durango, and many smaller towns are situated along major rivers that drain the eastern and western slopes of the Continental Divide. These early transportation corridors provided access to the mineral districts and continue today as the routes followed by modern highways. Despite the general decline in the minerals industry in the last decade, many former mining towns in scenic high-country locations have been rejuvenated and have grown in population in recent years in response to the outdoor recreation and ski industries.

East of the Rockies on the Great Plains, agricultural activities on irrigated and non-irrigated cropland, rangeland, or non-irrigated pastureland are the predominate industries; grazing is the dominant land use in the state (Erickson and Smith, 1985). Along rivers and on high mesas west of the mountains on the Colorado Plateau, agriculture as a whole is limited, but fruit orchards sustain a major local industry. Grazing is the dominant land use on the western slope of the Rockies and on the Colorado Plateau in the southwestern part of the state. The forested Rocky Mountains and the high mesas of the Colorado Plateau are used extensively both for forest production and for winter and summer recreation (Erikson and Smith, 1985).

GEOLOGY

Colorado's geology is complex and varies widely from place to place, but in general the bedrock geology is characteristic of each of the three major physiographic provinces (fig. 2). In addition, many of the radiometric anomalies noted on the aerial radiometric map (fig. 4; Duval and others, 1989) can be associated with specific bedrock formations. The following discussion of geology and soils of Colorado is condensed from Chronic and Chronic (1972), Mallory (1972), Heil and others (1977), Tweto (1979), several topical papers in Kent and Porter (1980), and Beach and others (1985).

The Great Plains east of the Rocky Mountains are characterized by relatively undeformed sedimentary rocks consisting primarily of sandstone, siltstone, and mudstone. The eastern half of

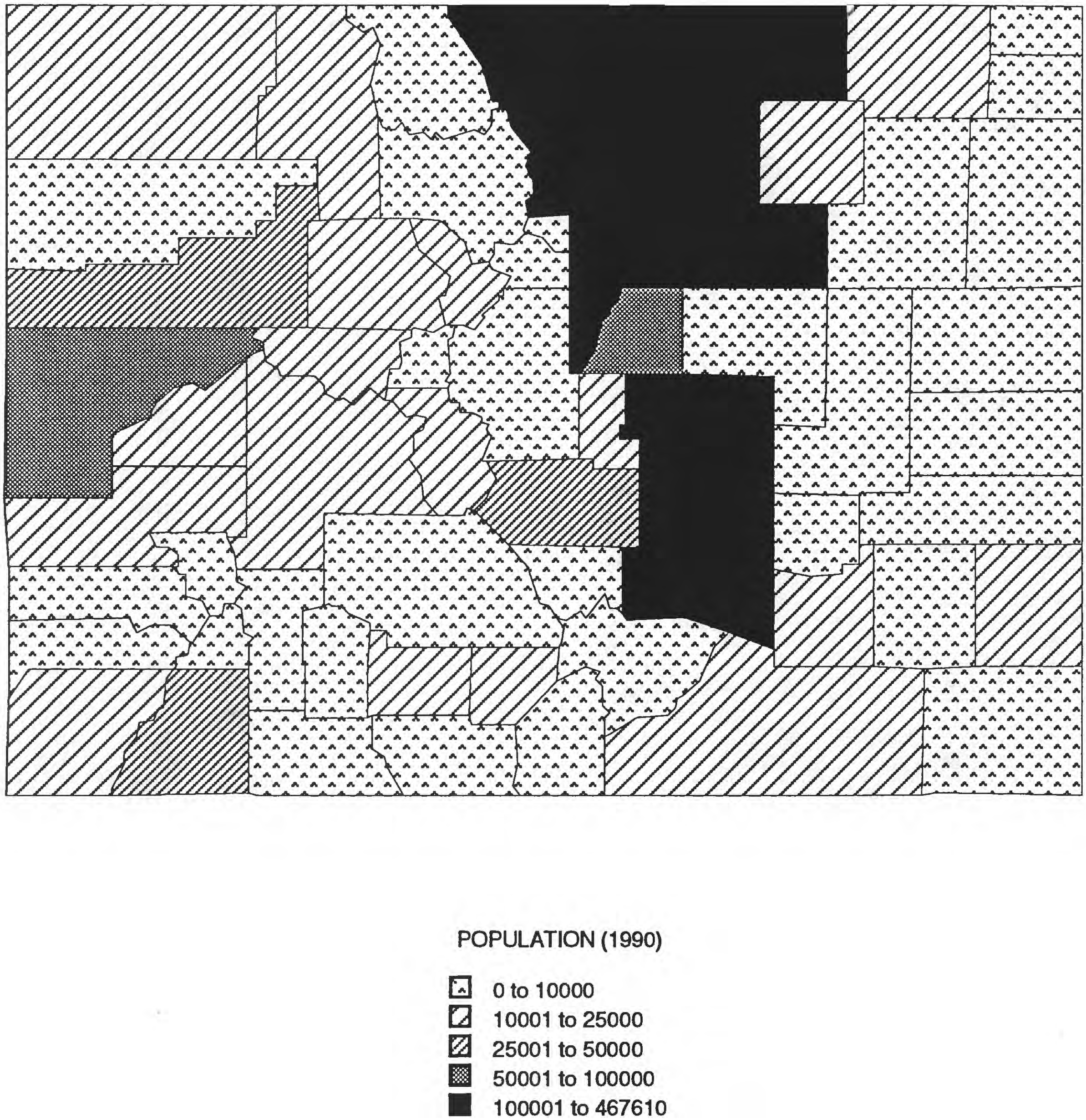


Figure 3A. Population of counties in Colorado (1990 U.S. Census data).

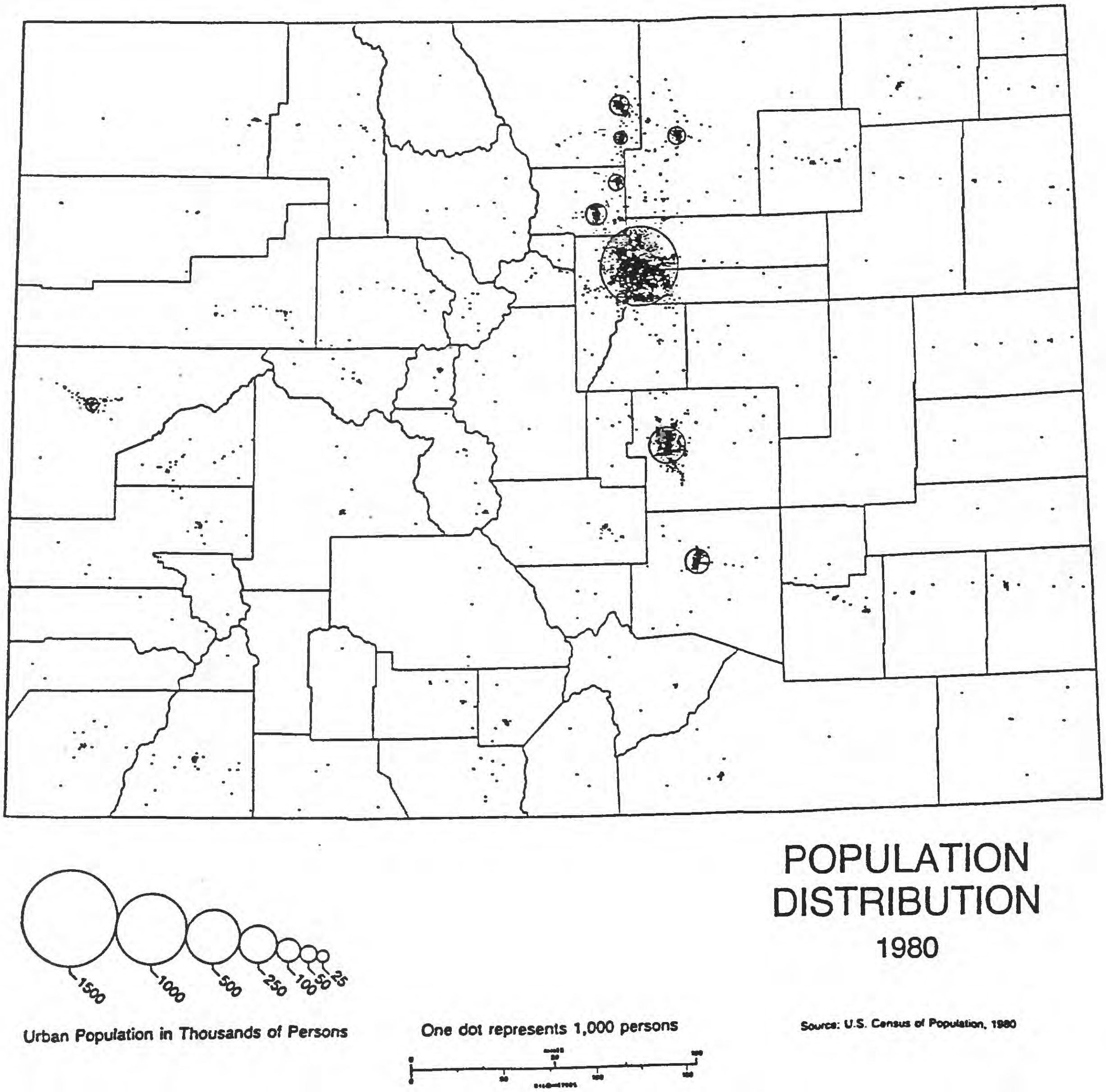


Figure 3B. Map showing population distribution of Colorado in 1980 (modified from Erickson and Smith, 1985).

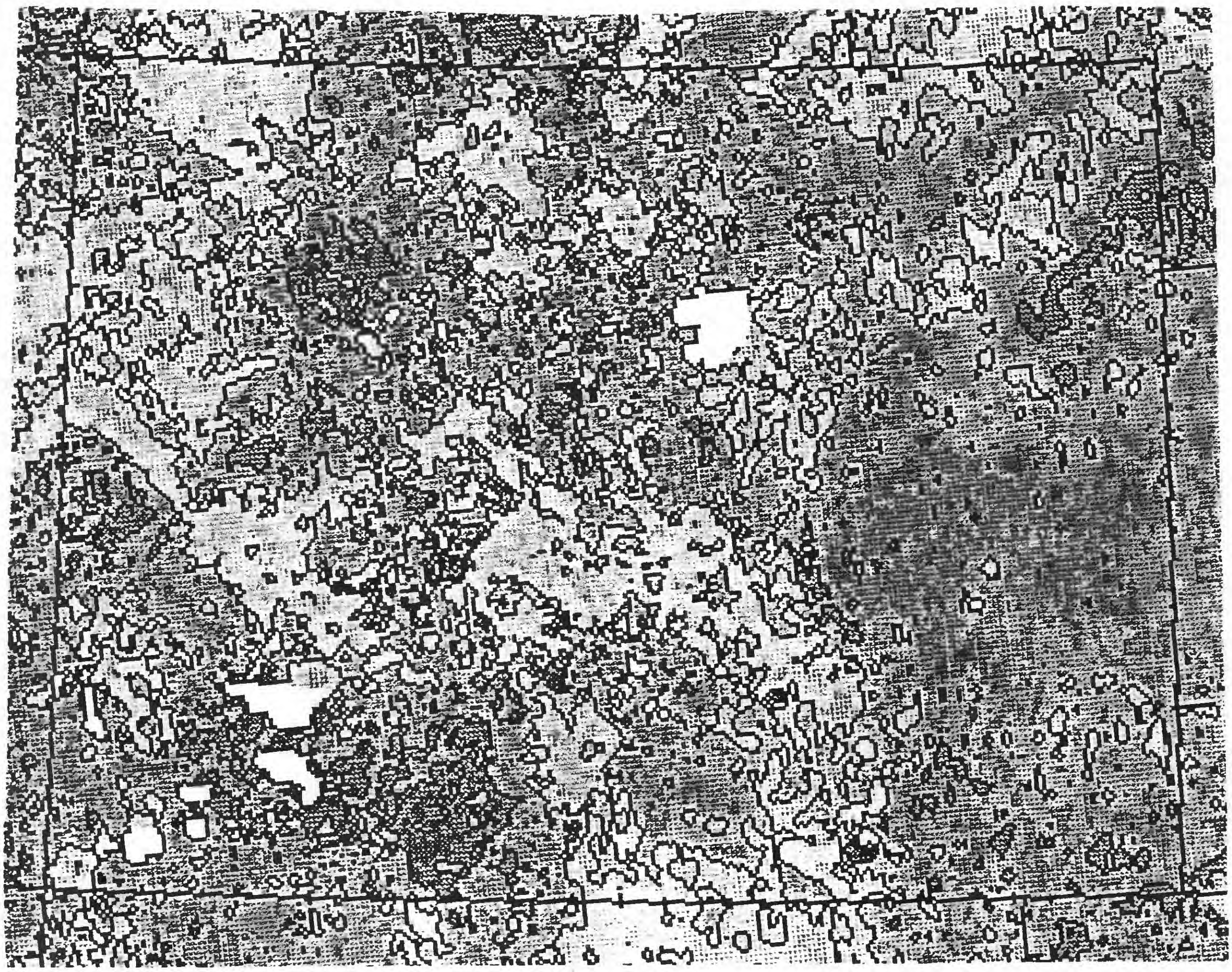


Figure 4. Aerial radiometric map of Colorado (after Duval and others, 1989). Contour lines at 1.5 and 2.5 ppm equivalent uranium (eU). Pixels shaded from 0 to 6.0 ppm eU at 0.5 ppm eU increments; darker pixels have lower eU values; white indicates no data.

the Great Plains in Colorado and a large area of the plains adjacent to the mountain front from Colorado Springs to north of Denver are underlain by Tertiary and Quaternary sedimentary rocks, whereas the remaining western part of the province is underlain by Cretaceous sandstones, shales, and limestones. In the southeastern part of Colorado, sedimentary strata consisting of Permian, Triassic, and Jurassic sandstones, mudstones, and minor limestones are exposed in the drainages of the Purgatoire and Cimarron Rivers.

The Rocky Mountains, including the southern Rocky Mountains and the Wyoming Basin, were formed during the Laramide orogeny, a Late Cretaceous to Eocene structural event that emplaced Precambrian and Cambrian igneous and metamorphic crystalline rocks and minor Cenozoic volcanic rocks adjacent to Paleozoic and Mesozoic sedimentary strata. The Paleozoic and Mesozoic sedimentary rocks consist of conglomerate, sandstone, shale, and limestone. The oldest rocks in Colorado are Precambrian granite intrusive rocks, Precambrian metamorphic gneiss, schist, and pegmatite, and sedimentary quartzite, slate, and phyllite exposed in the Rocky Mountains and locally on uplifts in the San Juan Mountains in southwestern Colorado. Paleozoic and Mesozoic sedimentary strata are steeply dipping where they have been uplifted by the igneous intrusions and along basement faults reactivated by Laramide structural uplift. Cambrian quartzite, and Ordovician, Devonian, and Mississippian limestone, dolomite, and minor sandstone are exposed along the western flank of the Rocky Mountains and in scattered outcrops around the White River uplift in west-central Colorado. Pennsylvanian, Permian, Triassic, Jurassic, and Cretaceous conglomerate, sandstone, shale, and minor limestone also are locally uplifted and exposed along the mountain fronts.

The Colorado Plateau and the Wyoming Basin provinces are underlain by uplifted, primarily flat-lying, locally folded, deeply eroded sedimentary rocks ranging in age from Pennsylvanian to Tertiary. Pennsylvanian and Permian rocks are predominantly arkosic conglomerate, fluvial and eolian sandstone, and minor marine limestone. Triassic strata comprise marginal-marine sandstone and shale and extensive continental fluvial and lacustrine sandstone, mudstone, and limestone. Jurassic rocks consist of widely exposed eolian sandstone, marine limestone and shale, and continental lacustrine and fluvial sandstone and mudstone. Cretaceous rocks form a thick sedimentary section in Colorado and consist of marine shale, sandstone, and limestone interfingered with nonmarine fluvial sandstone and shale. Tertiary sedimentary strata are dominantly lacustrine carbonate and mudstone and minor fluvial sandstone. Tertiary volcanic rocks of extrusive lava, tuff, breccia, and conglomerate and minor rhyolitic intrusive rocks compose the San Juan Mountains in southwestern Colorado and are also found in minor exposures throughout the state.

Uranium deposits (fig. 5A) and production (fig. 5B) in Colorado occur in rocks of many geologic ages and lithologies. A comprehensive report on the uranium deposits in Colorado, from which the following discussion is summarized, can be found in Chenoweth (1980). Sedimentary-hosted uranium deposits are the most common type of uranium occurrence in the State. Uranium-vanadium deposits in fluvial sandstones of the Salt Wash Member of the Upper Jurassic Morrison Formation occur in the Uravan mineral belt in western Colorado. The Uravan mineral belt is an arcuate area in Mesa, Montrose, and San Miguel Counties containing an abundance of closely spaced, high-grade ore deposits. Uranium-vanadium deposits also occur in the Salt Wash east of Meeker on Coal Creek anticline in Rio Blanco County. Uranium-vanadium deposits in eolian strata of the Middle Jurassic Entrada Sandstone are known northeast of Rifle in Garfield County, near Placerville in San Miguel County, and north of Durango at Barlow Creek-Graysill in San Juan and Dolores Counties. The Oligocene and Miocene Browns Park Formation is a fluvial, arkosic,

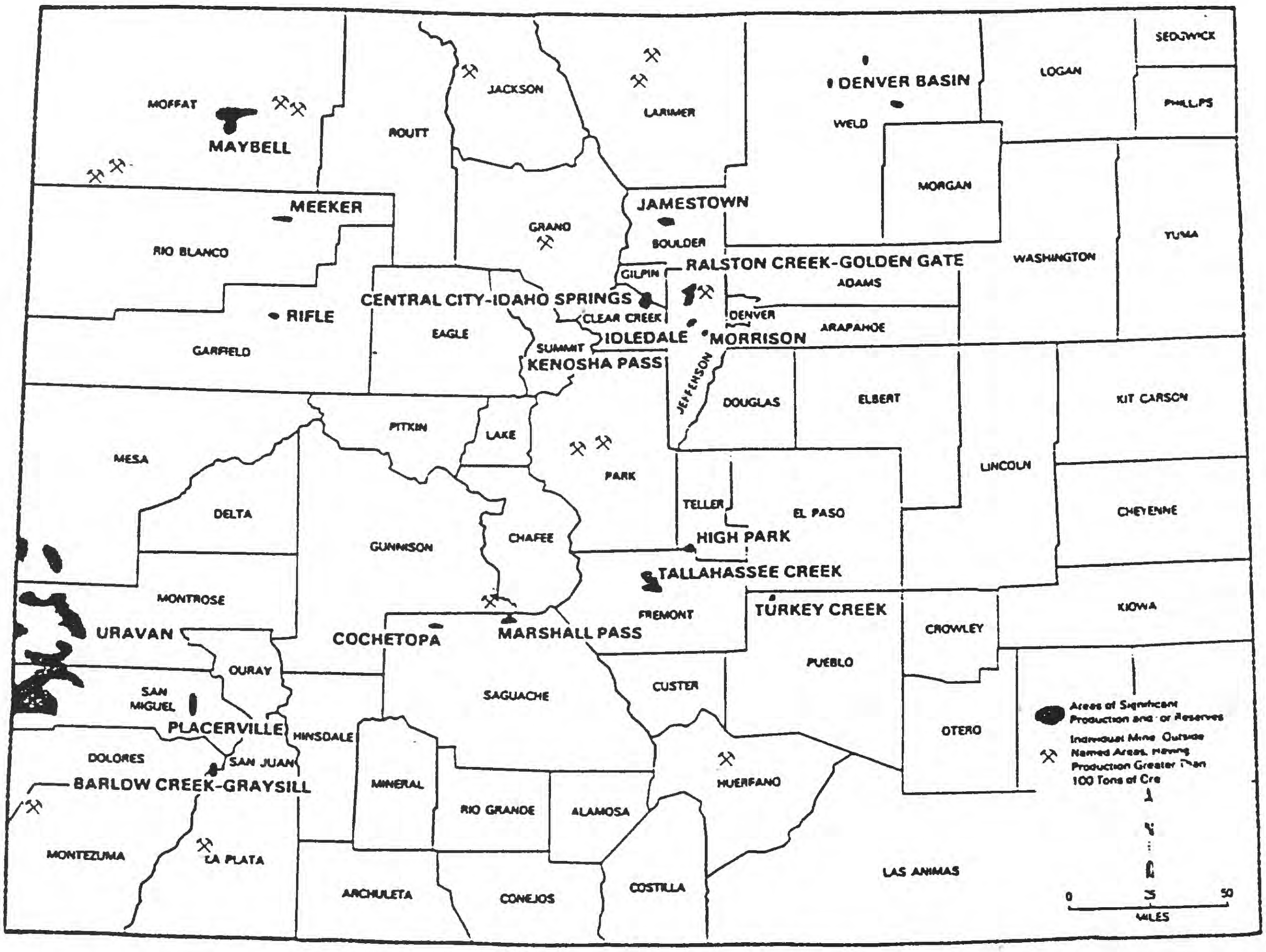
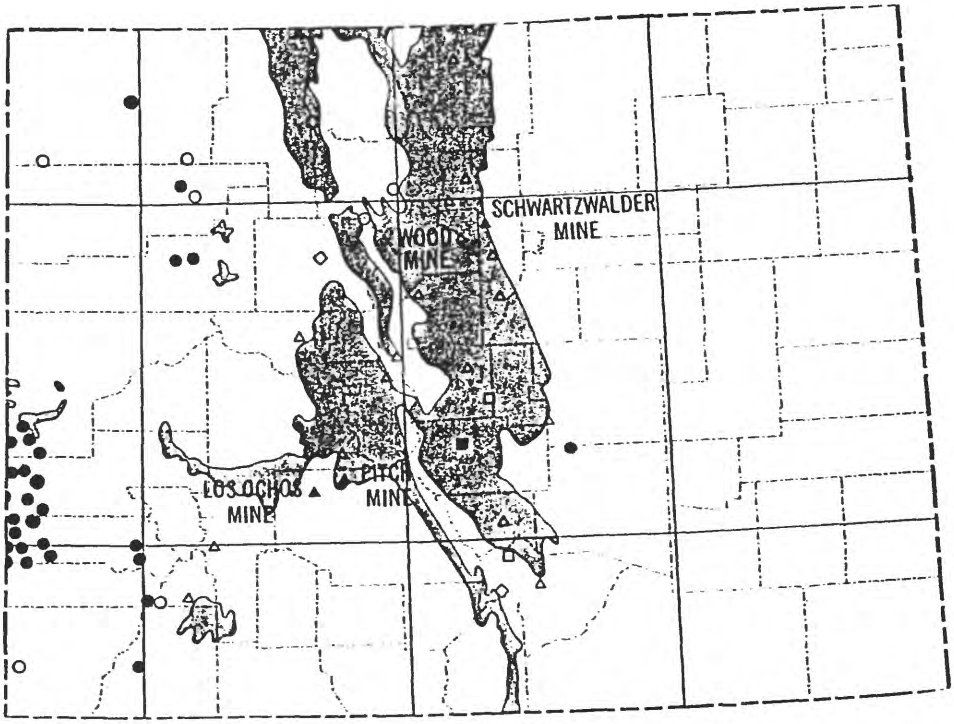
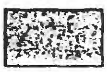


Figure 5 A. Map showing major uranium mines, significant uranium ore deposits, and uranium production (modified from Chenoweth, 1980).



EXPLANATION



Precambrian crystalline rocks exposed

URANIUM DEPOSITS OR GROUP OF DEPOSITS

Size (production plus reserves) of deposits that contains at least 0.1 percent U_3O_8

Tons			Age of host rock
More than 1,000,000	1,000 to 1,000,000	1 to 1,000	
■	■	□	Tertiary
●	●	○	Cretaceous and Jurassic
◆	◆	◇	Triassic and older

Deposits peneconcordant with sedimentary features of enclosing rocks
Symbol with a vertical stem indicates deposit is in coaly carbonaceous rock

Tons		Age of host rock
Over 100,000	Less than 100,000	
▲	△	See text

Veins, breccia zones, and related types of deposits

0 50 100 150 200 MILES

0 50 100 150 200 KILOMETERS

Figure 5B. Map showing major uranium mines and deposits, with known production (modified from Mallory, 1972).

locally tuffaceous sandstone that hosts uranium deposits near Maybell in Moffat County. The Tallahassee Creek area on the southeastern flank of the Thirty-nine Mile volcanic field in north-central Fremont County contains tabular uranium deposits in the Eocene Echo Park Alluvium, which contains arkosic sandstone and conglomerate, and the Oligocene Tallahassee Creek Conglomerate, which consists of volcaniclastic conglomerate and tuffaceous sandstone. The Upper Cretaceous Fox Hills Sandstone and Laramie Formation of the Denver Basin in Weld County contain roll front-type uranium deposits in fluvial sandstones. The Upper Cretaceous Dakota Sandstone has produced small amounts of uranium ore near Rabbit Ears Pass in Grand County, near Badito Cone in Huerfano County, and on the east flank of the Turkey Creek anticline in the northwest corner of Pueblo County. The Paleocene and Eocene Coalmont Formation has produced uranium ore near Hot Sulfur Springs in Grand County, and ore has been produced from the Oligocene Antero Formation near Hartsel in Park County. Minor amounts of uranium ore have been produced from fracture-controlled, sedimentary-hosted deposits in the Middle Pennsylvanian to Lower Permian Weber Sandstone and Maroon Formation in Moffat and Park Counties, the Middle Jurassic Curtis Formation in Moffat County, the Upper Jurassic Morrison Formation in El Paso County, and the Upper Cretaceous Dakota Sandstone and Laramie Formation in Jefferson County.

Production from vein-type uranium occurrences in Colorado is subordinate to sedimentary-hosted deposits, but significant ore bodies occur in the Front Range west of Denver in Precambrian rocks in Larimer, Boulder, Jefferson, Gilpin, Clear Creek, and Park Counties. Uranium has been known in the Central City district of Gilpin County since 1871, where pitchblende was first discovered in the United States on the tailings pile of the Wood mine. Since that time, important deposits have been found near Jamestown, Ralston Creek, Golden Gate Canyon, and Ideldale. These deposits, located near the Central City district, are hosted in the Precambrian (Early Proterozoic) metamorphic complex of the Idaho Springs Formation, which also hosts the Schwartzwalder uranium mine, the largest uranium mine in Colorado. Other Precambrian rocks along the Front Range locally have produced ore. Complicated fault-vein relationships produce uranium in the Marshall Pass area in northern Saguache and southeastern Gunnison Counties. Uranium also occurs along high-angle normal faults within the Middle and Upper Jurassic Junction Creek Sandstone and Upper Jurassic Morrison Formation of the Cochetopa area on the northern margin of the San Juan Mountains in northwestern Saguache County. Minor amounts of uranium ore have been produced from vein deposits in a variety of host rocks in the Park, Sawatch, and Sangre de Cristos Ranges and the San Juan and La Plata Mountains.

In addition to the known deposits in Colorado where uranium has been concentrated as ore, uranium also occurs in several rock formations at concentrations too low to be considered economic but that may still generate radon at levels considered to be a problem in indoor air. For example, the Upper Cretaceous Sharon Springs Member of the Pierre Shale, the Upper Cretaceous Mancos Shale, and the Miocene and Pliocene Ogallala Formation all contain low-level but consistent concentrations of uranium. Precambrian rocks such as the Middle Proterozic Pikes Peak Granite have consistent uranium concentrations and locally higher concentrations along fractures, faults, and shear zones (Schumann, Gundersen, and others, 1989). Tertiary volcanic rocks and ash-flow tuffs around calderas in the San Juan Mountains have low-level uranium concentrations. Many alluvial deposits and soils reworked from uranium-bearing igneous and sedimentary parent rocks, particularly along the Front Range, have significant potential to generate radon.

SOILS

A generalized soil map of Colorado (fig. 6) compiled from Heil and others (1977) and Erickson and Smith (1985) indicates that soils in Colorado consist of Mollisols and Aridisols on the Great Plains; Alfisols, Aridisols, and Inceptisols in the Rocky Mountains; and Entisols, with minor Alfisols, Mollisols, and Aridisols on the Colorado Plateau. Natrargids (sodium-rich Aridisols) are the major soil order in the Wyoming Basin in northwestern Colorado. It should be noted that many of the areas within these generalized soil orders, especially in the Rocky Mountains and on the Colorado Plateau, consist of bare bedrock with incipient to nonexistent soil development. In general, most soils in Colorado are moderately permeable; however, each soil order contains individual soil associations that range from slow to rapid permeability. Although the data in Heil and others (1977) refers most commonly to depth to bedrock in soil associations, which generally can vary from less than 20 inches to more than 60 inches, a few associations do indicate depth to seasonal high water table. For the Aridisols and Natrargids, several soil associations have depth to seasonal high water table from 2 to more than 6 feet. The Entisols and Mollisols include a few soil associations that have depth to seasonal high water table from 0 to 2 feet. The shrink-swell potential of many of Colorado's soils can affect radon concentrations in those soils (Schumann and others, 1989). Soils with high shrink-swell potential may cause building foundations to crack and thus allow radon to enter the structure. Swelling soils, which often crack as they dry, can have effectively increased soil permeability due to cracks. Several areas of Colorado have soils with high shrink-swell potential and include areas underlain by bentonitic Upper Cretaceous marine shales (Benton Formation) and Cretaceous to Tertiary rocks (Arapahoe and Denver Formations) in the Great Plains, in the Grand Valley on the Colorado Plateau, and in parts of the Uinta and Piceance basins in the Wyoming Basin province.

INDOOR RADON DATA

Indoor radon data for Colorado (fig. 7; Table 1) from the State/EPA Residential Radon Survey were compiled from 1986 to 1987 (Colorado Geological Survey, 1991). Data from only those counties in which five or more measurements were made are presented in figure 7. A map showing the counties in Colorado (fig. 8) is provided to facilitate discussion of correlations among the indoor radon data (fig. 7), geology (fig. 2), aerial radiometric data (fig. 4), and soils (fig. 6). In this discussion, "elevated" refers to screening indoor radon levels greater than 4.0 pCi/L. For the counties that have sufficient data to be shown on figure 7, the distribution of elevated indoor radon levels correlates with the bedrock geology and in general with the aerial radiometric data. Elevated indoor radon levels occur in the Great Plains region underlain by Cretaceous sedimentary shales and limestones. Elevated indoor radon levels also occur in the High Plains adjacent to the Front Range on the eastern flank of the Rocky Mountains in areas underlain by Permian, Triassic, Jurassic, and Cretaceous sedimentary rocks, in areas of alluvium derived from those rocks, and from the igneous rocks to the west in the Rocky Mountains. Elevated radon levels also occur in the Rocky Mountains, and especially in the Front Range, where the bedrock consists of Precambrian igneous and metamorphic rocks, some with faults and fracture zones, and numerous Paleozoic to Cenozoic sedimentary rocks. Elevated indoor radon levels also occur on the Colorado Plateau in regions underlain by Paleozoic, Mesozoic, and especially Cretaceous sedimentary rocks.

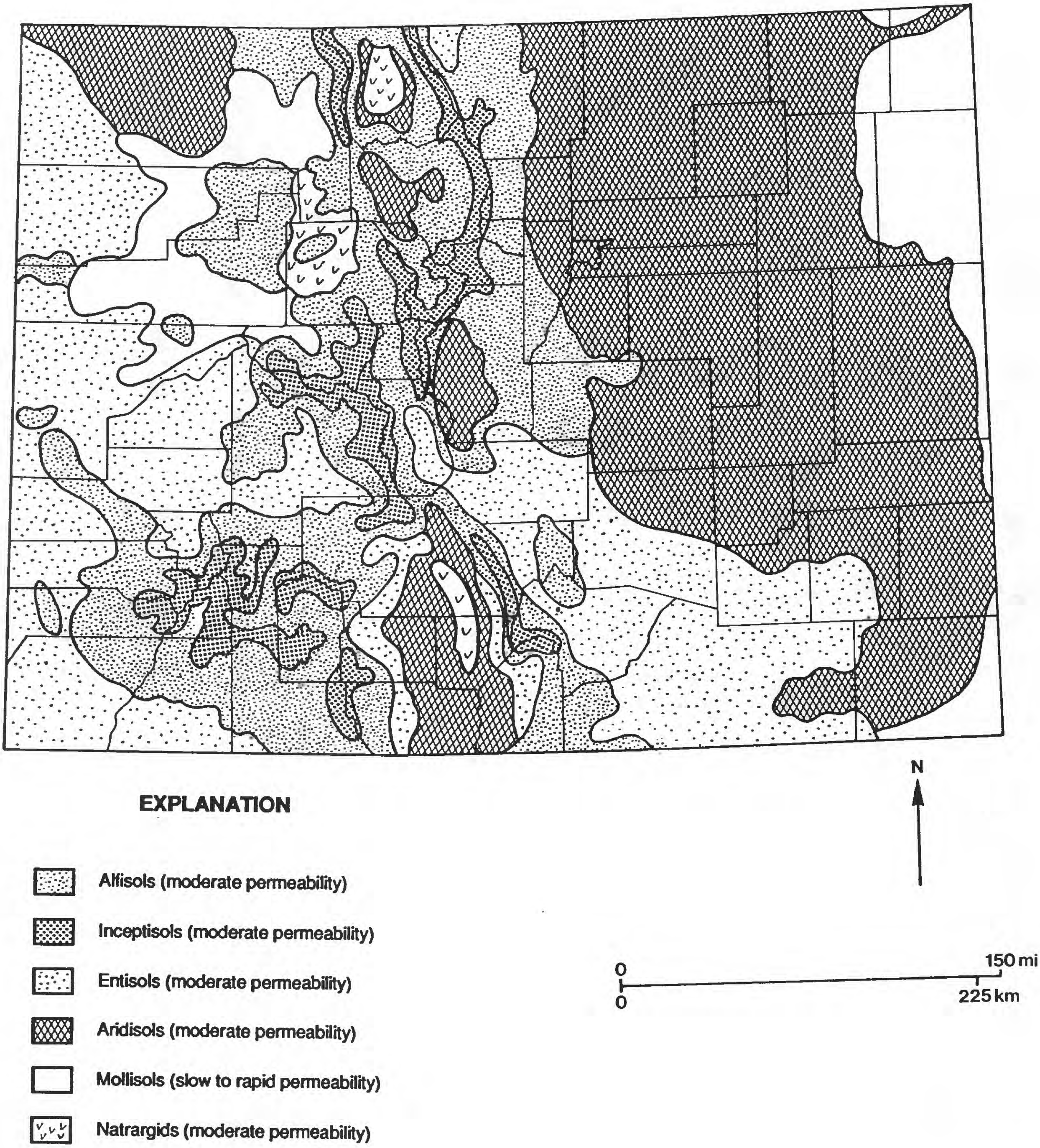


Figure 6. Map showing generalized soils of Colorado (modified from Erickson and Smith, 1985).

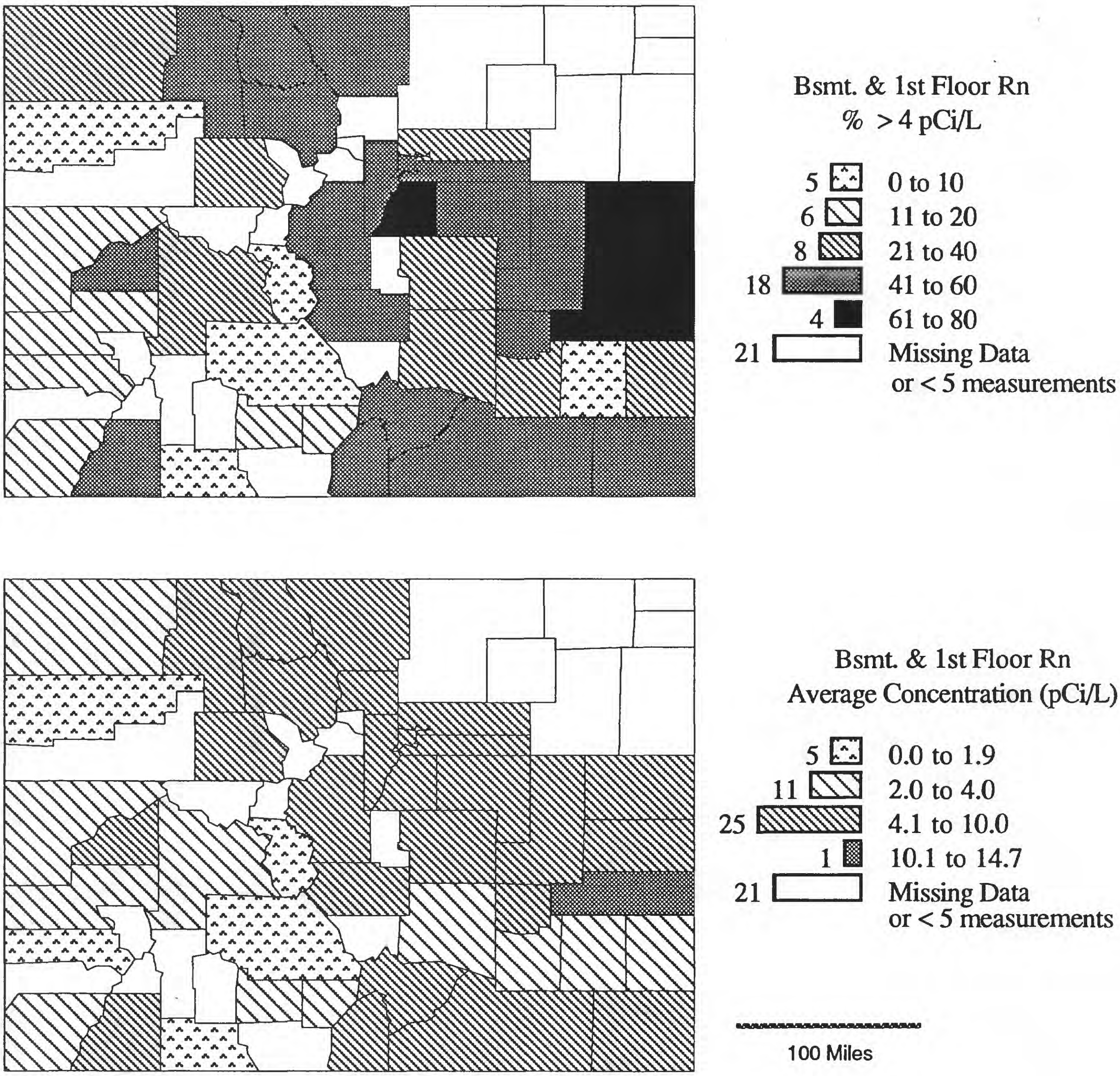


Figure 7. Screening indoor radon data from the EPA/State Residential Radon Survey of Colorado, 1986-87, for counties with 5 or more measurements. Data are from 2-7 day charcoal canister tests. Histograms in map legends show the number of counties in each category. The number of samples in each county (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 Colorado 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
ADAMS	33	5.7	3.7	3.3	7.3	39.8	36	3
ALAMOSA	6	2.5	2.0	1.9	1.9	6.1	17	0
ARAPAHOE	64	6.2	4.4	4.8	6.7	47.9	55	3
ARCHULETA	6	1.6	1.4	1.3	1.0	3.6	0	0
BACA	34	4.8	2.7	3.6	4.5	17.0	47	0
BENT	16	2.7	2.6	2.7	0.9	5.0	6	0
BOULDER	54	4.2	2.7	2.6	3.9	20.2	41	2
CHAFFEE	7	1.2	0.8	1.0	1.0	3.2	0	0
CHEYENNE	18	6.7	5.3	4.9	5.9	26.9	67	6
COSTILLA	14	4.8	3.6	3.2	3.5	12.6	43	0
CROWLEY	18	5.0	4.1	4.1	3.0	11.3	50	0
CUSTER	2	1.1	1.1	1.1	0.1	1.2	0	0
DELTA	19	4.2	3.4	3.3	3.0	11.5	42	0
DENVER	40	4.3	3.5	4.0	2.5	11.2	48	0
DOUGLAS	72	7.6	5.6	5.2	6.9	33.5	63	7
EAGLE	8	5.7	3.8	2.9	6.0	19.0	38	0
ELBERT	21	4.6	2.9	4.5	3.0	10.1	57	0
EL PASO	113	4.7	2.7	3.0	6.5	46.4	36	4
FREMONT	88	5.0	3.1	3.5	8.8	81.2	44	1
GRAND	23	5.4	2.3	4.0	7.0	34.1	48	4
GUNNISON	15	3.8	2.1	3.7	3.2	11.0	40	0
HUERFANO	19	5.0	4.1	4.0	3.9	18.7	47	0
JACKSON	6	6.8	4.6	4.3	6.0	15.0	50	0
JEFFERSON	50	5.1	3.6	3.5	4.4	24.1	48	2
KIOWA	13	14.7	3.6	4.9	22.3	70.9	69	23
KIT CARSON	8	7.2	5.6	7.8	4.5	13.8	63	0
LA PLATA	10	5.2	3.1	3.8	4.6	13.5	50	0
LARIMER	96	5.5	3.2	3.5	5.2	25.1	43	3
LAS ANIMAS	27	6.0	3.8	4.2	5.9	27.1	52	4
LINCOLN	14	4.6	3.1	4.1	4.5	18.4	50	0
MESA	73	2.7	2.1	2.2	2.0	11.5	15	0
MINERAL	3	14.0	5.4	3.5	20.3	37.4	33	33
MOFFAT	8	2.8	2.4	1.9	1.6	5.7	25	0
MONTEZUMA	17	2.6	1.7	1.5	3.2	13.4	12	0
MONTROSE	22	2.4	1.0	1.0	3.7	16.3	14	0
OTERO	19	3.5	2.5	3.0	3.0	12.7	21	0
OURAY	2	2.8	2.0	2.8	2.8	4.8	50	0
PARK	9	5.2	2.1	2.6	5.4	14.7	44	0
PROWERS	18	2.6	2.1	1.9	2.1	8.7	22	0
PUEBLO	32	2.5	1.7	1.7	2.3	10.4	28	0
RIO BLANCO	16	1.8	1.1	1.4	1.6	7.0	6	0

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

COUNTY	NO. OF MEAS.	MEAN	GEOM. MEAN	MEDIAN	STD. DEV.	MAXIMUM	%>4 pCi/L	%>20 pCi/L
RIO GRANDE	6	2.9	2.7	2.7	1.3	5.1	17	0
ROUTT	14	5.5	3.6	3.3	5.8	21.4	43	7
SAGUACHE	9	1.4	1.2	1.2	0.8	2.8	0	0
SAN MIGUEL	9	1.6	0.9	0.8	1.8	5.4	11	0
TELLER	3	99.7	57.6	71.6	104.2	215.0	100	67
WASHINGTON	1	7.8	7.8	7.8	***	7.8	100	0
YUMA	3	11.0	7.6	9.5	9.7	21.4	67	33

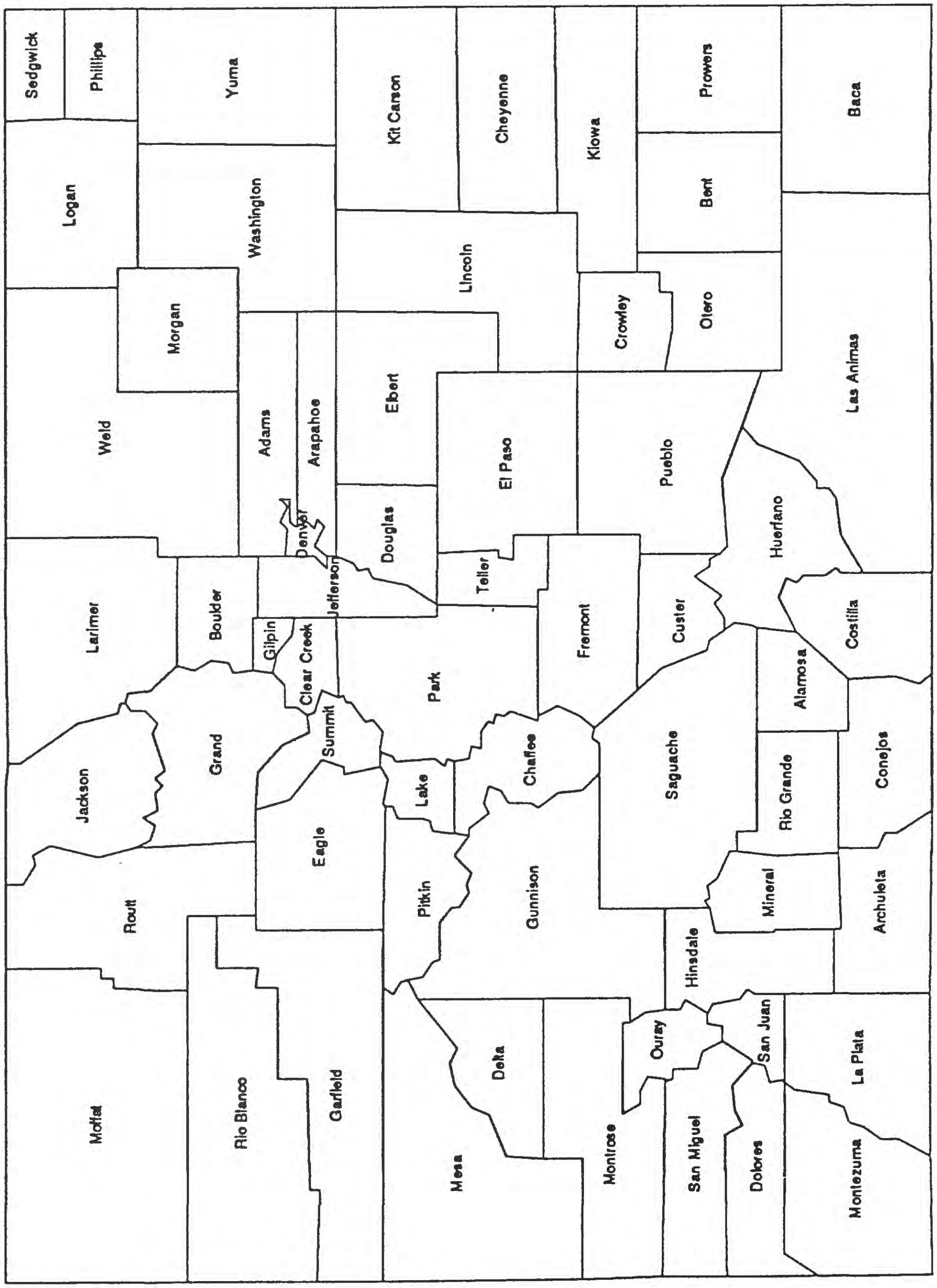


Figure 8. Map showing counties in Colorado.

The highest indoor radon levels measured in Colorado as of this writing were greater than 600 pCi/L. These levels are associated with faults and mineralized shear zones in igneous and metamorphic crystalline rocks in the Front Range of Jefferson County near Conifer (Schumann, Gundersen, and others, 1989) and in faulted Sharon Springs Member of the Pierre Shale along the mountain front in Larimer County near Fort Collins, and in the Highlands Ranch subdivision in the southern Denver metropolitan area. The highest indoor radon value measured in the State/EPA Residential Radon Survey of Colorado was 215 pCi/L in Teller County (Table 1).

The complex geology in each county of Colorado and the scale of maps used in this report makes it difficult to characterize individual rock units that may be responsible for the specific elevated radon levels; the reader is referred to the geologic discussion in this report and should note that the specific geology at any particular site is critical to discerning the factors responsible for measured elevated radon levels. Each of the geologic terranes with elevated radon levels corresponds to areas of anomalously high radiometric signatures on the aerial radiometric map (fig. 4) that reflect uranium-bearing bedrock or alluvium and soils derived from those rocks.

GEOLOGIC RADON POTENTIAL

A comparison of geology (fig. 2) with aerial radiometric data (fig. 4) and indoor radon data (fig. 7; Table 1) provides preliminary indications of rock types and geologic features suspected of producing elevated radon levels. An overriding factor in the geologic evaluation is the abundance and widespread outcrops of known uranium-bearing and uranium-producing formations in the state (fig. 5; Chenoweth, 1980). Because of the widespread occurrence of uranium-bearing rock formations and alluvium, and soils derived from them, virtually all areas of Colorado have the potential for some indoor elevated radon levels; however, even in areas underlain by rocks known to contain uranium, other mitigating factors locally may interact to produce an environment that does not have elevated radon levels. Colorado has many uranium-bearing rocks throughout the state, as discussed in the geology section of this report (fig. 5), but all of those rocks are not highly uraniferous at every locality. The following list is an overview of the rocks that are most likely to produce elevated indoor radon levels. In the Great Plains, sedimentary rocks such as the Upper Cretaceous and Paleocene Dawson Arkose, and various Cretaceous sedimentary rocks including the Dakota Formation, Fox Hills Sandstone, and Laramie Formation, the Pierre Shale (especially the Sharon Springs Member), all have the potential to produce locally elevated indoor radon levels. In addition, the Upper Cretaceous and Paleocene Denver Formation and the Upper Cretaceous Arapahoe Formation, along with Tertiary and Quaternary alluvium and soils derived from these rocks and from uplifted Paleozoic and Mesozoic sedimentary rocks and Precambrian igneous rocks in the Rocky Mountains also have potential for producing locally elevated radon levels.

In the Rocky Mountains, outcrops of Precambrian igneous and metamorphic crystalline rocks such as the Pikes Peak Granite, the Silver Plume Granite, and the Idaho Springs Formation, particularly where they are fractured, faulted, or sheared, have the potential to contain concentrations of uranium minerals and to produce elevated radon levels. Uplifted Paleozoic and Mesozoic sedimentary rocks, and smaller outcrops of Tertiary volcanic and sedimentary rocks, are also locally uraniferous and may produce elevated radon levels.

On the Colorado Plateau and in the Wyoming Basin, many rock formations are known to produce uranium ore and to locally contain low-level concentrations of uranium where ore is not present. Outcrops of the Salt Wash Member of the Morrison Formation are probably the most likely to contain significant uranium orebodies, but many other formations have produced uranium occurrences in Colorado. Locally, the Middle Jurassic Entrada Sandstone, the Oligocene and Miocene Browns Park Formation, the Eocene Echo Park Alluvium, the Oligocene Tallahassee Creek Conglomerate, and the Paleocene and Eocene Coalmont Formation all have potential to produce elevated radon levels. In the San Juan Mountains, various extrusive volcanic rocks locally contain above-average uranium concentrations that may produce elevated radon levels.

Ground water in contact with uranium-bearing bedrock has the potential to accumulate radon and to contribute to indoor radon levels (Nazaroff and Nero, 1988). Municipal water treatment generally dissipates radon accumulations in water supplies, but individual wells used as a source of domestic water that are located in bedrock with high uranium concentrations can contribute significant levels of radon to indoor air (Hess and others, 1990; Lawrence and others, 1989, in press). In Colorado, domestic water wells that tap ground water in uranium-bearing bedrock, especially the fractured, faulted, or sheared Precambrian rocks of the Rocky Mountains, have the potential to significantly contribute to elevated indoor radon levels (Lawrence and others, 1989), and waterborne radon levels as high as 3,000,000 pCi/L have been found in the Lyons, Colorado, area. The Ogallala aquifer, a principal source of ground water on the Great Plains, and the Dakota Group aquifer (Vinckier, 1982), located in the Canon City embayment of Fremont and Pueblo Counties, also contain low-level uranium concentrations. In such areas, ground water may contribute significantly to indoor radon but on a highly variable basis depending on water usage.

SUMMARY

For purposes of assessing the radon potential of the state, Colorado can be divided into nine general areas (termed Area 1 through Area 9), delineated on the basis of similar geology and other factors listed in Table 2 (see figure 9 and Table 2) and scored with a Radon Index (RI), a semi-quantitative measure of radon potential, and an associated Confidence Index (CI), a measure of the relative confidence of the assessment based on the quality and quantity of data used to make the evaluations. For further details on the ranking schemes and the factors used in the evaluations, refer to the Introduction chapter to this booklet.

Areas 1, 2, 3, 4, and 6 each have high radon potential (RI=15, 14, 13, 13, and 12, respectively) associated with a high or moderate confidence index (CI=11, 10, 9, 9, and 8, respectively), and area 5 has a high radon potential (RI=12) with a moderate confidence index (CI=8) on the basis of high indoor radon measurements, high surface radioactivity as evidenced by the aerial radiometric data, and the presence of rock formations such as Precambrian granite, Jurassic sandstone and limestone, or Cretaceous to Tertiary sandstone, shale, and volcanic rock that are known to contain or produce uranium. Area 1 encompasses the Rocky Mountains and contains primarily Precambrian granite that has low but consistent uranium concentrations and abundant shear zones that are known to produce radon in several areas (Schumann, Gundersen, and others, 1989); it also contains outcrops of sedimentary rocks shed from the granitic highlands. Area 2 just east of the Rocky Mountains in central Colorado contains primarily outcrops of the Dawson Arkose that was shed as alluvial fan and river deposits sourced in the granite mountains to the west. Area 3 is primarily underlain by marine shales of the Mancos Shale and by Tertiary sandstones. Area 4 is underlain by variable geology and includes uranium-bearing Jurassic sedimentary rocks of the Uravan mineral belt. Area 5 is underlain primarily by Tertiary sandstone, primarily the Ogallala Formation, and in part, is covered to varying degrees by windblown eolian sand and silt (loess) deposits. Both the bedrock and the loess have the capacity to contribute to high radon values, whereas the thicker eolian sand generally is associated with relatively lower

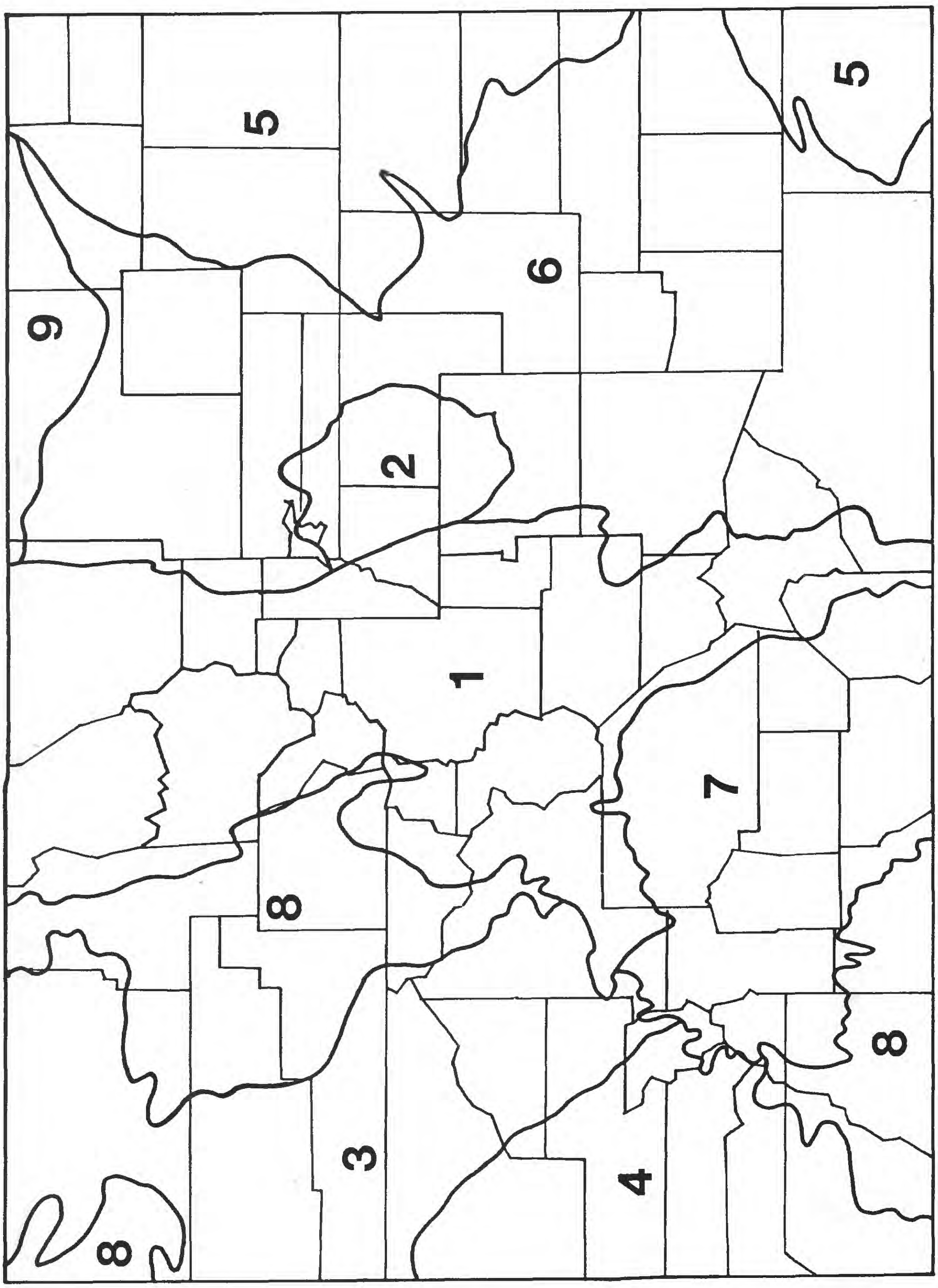


Figure 9. Map showing radon potential areas in Colorado.

radon values. Area 6 in eastern Colorado contains variable geology including Quaternary deposits, Cretaceous marine shales that locally have a high radiometric signature, and small areas of older sedimentary rocks.

Areas 7, 8, and 9 have moderate radon potential (RI=11 for each area) associated with moderate confidence indices (CI=9, 9, and 8, respectively). Area 7 in southwestern Colorado contains primarily volcanic rocks of the San Juan volcanic field. Area 8 comprises three parts of western Colorado: sedimentary outcrops of the easternmost Uinta Mountains, west of the Rocky Mountains, and the northern part of the San Juan Basin in southwestern Colorado. Area 9 contains primarily Teriary sedimentary rocks.

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 Colorado.

FACTOR	Area 1 RI	Area 1 CI	Area 2 RI	Area 2 CI	Area 3 RI	Area 3 CI
INDOOR RADON	3	3	3	3	2	2
RADIOACTIVITY	3	3	3	3	3	3
GEOLOGY	3	3	3	2	3	2
SOIL PERM.	2	2	2	2	2	2
ARCHITECTURE	3	--	3	--	3	--
GFE POINTS	1	--	0	--	0	--
TOTAL	15	11	14	10	13	9
RANKING	HIGH	HIGH	HIGH	HIGH	HIGH	MOD

FACTOR	Area 4 RI	Area 4 CI	Area 5 RI	Area 5 CI	Area 6 RI	Area 6 CI
INDOOR RADON	2	2	3	1	3	2
RADIOACTIVITY	3	3	2	3	2	3
GEOLOGY	3	2	3	2	3	2
SOIL PERM.	2	2	2	2	2	2
ARCHITECTURE	3	--	2	--	2	--
GFE POINTS	0	--	0	--	0	--
TOTAL	13	9	12	8	12	9
RANKING	HIGH	MOD	HIGH	MOD	HIGH	MOD

FACTOR	Area 7 RI	Area 7 CI	Area 8 RI	Area 8 CI	Area 9 RI	Area 9 CI
INDOOR RADON	2	2	2	2	2	1
RADIOACTIVITY	1	3	2	3	3	3
GEOLOGY	3	2	2	2	2	2
SOIL PERM.	2	2	2	2	2	2
ARCHITECTURE	3	--	3	--	2	--
GFE POINTS	0	--	0	--	0	--
TOTAL	11	9	11	9	11	8
RANKING	MOD	MOD	MOD	MOD	MOD	MOD

RADON INDEX SCORING:

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

Possible range of points = 3 to 17

CONFIDENCE INDEX SCORING:

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

Possible range of points = 4 to 12

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PRELIMINARY GEOLOGIC RADON POTENTIAL ASSESSMENT OF MONTANA

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INTRODUCTION

Montana lies along the border with Canada in the continental interior of the United States between 45 and 49 degrees north latitude and 104 and 116 degrees west longitude. It covers an area of 147,138 square miles and is the fourth largest state in the union; only Alaska, Texas, and California are larger. Montana is divided into a number of counties shown on figure 1. It is a rural state and agriculture, ranching, forestry, and mining are major economic activities. Most of the counties in Montana have less than 10,000 inhabitants. Yellowstone County, which contains the city of Billings, is the only county that has a population of greater than 100,000 people (figs. 1, 2).

This is a generalized assessment of the geologic radon potential of rocks, soils, and surficial deposits of Montana. 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 Montana Bureau of Mines and Geology. Addresses and phone numbers for these agencies are listed in chapter 1 of this booklet.

GEOGRAPHIC SETTING

Montana can be divided into three physiographic divisions (fig. 3). Each division covers approximately one third of the State and forms a diagonal (NW-SE) band. The westernmost physiographic division is the Rocky Mountains. This division is made up of 42 named mountain areas (Perry, 1962). The major mountain ranges are shown on figure 4. These mountain ranges are separated by large valleys 5 to 25 miles wide and up to 50 or more miles long (Perry, 1962).

The middle physiographic division, Plains and Mountains, is a continuation of the Great Plains that is broken by isolated island-like mountains ranges (figs. 3, 4). The easternmost physiographic division in Montana (fig. 3) is a part of the Great Plains Province. The glaciated parts of the Great Plains in Montana (delineated on figure 5) are topographically smoother and less dissected than the unglaciated parts found in the south.

The Missouri and Yellowstone Rivers with their tributaries form the major drainage systems in Montana (fig. 4). Topographic elevations in Montana range from about 2,000 feet in the east, where the Missouri and Yellowstone Rivers exit the State, to more than 12,000 feet in the mountains of the west. Most of the major mountain areas receive 40 or more inches of precipitation per year, and some of the mountain areas in the northwestern part of the State receive over 100 inches. Yearly precipitation in the intermontane valleys in the southwestern part of the state is 12 inches or less, whereas the intermontane valleys in the northwestern part of the state

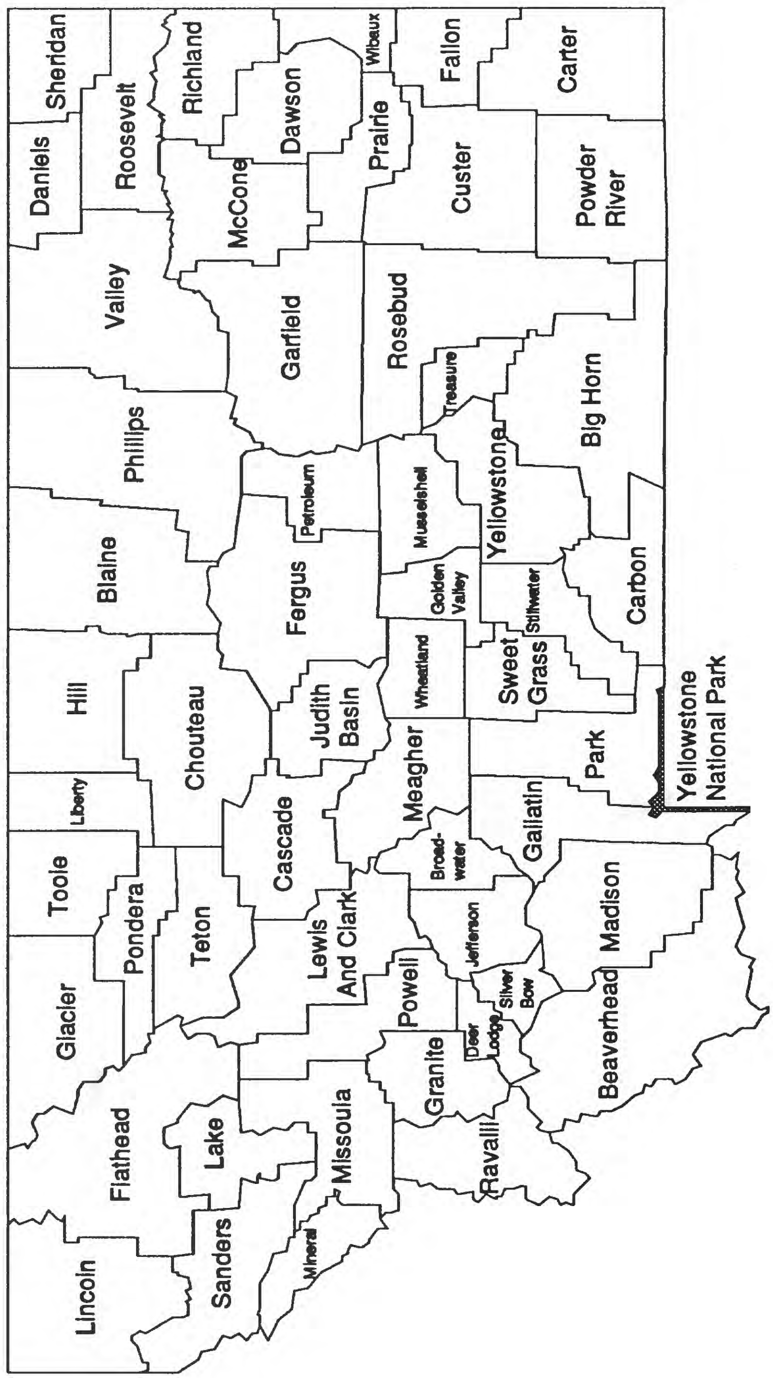


Fig. 1. Counties

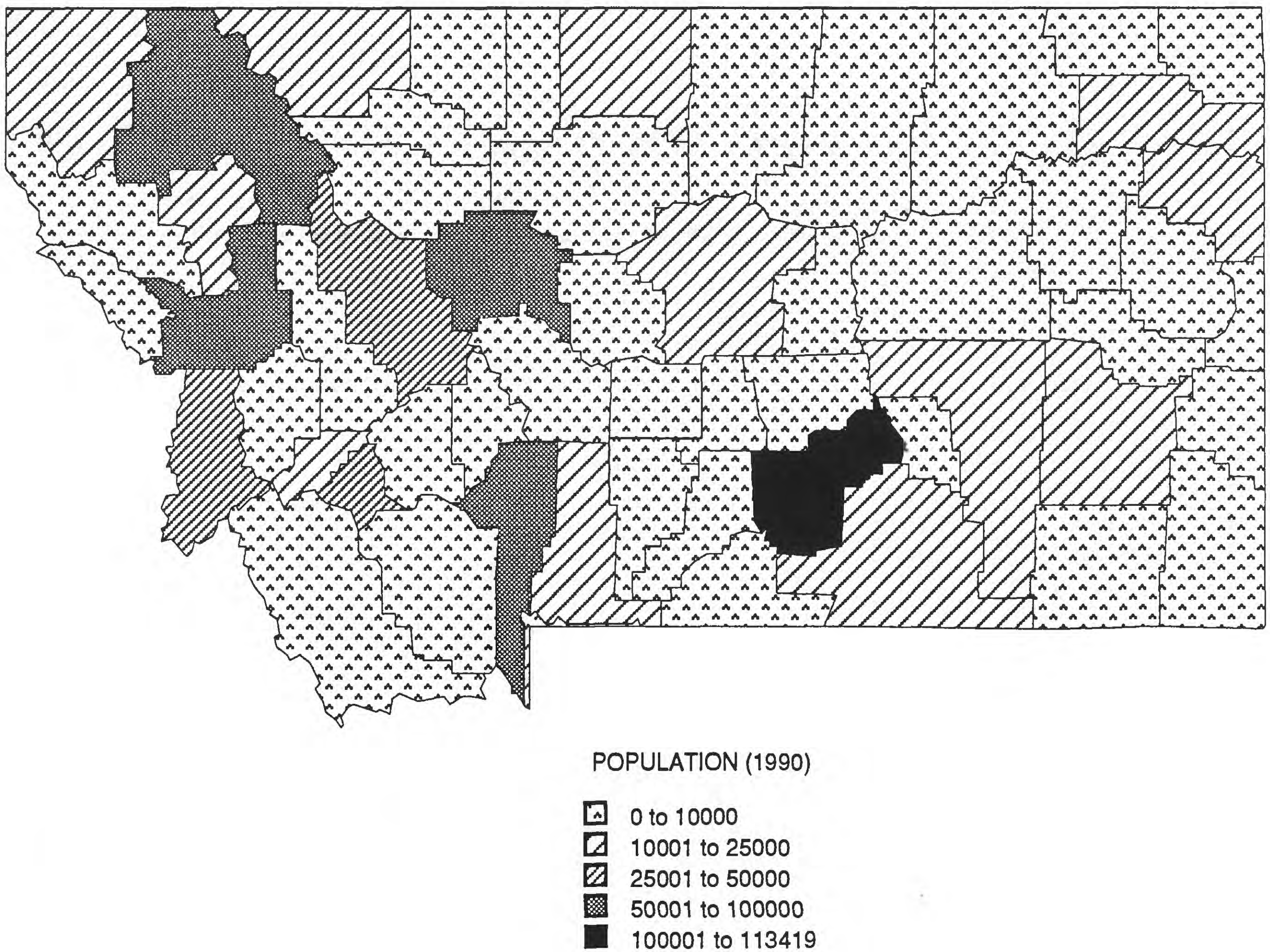


Figure 2. Population of counties in Montana (1990 U.S. Census data).

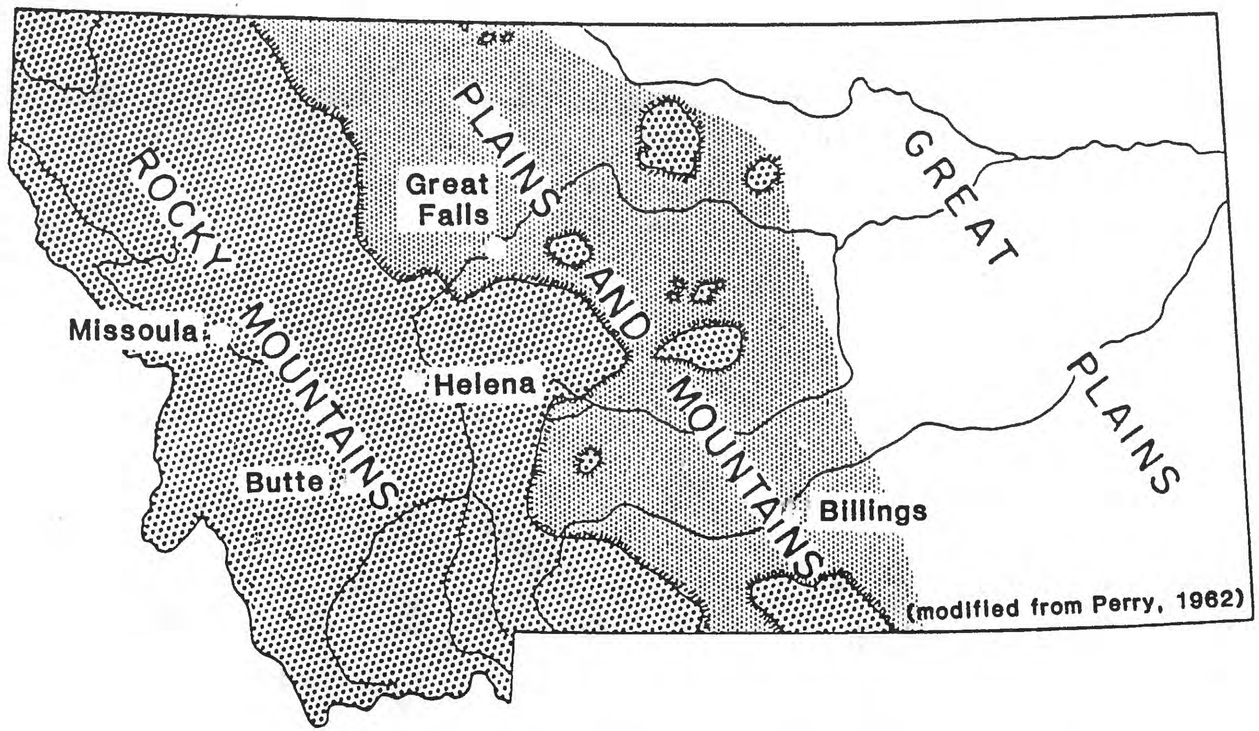


Fig. 3. Physiographic Divisions

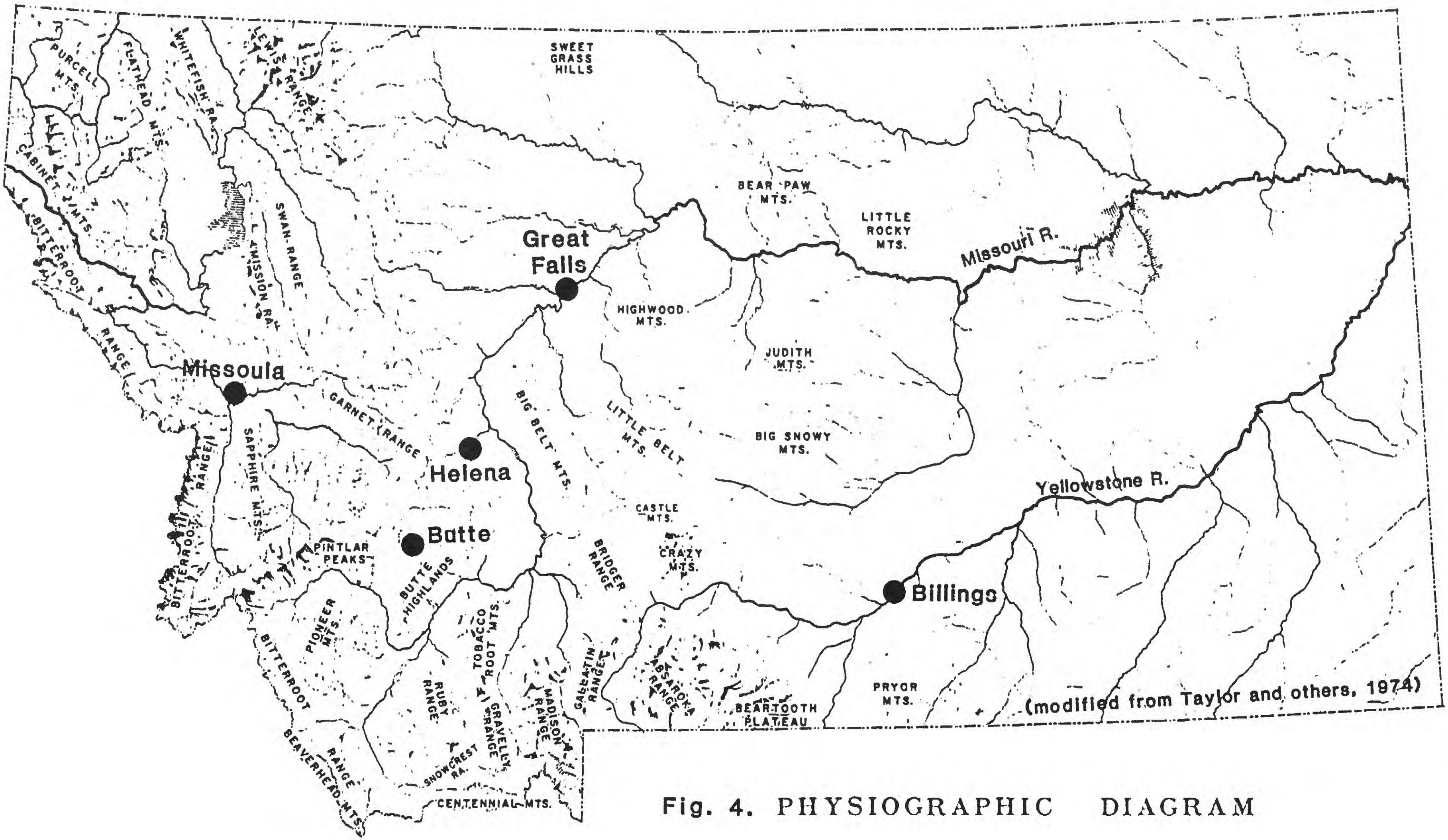


Fig. 4. PHYSIOGRAPHIC DIAGRAM

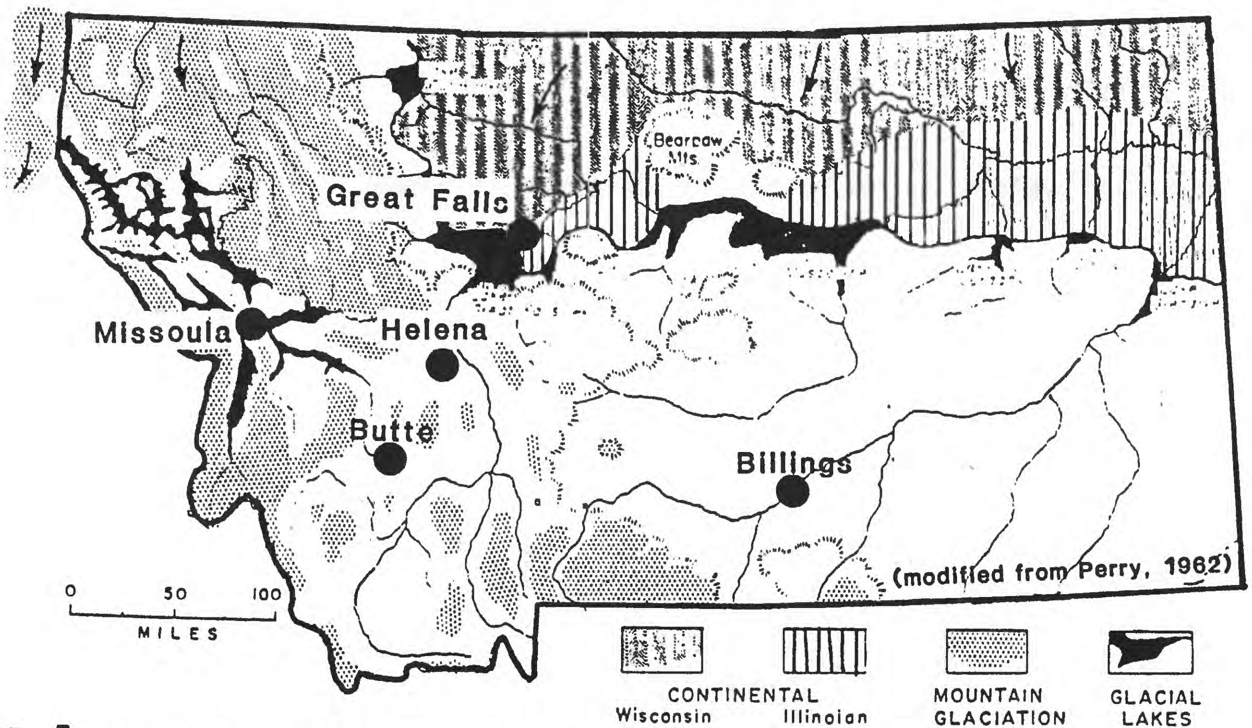


Fig. 5. -Areas of Glaciation in Montana. A general composite map showing areas where glaciation occurred. Glacial ice in the northern Rockies was both Cordilleran ice which moved in from Canada, and mountain glaciers. They merged together. Ice developed in both Illinoian (?) stage and Wisconsin stage in the mountains as well as on the plains. Ice from the mountain glaciers flowed down creek valleys to lower elevations where it melted, even in Yellowstone River valley south of Livingston. Where continental ice moved across valleys, such the Missouri River, Yellowstone River, and the Clark Fork of Columbia River, large lakes developed in front of the ice.

receive about 16 inches. Areas within the Great Plains generally receive 12 or less inches of precipitation per year, with more than half of the annual precipitation falling during the growing season (Taylor and others, 1974).

GEOLOGIC SETTING

Geologic formations found in Montana range in age from Precambrian to Holocene. (Note--A geologic time scale is provided for reference in the introduction to this volume.) A simplified geologic map of the State is shown in figure 6. Precambrian rocks are only exposed in the western part of the State and are dominantly metamorphic rocks. The oldest Precambrian rocks are found in the southwestern part of the state and consist of gneiss, schist, quartzite, and marble. The younger Precambrian rocks, known as the Belt Supergroup, dominate the northwestern part of Montana, but are also present in southwestern corner of the State. The Belt Supergroup is made up largely of quartzites, argillites, impure limestones, and conglomerates.

Paleozoic rocks do not have an extensive outcrop pattern in the State, but are found in some of the mountain areas (fig. 6). The Paleozoic rocks are dominantly limestones and dolomites, but some sandstones and shales are present. Mesozoic rocks are present in the eastern two thirds of the State (fig. 6) and consist of sandstones, shales, conglomerates, limestones, and some gypsum-bearing rocks. Cenozoic rocks consist of massive sandstones, shales, coals, clinker, volcanic ash, glacial deposits, and lacustrine deposits.

Figure 5 shows the extent of Pleistocene glaciation in Montana. The continental glaciers smoothed out the northern part of the Great Plains in Montana by filling previously existing valleys with glacial deposits. The ice blocked many rivers, which previously flowed north, and formed huge glacial lakes. Water depth in some of these lakes reached 2,000 feet, which was the thickness of the ice. Some of these ice-dammed lakes were over 100 miles long and covered hundreds to thousands of square miles. Tremendous floods, which produced extensive, very coarse-grained deposits (abundant cobbles and boulders), occurred when the ice dams were breached. Valley deposits that formed in the lakes or that were deposited during the floods are shown in figure 7.

SOILS

Montana has 8 major soil types (fig. 8) that can be practically shown at the scale of this report. Highly permeable soils allow convective transport of radon (Sextro and others, 1987). Alluvial soils (fig. 8) are commonly highly permeable because the fines have been winnowed by the moving water. The alluvial soils that formed on the great glacial flood deposits found in the southwestern part of the State are probably highly permeable. Soil permeabilities greater than 6 inches per hour (water percolation rate listed in soil surveys) are considered highly permeable. Duval, Otton, and Jones (1989), in a study for the Bonneville Power Administration, examined some of the soil surveys for the western two-thirds of Montana. They found soils or intervals within soils that were described in the soil reports as having permeabilities greater than 6 inches per hour for the following counties: Bighorn, Blaine, Broadwater, Carbon, Cascade, Judith Basin, Lewis and Clark, Missoula, Phillips, Ravalli, and Stillwater.

Fine-textured shallow to moderately deep soils over shale (fig. 8) are expected to have low to moderate permeabilities and may inhibit radon transport. Soils above timberline (fig. 8) and soils on forested mountain slopes in Montana receive 40 to, in some cases, more than 100 inches

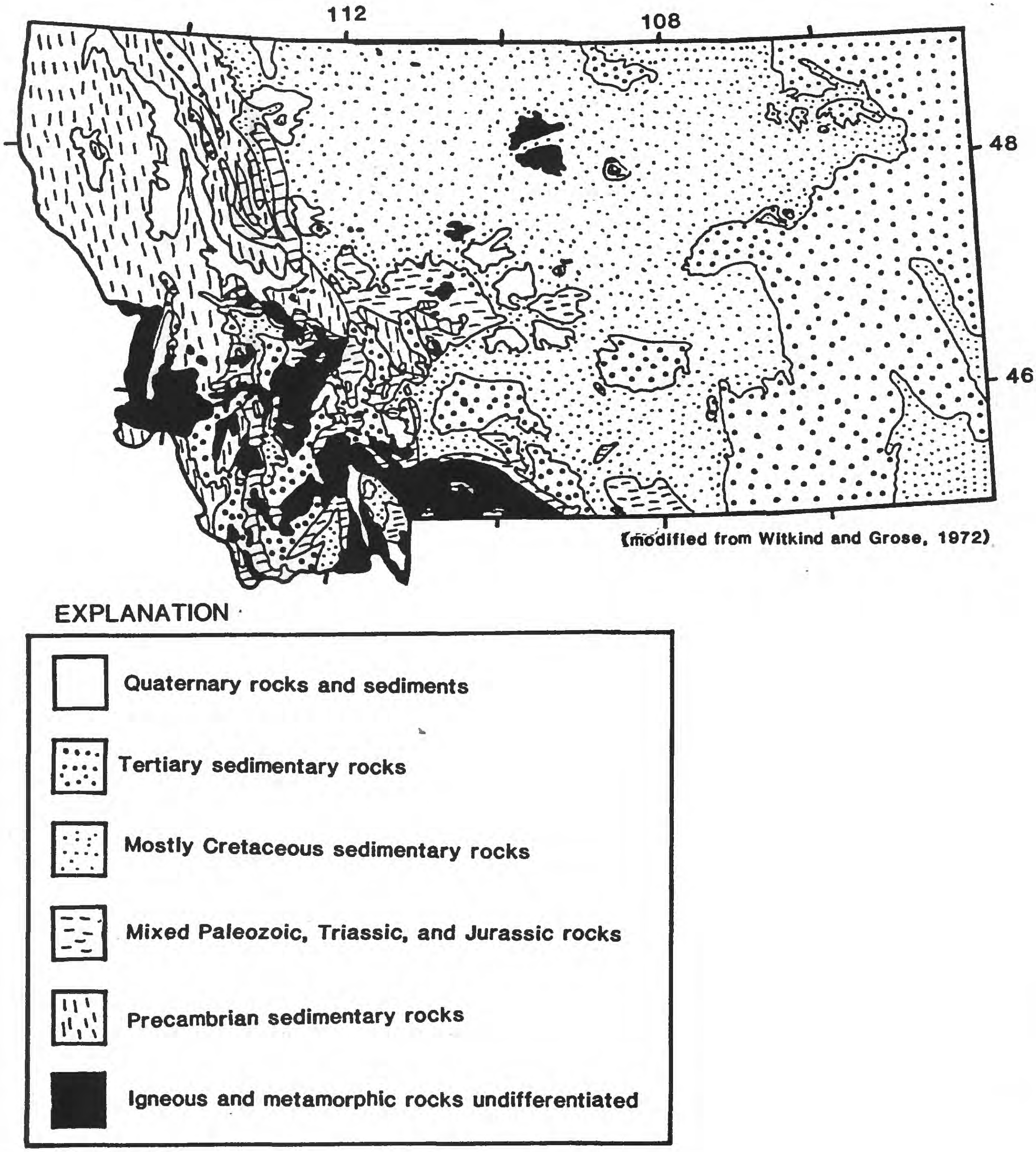


Fig 6. Geologic Map of Montana

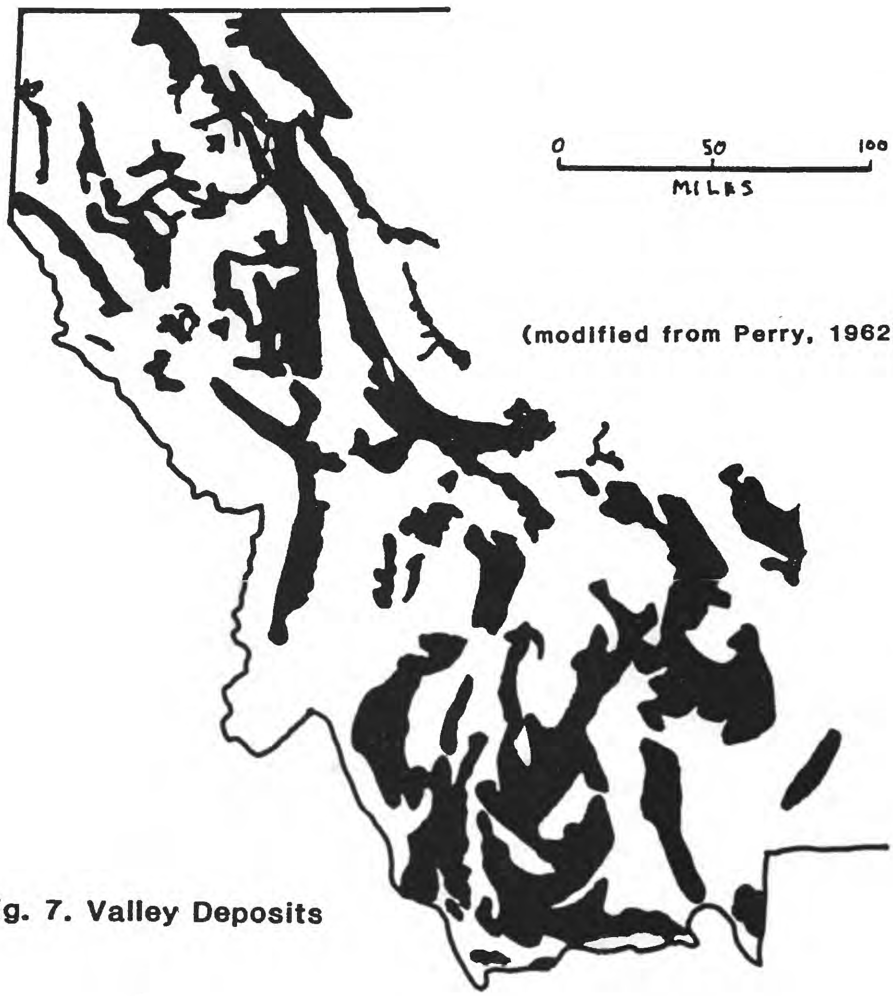
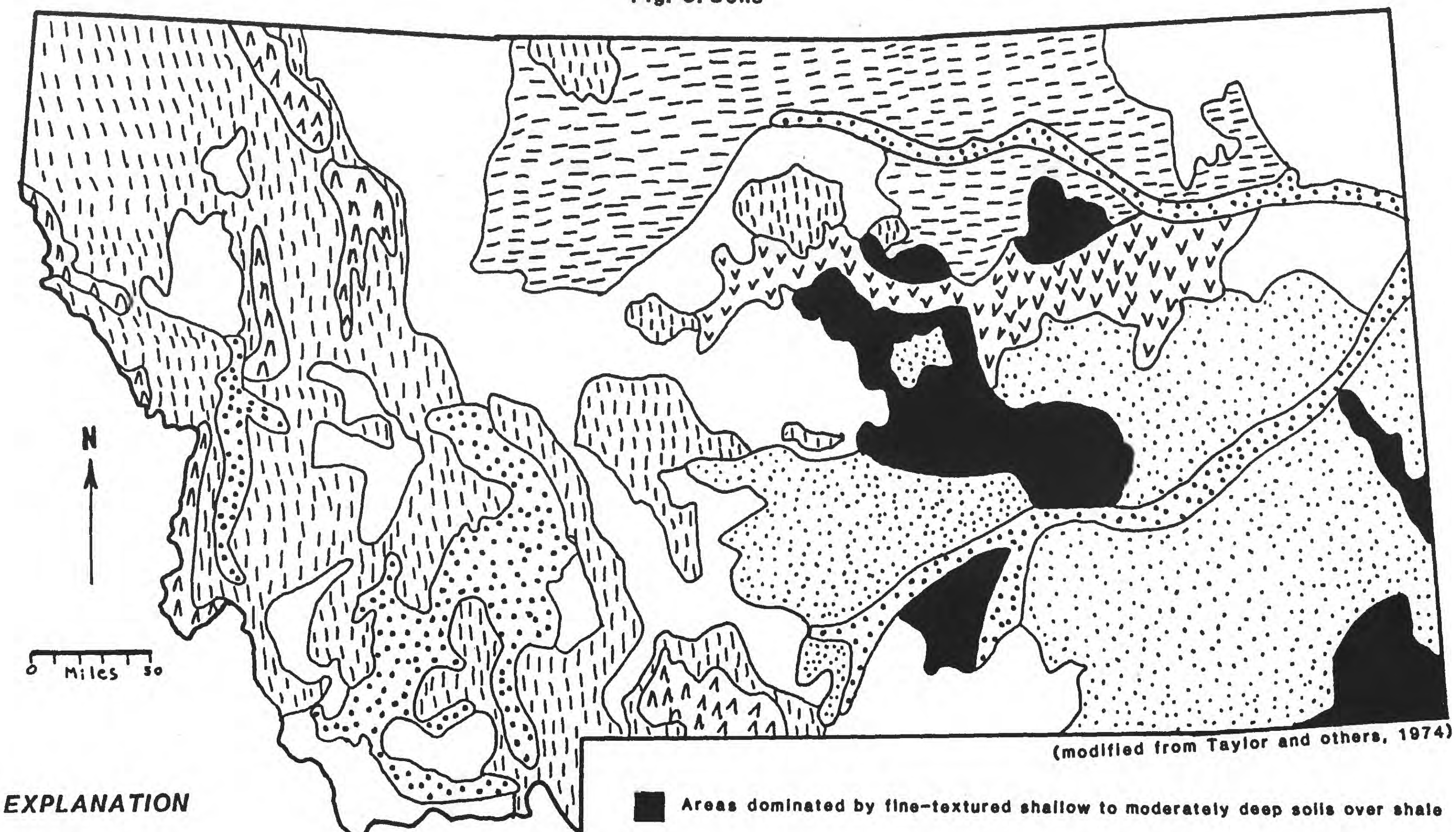


Fig. 7. Valley Deposits

Fig. 8. Soils



(modified from Taylor and others, 1974)

EXPLANATION

- Areas at or above timberline
- Areas dominated by alluvial soils
- Areas dominated by rough gullied land
- Areas dominated by Chestnut and Chernozem soils
- Areas dominated by Lithsols and Brown soils on uplands
- Areas dominated by fine-textured shallow to moderately deep soils over shale
- Areas dominated by Brown and Solodized-Solenetz soils of the northern till plain
- Areas dominated by Gray Wooded and Brown Podzolic soils on forested mountain slopes

of precipitation per year. Not many homes have been constructed above timberline, but many are found on forested mountain sides where high precipitation occurs. The resulting high soil moisture content in these areas can retard radon transport through soil pore spaces.

INDOOR RADON DATA

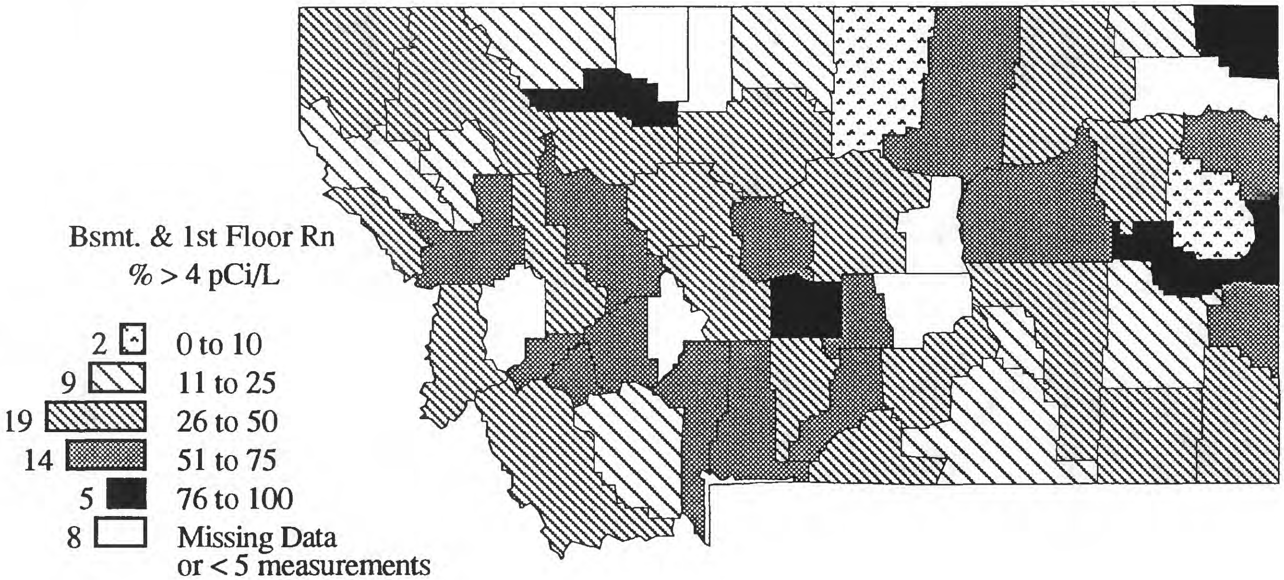
Figure 9 shows graphically the State/EPA Residential Radon Survey data used in this report. The average measured indoor radon concentration was 4.1 pCi/L or greater for the following counties with 5 or more measurements: Beaverhead, Chouteau, Deer Lodge, Flathead, Gallatin, Garfield, Golden Valley, Jefferson, Judith Basin, Lewis and Clark, McCone, Meagher, Missoula, Park, Phillips, Pondera, Powder River, Powell, Prairie, Ravalli, Richland, Sanders, Sheridan, Silver Bow, Sweer Grass, Wheatland, and Wibaux (fig. 9). Table 1 presents a summary of the State/EPA Residential Radon Survey data. Two counties had maximum screening indoor radon concentrations over 100 pCi/L, Flathead County and Lewis and Clark County (Table 1). With 833 measurements made in the State the average radon concentration for the State was 5.9 pCi/L and the percent of homes measured with screening indoor radon concentrations equal to or greater than 4 pCi/L was 43.6 percent.

GEOLOGIC RADON POTENTIAL

Areas in the vicinity of known uranium occurrences have a high radon potential for several reasons other than the unlikely occurrence that homes would be built over an ore body itself: (1) Noncommercial concentrations of uranium are often also present in an area that contains ore-grade deposits; (2) Even minor mineralization (primary or secondary) of uranium along faults and fractures is enough to produce a radon hazard in homes built above them; (3) Sediments eroded and transported from rocks with elevated uranium and soils that develop on them are also likely to have elevated uranium levels. Figures 10A and 10B show known uranium occurrences in Montana. Most of these occurrences are concentrated within the Rocky Mountains physiographic division (fig. 3), where, coincidentally, a large proportion of the population of Montana resides.

Figure 11 is an equivalent uranium (eU) map for Montana. By comparing figure 6 with figure 11 it can be seen that most of the areas with more than 2.5 ppm eU in the western part of the state correspond to igneous and metamorphic rocks. As mentioned in the introduction to this volume, igneous and metamorphic rocks tend to be good sources of radon. Likewise, marine black shales tend to be good sources of radon because they are frequently uranium-bearing (Fix, 1958). The Cretaceous sedimentary rocks (fig. 6) include the Pierre Shale, parts of which are known to be uranium-bearing (Tourtelot, 1956). The surficial materials in the eastern half of the State dominantly have eU signatures between 1.5 and 2.5 ppm, although some areas with eU signatures above and below this range exist (fig. 11).

The glaciated portions of both the Great Plains and the Plains and Mountains physiographic divisions have a higher radon potential than their counterparts to the south because glacial action crushes and grinds up rocks. This crushing and grinding enhances weathering and increases the surface area from which radon may emanate and also exposes more uranium and radium at grain surfaces where they are more easily leached. Leached uranium and radium may be carried to a soil depth below the detection limit of surface gamma-ray surveys (approximately 30 cm), but still are present at depths shallow enough to allow generated radon to migrate into a home.



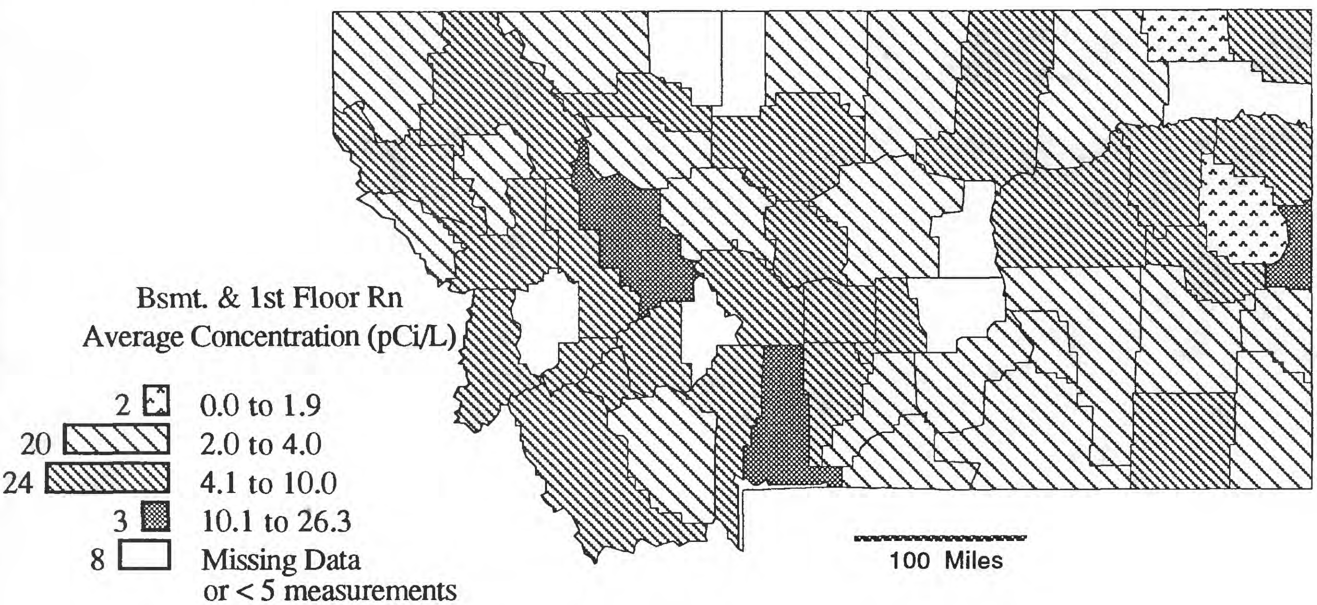


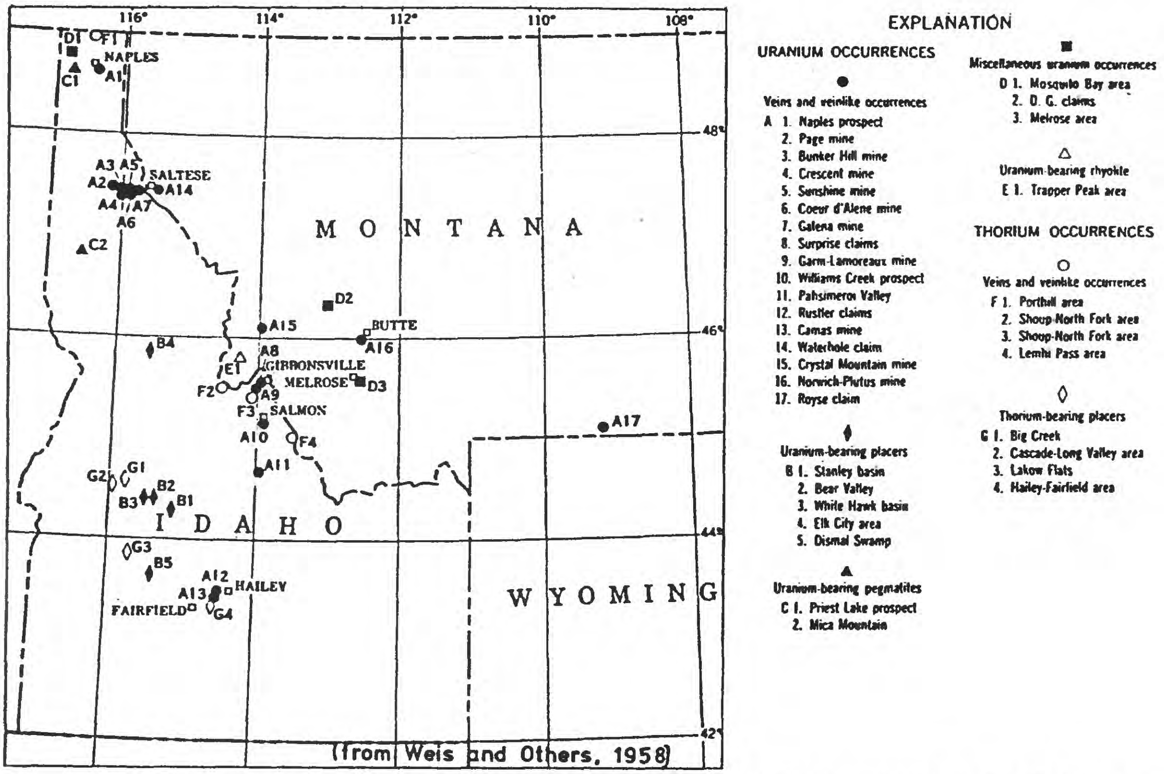
Figure 9. Screening indoor radon data from the State/EPA Residential Radon Survey of Montana, 1991-92, for counties with 5 or more measurements. Data are from 2-7 day charcoal canister tests. Histograms in map legends show the number of counties in each category. The number of samples in each county (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 Montana conducted during 1991-92. 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
BEAVERHEAD	15	6.3	3.5	2.8	10.0	40.7	33	7
BIG HORN	9	2.5	2.0	1.9	2.1	7.7	11	0
BLAINE	10	2.8	2.4	2.6	1.7	6.8	10	0
BROADWATER	4	8.3	2.0	2.2	13.6	28.5	25	25
CARBON	11	3.2	2.4	2.5	2.3	6.7	45	0
CARTER	9	3.8	3.2	3.3	1.9	6.5	44	0
CASCADE	70	3.8	2.5	2.0	4.2	19.7	26	0
CHOUTEAU	12	4.3	3.6	4.1	2.7	11.8	50	0
CUSTER	14	3.1	2.4	2.5	2.8	12.0	21	0
DANIELS	5	1.8	1.5	1.2	1.4	4.2	20	0
DAWSON	10	1.8	1.2	1.3	2.1	7.6	10	0
DEER LODGE	9	7.2	5.0	4.1	6.7	21.6	56	11
FALLON	5	3.7	3.1	4.0	2.2	6.4	40	0
FERGUS	12	3.9	2.9	3.6	2.7	8.9	42	0
FLATHEAD	43	8.9	3.3	2.6	22.5	133.6	30	5
GALLATIN	49	6.1	4.2	5.3	4.9	20.2	57	2
GARFIELD	5	6.0	4.2	4.4	5.0	13.8	60	0
GLACIER	5	2.3	1.8	2.1	1.6	4.4	20	0
GOLDEN VALLEY	6	4.9	4.5	4.6	2.2	8.9	67	0
GRANITE	4	5.0	4.5	4.2	2.8	9.1	50	0
HILL	9	2.9	2.3	2.7	1.8	6.0	22	0
JEFFERSON	6	9.2	4.4	6.9	9.6	26.9	67	17
JUDITH BASIN	7	6.7	5.4	6.7	4.3	14.7	71	0
LAKE	9	3.0	1.6	1.4	4.3	13.9	22	0
LEWIS AND CLARK	58	10.7	5.0	4.0	17.8	115.1	48	16
LIBERTY	4	8.5	6.7	8.7	6.0	13.9	50	0
LINCOLN	20	3.9	1.9	1.8	6.8	31.7	30	5
MADISON	8	2.7	2.2	2.1	2.0	7.3	13	0
MCCONE	8	4.4	3.7	3.9	2.5	9.3	50	0
MEAGHER	6	4.9	4.2	3.8	3.1	10.6	50	0
MINERAL	5	2.5	1.5	2.5	1.9	4.4	40	0
MISSOULA	60	6.6	4.6	4.6	6.5	42.2	58	3
MUSSELSHELL	4	2.7	2.6	2.4	1.2	4.4	25	0
PARK	14	10.4	3.3	4.5	17.1	63.4	64	14
PETROLEUM	3	5.0	3.7	4.3	4.0	9.3	67	0
PHILLIPS	11	6.4	4.4	6.4	5.3	17.0	55	0
PONDERA	6	5.9	5.1	5.1	3.6	12.2	83	0
POWDER RIVER	12	4.3	3.2	3.9	3.4	13.1	42	0
POWELL	6	6.0	4.7	3.8	4.5	12.8	33	0
PRAIRIE	6	6.9	5.2	7.2	3.4	10.5	83	0
RAVALLI	30	9.3	4.9	3.4	12.4	51.6	47	13

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

COUNTY	NO. OF MEAS.	MEAN	GEOM. MEAN	MEDIAN	STD. DEV.	MAXIMUM	%>4 pCi/L	%>20 pCi/L
RICHLAND	11	4.8	4.4	5.4	1.9	7.7	64	0
ROOSEVELT	4	3.6	3.4	4.0	1.1	4.5	25	0
ROSEBUD	11	3.0	2.4	3.3	1.7	5.6	27	0
SANDERS	14	9.9	2.7	1.8	20.2	69.1	21	14
SHERIDAN	9	9.3	7.1	6.7	7.6	27.1	89	11
SILVER BOW	35	9.5	6.1	6.7	9.3	44.3	69	11
STILLWATER	9	4.0	3.2	4.9	2.3	6.8	56	0
SWEET GRASS	10	5.3	3.6	4.3	4.3	12.5	50	0
TETON	5	4.0	2.0	2.3	4.9	12.2	40	0
TOOLE	2	2.4	2.3	2.4	1.1	3.2	0	0
TREASURE	6	2.6	2.0	2.1	1.8	5.8	17	0
VALLEY	7	3.8	3.6	3.0	1.4	5.6	43	0
WHEATLAND	5	7.8	5.1	5.0	8.6	22.8	80	20
WIBAUX	5	26.3	24.7	22.1	11.5	46.0	100	80
YELLOWSTONE	101	3.7	2.9	3.2	2.7	14.6	32	0



—Index map showing the location of uranium- and thorium-bearing deposits and occurrences in Idaho and Montana.

Fig. 10A. Uranium Occurrences

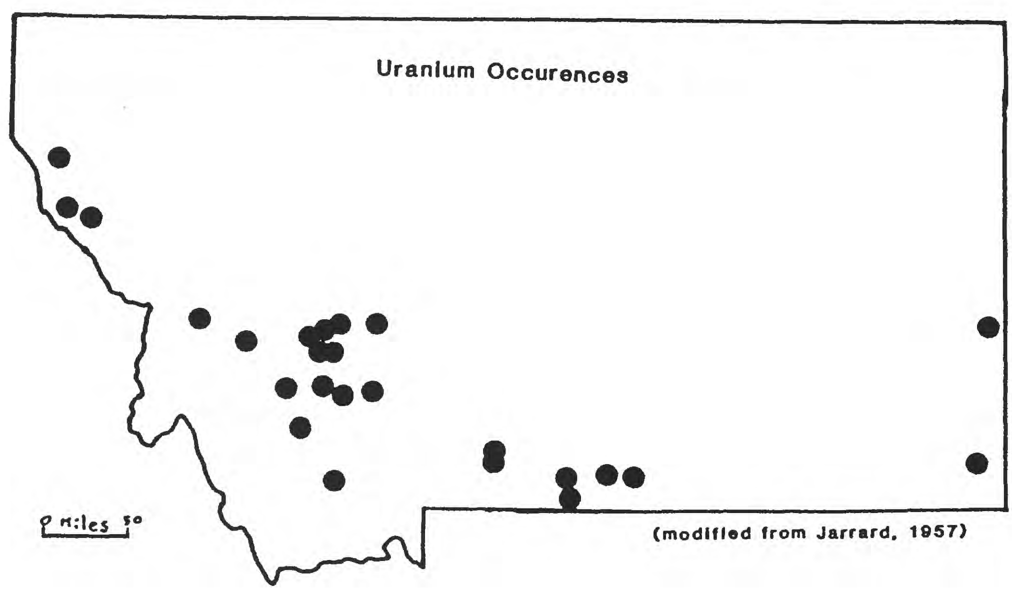


Fig. 10B. Uranium Occurrences

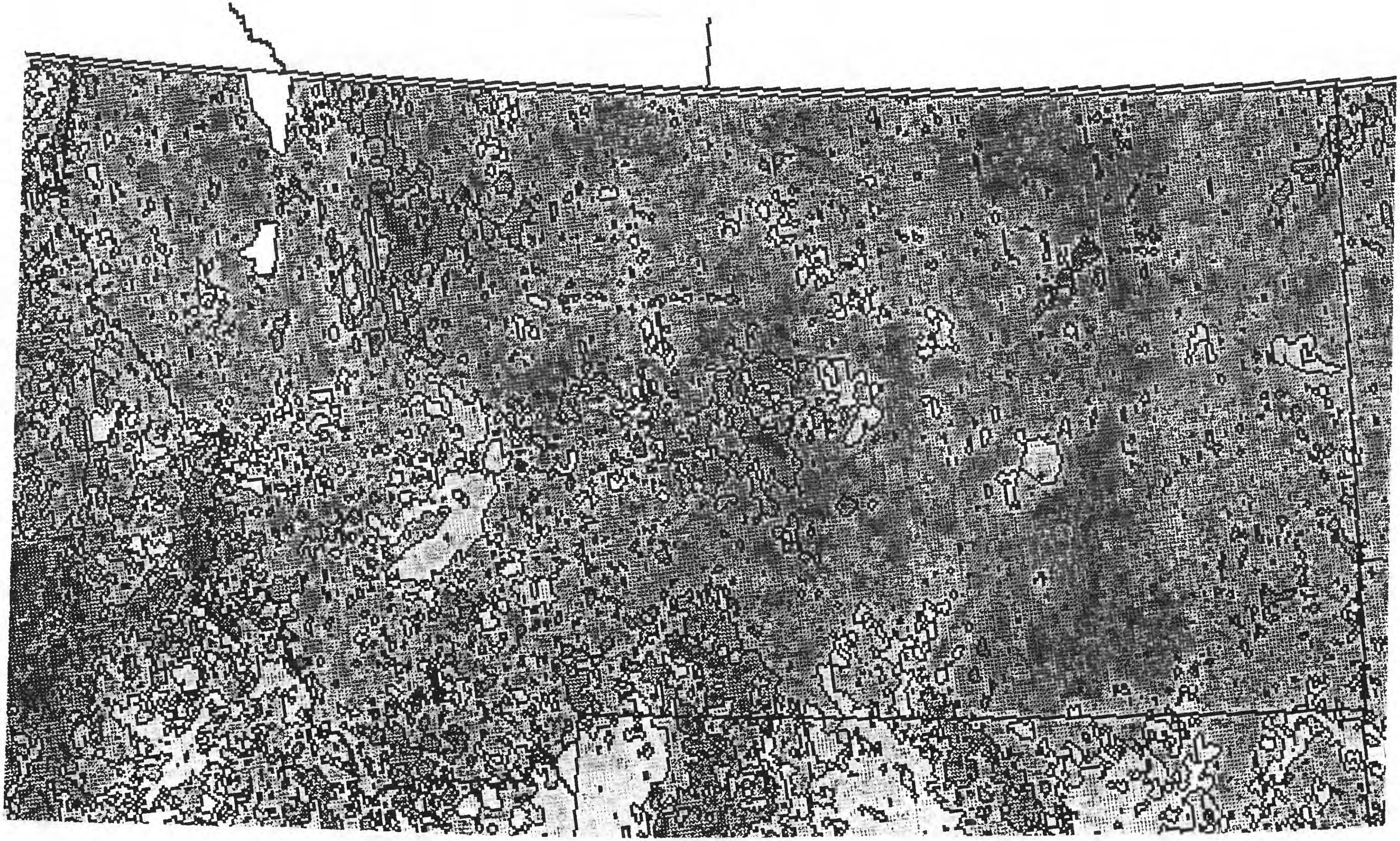


Figure 11. Aerial radiometric map of Montana (after Duval and others, 1989). Contour lines at 1.5 and 2.5 ppm equivalent uranium (eU). Pixels shaded from 0 to 6.0 ppm eU at 0.5 ppm eU increments; darker pixels have lower eU values; white indicates no data.

Considering the geology, the known uranium occurrences, and the alluvial soils with high permeability, the Rocky Mountain physiographic division has a high geologic radon potential. Other mountain areas in the Mountains and Plains physiographic division have rocks with similar lithologies and eU to those found in the Rocky Mountains. In addition, some also contain known uranium occurrences. Consequently, they have been grouped with the Rocky Mountains as having a high geologic radon potential. Lloyd (1983) found that the average radon concentrations in outside air at a monitoring station on Hornet street in Butte were between 3 and 6 pCi/L from May through October. When outside air concentrations are above 4 pCi/L, air inside homes is also expected to be above 4 pCi/L. Other areas in Butte tested at this time were not nearly as extreme, but this stresses the importance of ambient radon concentration in outside air. Temperature inversions occur in the intermontane valleys of the Rocky Mountain physiographic division during the winter months and may trap radon and other air pollutants and exacerbate radon mitigation attempts. Because of the construction techniques employed in the mountain regions of Montana, mitigation using sub-slab suction has been very effective and can frequently be done with less than $300 worth of materials (Personal communication with Adrian Howe, Montana Department of Health and Environmental Science, 1992).

SUMMARY

Geologic radon potential areas for Montana are shown in figure 12. These areas have been evaluated using the RADON INDEX MATRIX (RI) and the CONFIDENCE INDEX MATRIX (CI) discussed in the introduction to this volume. This evaluation is presented in Table 2. Area 1 consists of the Rocky Mountains and other mountain areas and has a high radon potential at a high confidence level. Area 2, which is the glaciated portion of the Great Plains, has a high geologic radon potential at a moderate confidence level. This area was assigned 2 GFE points despite a number of the counties having indoor radon averages below 4 pCi/L (fig. 9) because similar lithologic units in the glaciated area of North Dakota have showed a high incidence of homes with greater than 4 pCi/L (Schumann and others, 1991). Area 3, underlain primarily by Cretaceous and Tertiary sedimentary rocks, is ranked in geologic radon potential at a moderate confidence level. Area 4, which is made up of Tertiary sedimentary rocks that are known uranium producers in the Powder River Basin in Wyoming, has a high radon potential at a moderate confidence level. Area 5, mostly Cretaceous sedimentary rocks, ranked in the high end of the moderate range at a moderate confidence level.

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 <u>not</u> 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 Montana.

FACTOR	Area 1 RI	Area 1 CI	Area 2 RI	Area 2 CI	Area 3 RI	Area 3 CI
INDOOR RADON	3	3	2	3	2	3
RADIOACTIVITY	3	3	2	2	2	2
GEOLOGY	3	2	3	2	2	2
SOIL PERM.	2	2	2	2	2	2
ARCHITECTURE	2	-	2	-	2	-
GFE POINTS	0	-	2	-	0	-
TOTAL	13	10	13	9	10	9
RANKING	HIGH	HIGH	HIGH	MOD	MOD	MOD

FACTOR	Area 4 RI	Area 4 CI	Area 5 RI	Area 5 CI
INDOOR RADON	3	3	3	3
RADIOACTIVITY	2	2	2	2
GEOLOGY	3	2	2	2
SOIL PERM.	2	2	2	2
ARCHITECTURE	2	-	2	-
GFE POINTS	0	-	0	-
TOTAL	12	9	11	9
RANKING	HIGH	MOD	MOD	MOD

RADON INDEX SCORING:

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

Possible range of points = 3 to 17

CONFIDENCE INDEX SCORING:

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

Possible range of points = 4 to 12

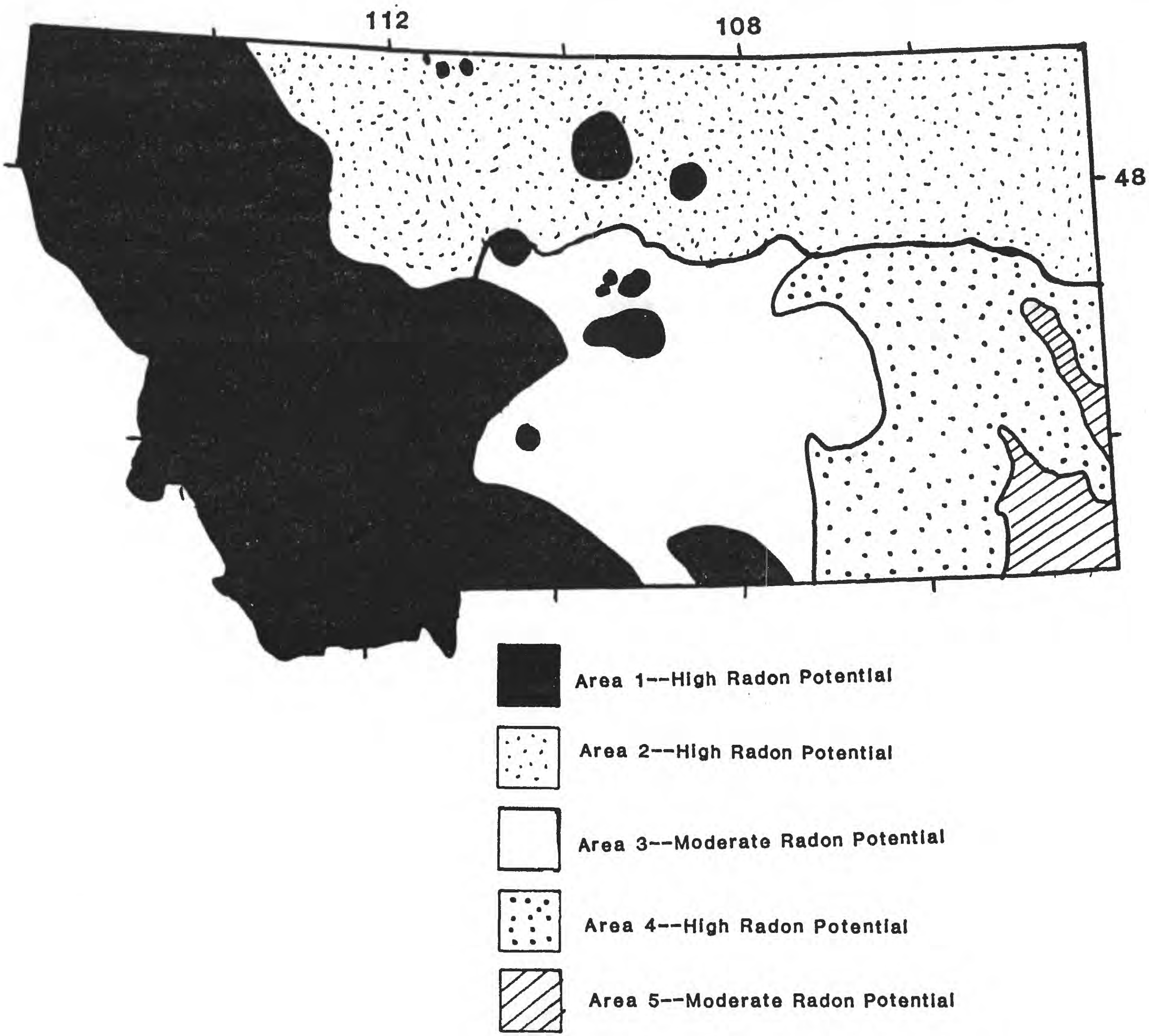


Fig. 12. Radon Potential Areas

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PRELIMINARY GEOLOGIC RADON POTENTIAL ASSESSMENT OF NORTH DAKOTA

by
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INTRODUCTION

Many of the rocks and soils in North Dakota 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 about 1600 homes conducted during the winter of 1987-88 by the North Dakota State Department of Health and the EPA, 63 percent of the homes tested had indoor radon levels exceeding this value. Every county sampled had one or more homes exceeding 4 pCi/L, although some areas had more than others.

This is a generalized assessment of geologic radon potential of rocks, soils, and surficial deposits of North Dakota. 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

North Dakota lies within the Interior Plains physiographic division, with the northeastern part of the State falling in the Central Lowlands Province and the southwestern part in the Great Plains Province. The Central Lowlands were generally characterized by tall-grass prairie prior to human settlement, whereas the Great Plains were covered primarily by short- and medium-grass prairie. Within the State the physiography is further subdivided into several areas characterized by specific features (fig. 1). Much of the topography of North Dakota is subdued and gently rolling due to the influence of glaciers, which covered about three-quarters of the State with Pleistocene-age glacial drift and lake deposits. One of the most prominent features is the Red River Valley along the eastern border of the State, which is underlain mostly by silt and clay deposits of glacial Lake Agassiz. The part of the Red River Valley that lies within North Dakota is 30-40 miles wide and narrows to about 10 miles at the southern end. An escarpment of varying height (the Pembina Escarpment) separates the valley from the Drift Prairie region to its west. The Drift Prairie (or Glaciated Plains) is a region of gently undulating to hilly plains underlain by glacial deposits. Moraines and eskers form low hills, and the many small lakes and marshes indicate the generally poor drainage characteristics of this area (Hainer, 1956). Areas of plains formed on glacial lake deposits include the Souris Lake Plain and the area around Devil's Lake (fig. 2). The Turtle Mountains are an area of drift-mantled hills rising 400 to 800 feet above the surrounding landscape and located in the north-central part of the State along the Canadian border. Beneath the glacial deposits, the Turtle Mountains are capped by resistant Tertiary sandstones and shales.

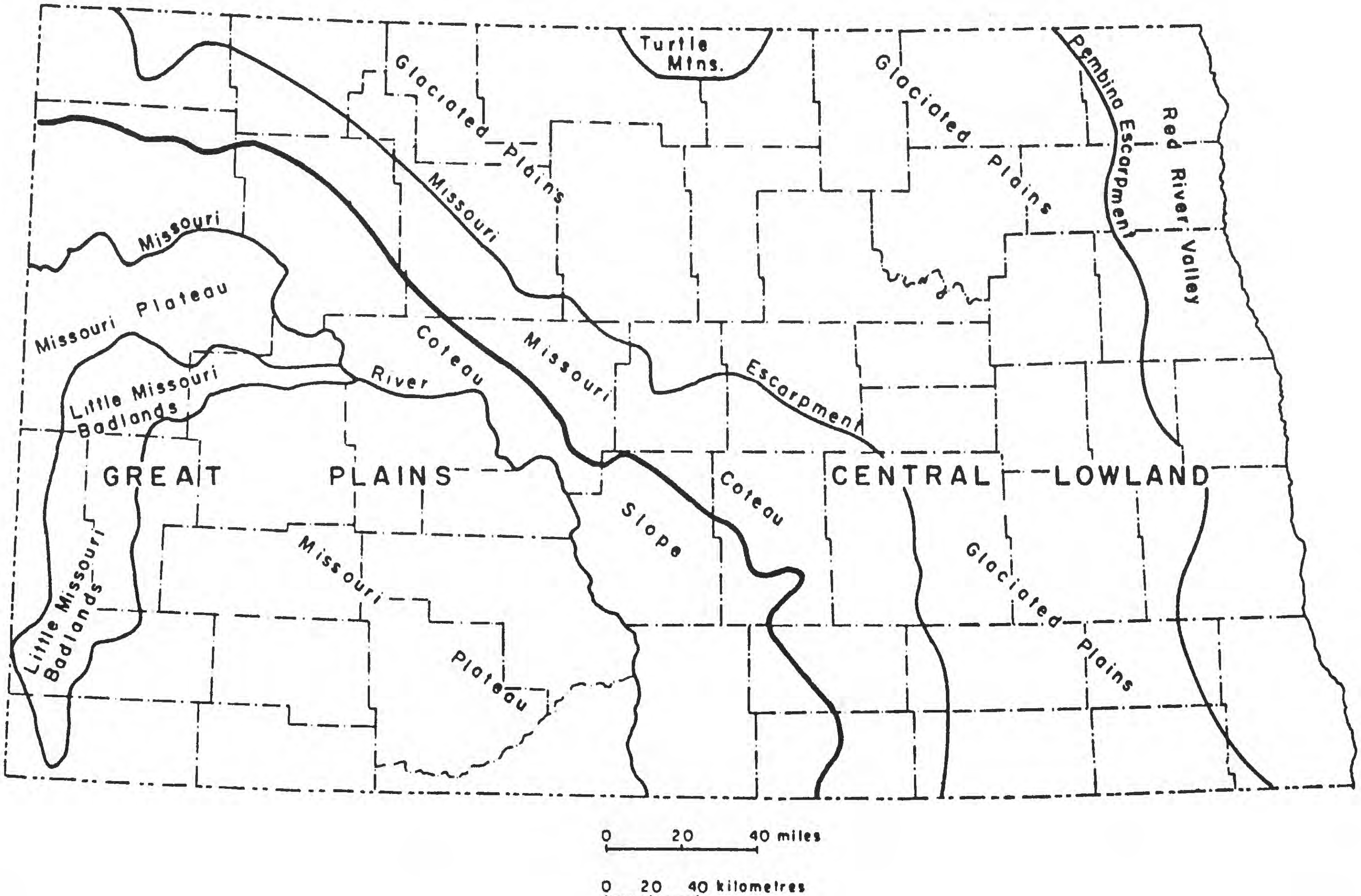


Figure 1. Physiographic provinces of North Dakota (modified from Bluemle, 1977).

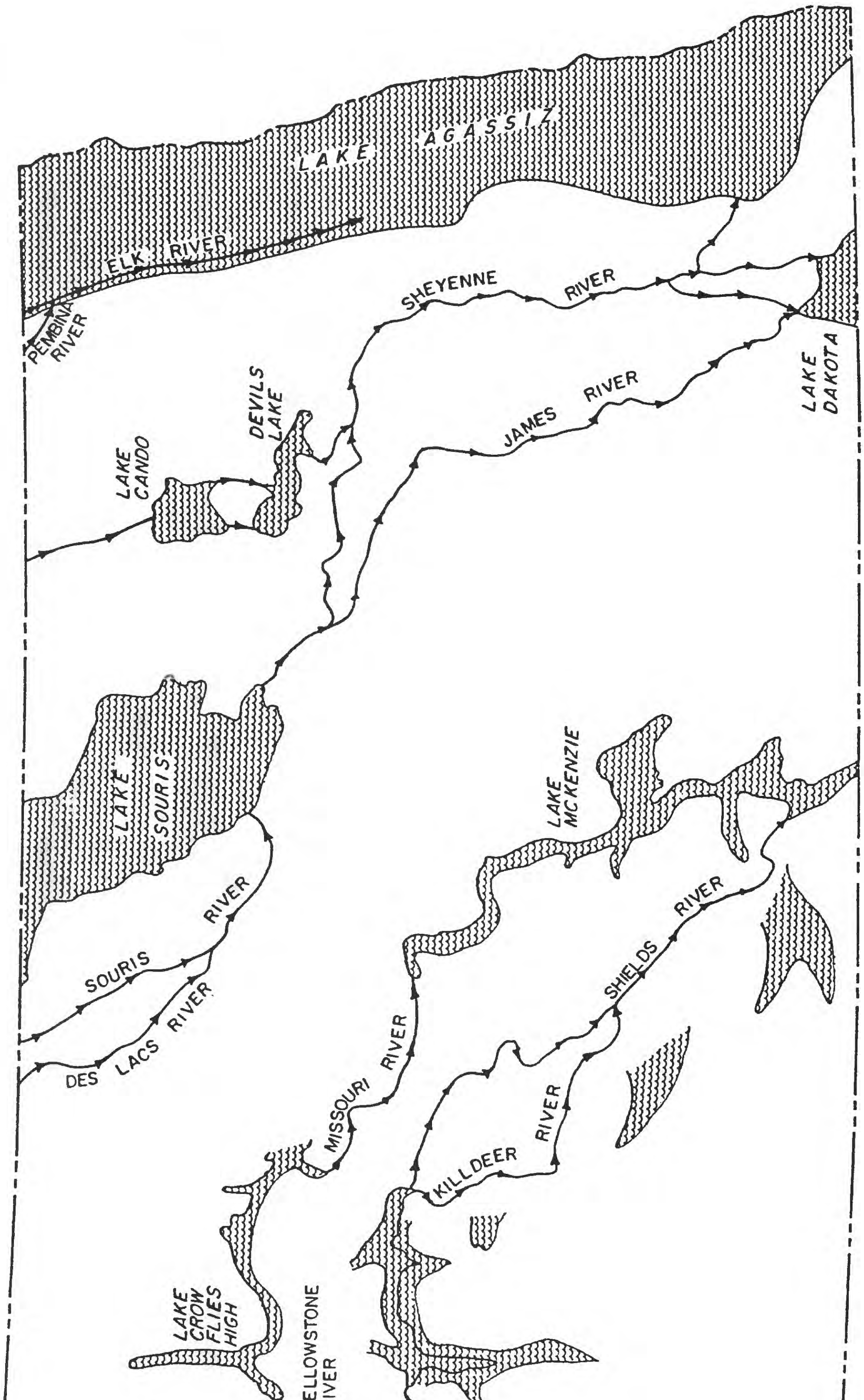


Figure 2. Glacial lakes of North Dakota (from Clayton and others, 1980a).

The Drift Prairie is separated from the Missouri Plateau to the west by an escarpment called the Missouri Coteau, or "hills of the Missouri". The escarpment is a line of terminal moraines rising 300 to 500 feet above the Drift Prairie and trending northwest to southeast. The Missouri Plateau, in the western half of the State, is different in character east and west of the Missouri River. In general, areas north and east of the Missouri River are covered by ground moraine and outwash, whereas areas to the south and west of the river have thin, discontinuous glacial deposits with only scattered boulders in the vicinity of the glacial limit (Hainer, 1956). The area northeast of the river exhibits typical subdued glacial topography, in contrast to the mostly unglaciated area southwest of the river, where the topography ranges from dissected, gently sloping plains to buttes and badlands (fig. 1).

Much of North Dakota's industry and land use is devoted to agriculture and livestock production. Mining and production of energy resources (oil, gas, and coal) are also important in the western part of the State. Much of the population of the North Dakota is concentrated near population centers including Bismarck, Minot, Grand Forks, and Fargo (fig. 3).

GEOLOGY

Bedrock geology. Only Upper Cretaceous and younger rocks are exposed at the surface in North Dakota. Older rocks directly underlie the glacial deposits in parts of the State but they are not exposed at the surface. A brief discussion of pre-glacial bedrock geology is important because in most cases the mineralogical constituents of the glacial sediments are derived from nearby underlying bedrock. Figure 4 is a generalized bedrock geologic map of North Dakota showing the units that are exposed at the surface in unglaciated areas, and units that directly underlie the glacial deposits in glaciated areas; that is, units which would be exposed at the surface if glacial deposits were not present. The information in this section is derived mainly from Bluemle (1977), Clayton and others (1980a), and Hainer (1956).

Precambrian igneous and metamorphic rocks directly underlie glacial deposits in the Red River Valley in the southeastern part of the State. These rocks form a basement beneath younger sedimentary rocks in the remainder of the State. The Upper Cretaceous Carlile and Niobrara Formations are exposed only in river valleys and in outcrops along the Pembina Escarpment in the eastern part of the State. The Upper Cretaceous Pierre Shale is exposed primarily along the Little Missouri and Missouri River valleys in the south-central and southwestern parts of the State. All three units are dark to light gray shales deposited in offshore marine environments. The Upper Cretaceous Fox Hills and Hell Creek Formations are brown to gray sandstones and shales of coastal marine and continental origin. These units are exposed mainly in the south-central and southwestern parts of the State. Tertiary sedimentary rocks, including the Ludlow, Cannonball, Slope, Bullion Creek (formerly called the Tongue River Member of the Fort Union Formation [Clayton and others, 1980a], or the Tongue River Formation [Jacob, 1976]), Sentinel Butte, and Golden Valley Formations, and the White River Group (fig. 4) consist of sandstone, siltstone, clay, shale, and some freshwater limestone deposited primarily in river, delta, lake, and wetland environments. Coal occurs in most of the Tertiary units but is most abundant in the Bullion Creek and Sentinel Butte Formations. Coal beds in the Bullion Creek Formation are as much as 13 m thick (Leonard and others, 1925).

Glacial Geology: Ice advanced from the north and northwest in as many as 15 separate glacial advances before and during Wisconsin time, leaving as much as 200 m of glacial deposits (Clayton and others, 1980a). The Wisconsinan-age deposits shown in white on figure 5 were

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

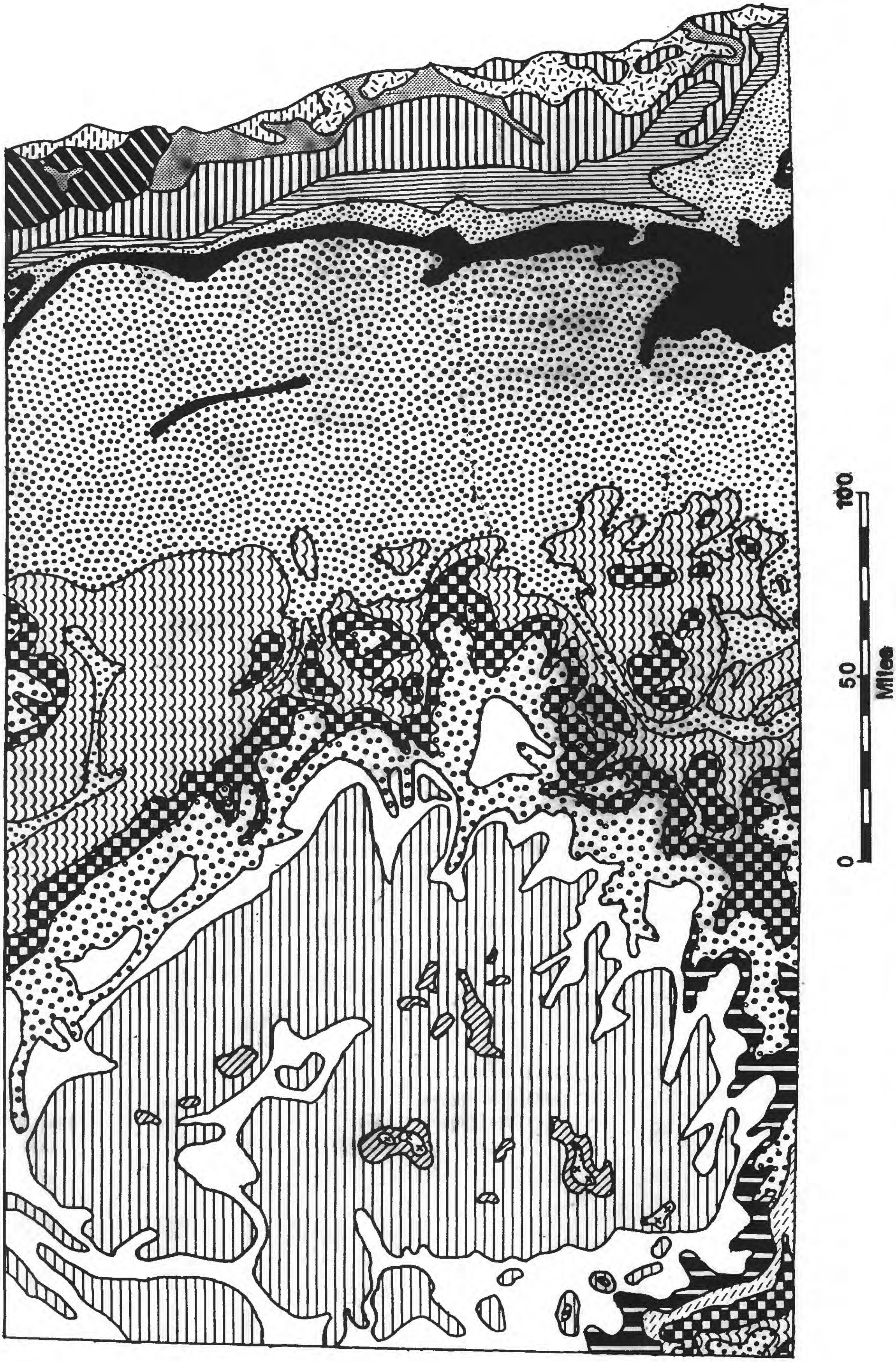


Figure 4. Generalized bedrock geologic map of North Dakota (redrawn from Bluemle, 1988).

BEDROCK GEOLOGIC MAP OF NORTH DAKOTA
EXPLANATION

Tertiary Rocks

White River Group - sandstone, siltstone, and shale

Golden Valley Formation - sandstone, siltstone, and shale

Sentinel Butte Formation - sandstone, siltstone, and shale

Bullion Creek Formation - sandstone, siltstone, and shale

Slope Formation - sandstone, siltstone, and shale

Cannonball Formation - sandstone and shale

Ludlow Formation - sandstone, siltstone, and shale

Cretaceous Rocks

Hell Creek Formation - sandstone, siltstone, and shale

Fox Hills Formation - sandstone and shale

Pierre Formation - gray shale

Niobrara Formation - shale

Carlile Formation - black shale

Greenhorn Formation - sandstone and shale

Belle Fourche, Mowry, Newcastle, and Skull Creek Formations - sandstone and shale

Inyan Kara Formation - sandstone and shale

Jurassic Rocks

Mostly shale with some limestone (beneath glacial cover)

Ordovician Rocks

Limestone and dolomite (beneath glacial cover)

Precambrian Rocks

Metamorphic and igneous rocks (beneath glacial cover) probably all deposited during the period of about 20,000-11,600 years before present (B.P.). Lake Agassiz existed between about 12,000 and 8,500 B.P. (Clayton and others, 1980a).

Wisconsinan-age glacial deposits were emplaced by three main glacial lobes (fig. 5). The Red River lobe covered northeastern North Dakota and northwestern Minnesota and was mostly confined to the area of the Red River Valley. The Des Moines and James lobes covered eastern North Dakota, western and southern Minnesota, and extended into eastern South Dakota and central Iowa (Clayton and others, 1980a). The tills of all the ice advances are lithologically generally similar and were derived primarily from Upper Cretaceous and Tertiary shales, siltstones, and sandstones that comprise the underlying bedrock in North Dakota and southern Manitoba and Saskatchewan. Some of the deposits in the northeastern part of the State also include carbonate-rich till derived from Paleozoic limestone and dolomite in southern Manitoba (Moran and others, 1976) and granite, gneiss, and basalt from the Canadian Shield (Clayton and others, 1980a). Tills in the northwestern part of the State contain a larger component of Tertiary sandstones and shales. Virtually all of the tills have Pierre Shale as a source component; it is a dominant component of the tills in the central and eastern parts of the State. Most of the tills consist of nearly equal parts sand, silt, and clay (Lemke, 1960; Winters, 1963). Lacustrine deposits of glacial lakes Agassiz, Souris, Dakota, and Devil's Lake (fig. 2) are composed primarily of silty clays and clays, and are commonly interbedded with tills. The unoxidized tills are typically dark olive gray to bluish gray. Iron oxidation and accumulation of calcium carbonate ($CaCO_3$) are common weathering effects (Lemke and others, 1965).

Uranium geology: Uranium occurrences of economic interest have been found primarily in coals and carbonaceous shales, mostly in the Bullion Creek (Tongue River) Formation. The Ludlow Formation also contains uraniferous lignites in the Cave Hills and Slim Buttes areas (Jacob, 1976). The source of uranium in the coals is generally believed to be nearby volcanic rocks (Denson and Gill, 1965; Hansen, 1964; Jacob, 1976). Uranium also occurs in some of the sandstones of the Bullion Creek and in some ash clay beds of the White River Group (Bergstrom, 1956). Uranium probably occurs in higher-than-average amounts (average crustal abundance is 2.5 parts per million [Carmichael, 1989]) in much of the Upper Cretaceous sandstone and shale underlying the glacial deposits, especially the carbonaceous units of the Pierre Shale. In general, the Pierre Shale as a whole contains higher-than-average amounts of uranium, in part because it was deposited under reducing conditions under which uranium is relatively immobile and thus more likely to concentrate at the site of deposition, and because it contains an abundance of clay minerals that form weak bonds with metals, including uranium.

SOILS

The dominant soil types in North Dakota are Mollisols (formerly called Chernozems and Chestnut soils) (fig. 6) that cover more than 60 percent of the State (U.S. Soil Conservation Service, 1977; Omodt and others, 1968). Most of the soils are of low to moderate permeability (fig. 7) and contain swelling clays. The soils with the lowest permeability are generally associated with glacial lake deposits and with collapsed glacial sediments in the Missouri Coteau (fig. 7). Many soils contain significant accumulations of $CaCO_3$ at depth, especially in the eastern part of the State. Soils derived from tills are generally younger than those developed on bedrock, but the rate of soil development in tills is probably accelerated by glacial crushing and mixing, which made the potentially mobile chemical constituents of the mineral matter in the tills more accessible to weathering agents such as percolating water (Jenny, 1935; Schumann and others, 1991).

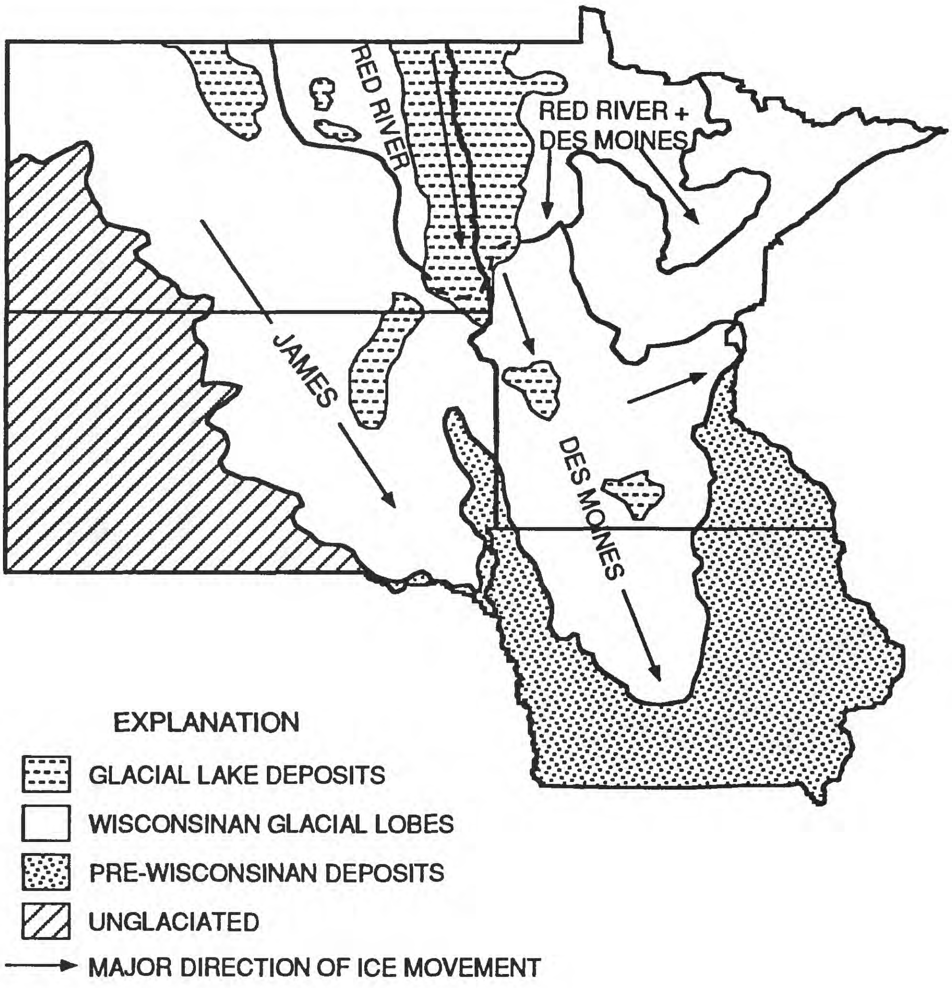


Figure 5. Generalized map showing limits of advances and directions of ice movement for the James, Red River, and Des Moines lobes in North and South Dakota, Minnesota, and Iowa. Modified from Hallberg and Kemmis (1986) and G.M. Richmond, personal communication (1992).

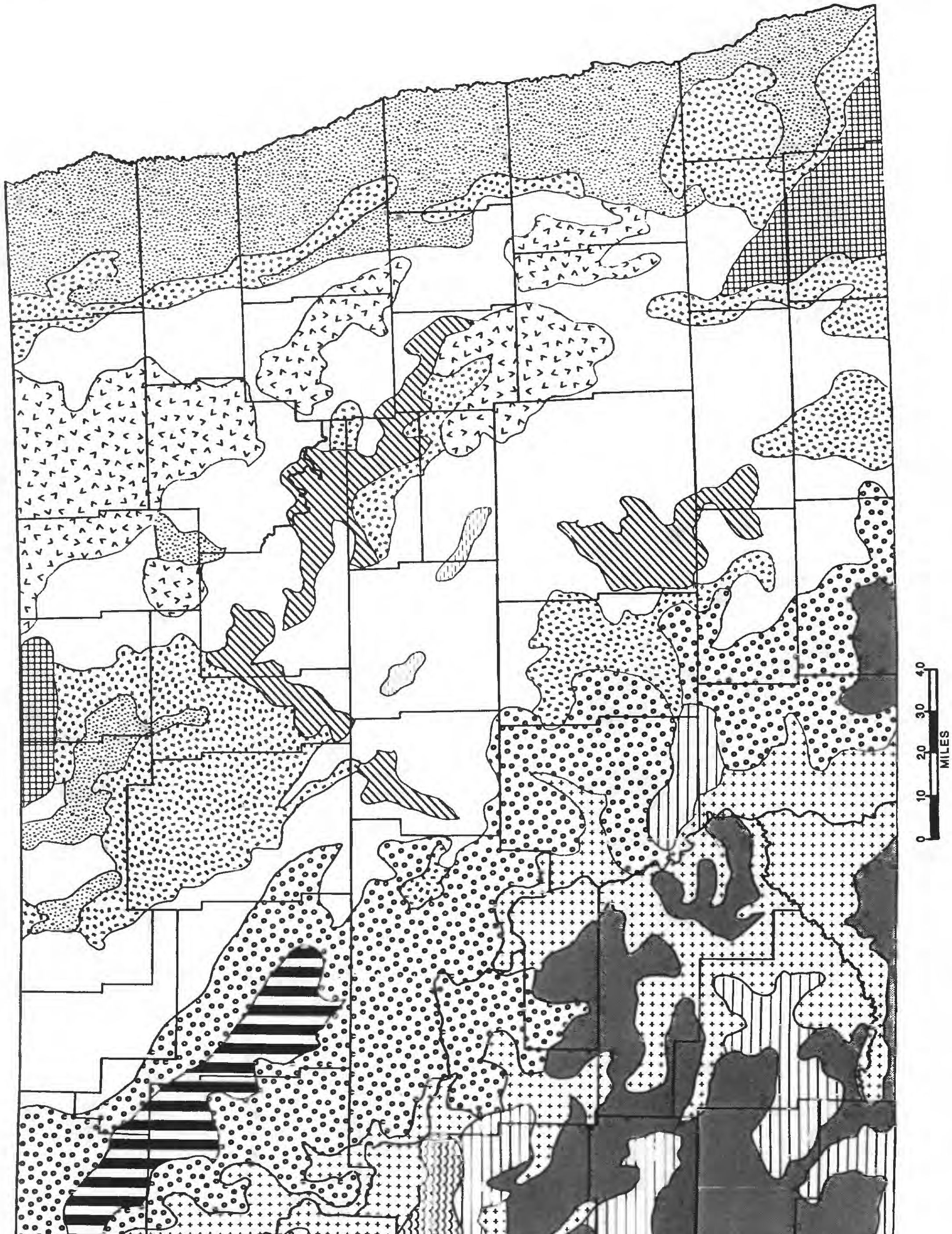


Figure 6. Major soils of North Dakota (modified from U.S. Soil Conservation Service, 1977).

GENERALIZED SOIL MAP OF NORTH DAKOTA
EXPLANATION

Mollisols & Alfisols–deep, fine-loamy and clayey soils developed in glacial till

Mollisols–deep, clayey and silty, calcic soils developed in glacial lake sediments

Mollisols & Entisols–deep, coarse loamy and sandy soils developed on outwash and glacial lake plains

Mollisols–deep, fine-loamy to clayey, calcic soils developed on glacial till

Mollsiols–deep, fine-loamy soils developed on glacial till

Mollisols & Entisols–deep, clayey to coarse-loamy, calcic soils developed on glacial till

Mollisols–deep, clayey and fine-loamy, saline soils developed on glacial till

Mollisols & Entisols–deep, clayey and fine loamy soils developed on glacial till

Mollisols & Entisols–shallow to moderately deep, clayey and loamy soils developed on residuum

Mollisols & Entisols–shallow to moderately deep, loamy and sandy soils developed on residuum and till

Mollisols, Entisols, and Inceptisols–shallow to deep, fine-silty to fine-loamy soils developed on residuum and till

Entisols and Mollisols–shallow to moderately deep, loamy soils developed on residuum

Entisols, Aridisols, and Mollsiols–shallow to deep, clayey and loamy soils developed on residuum

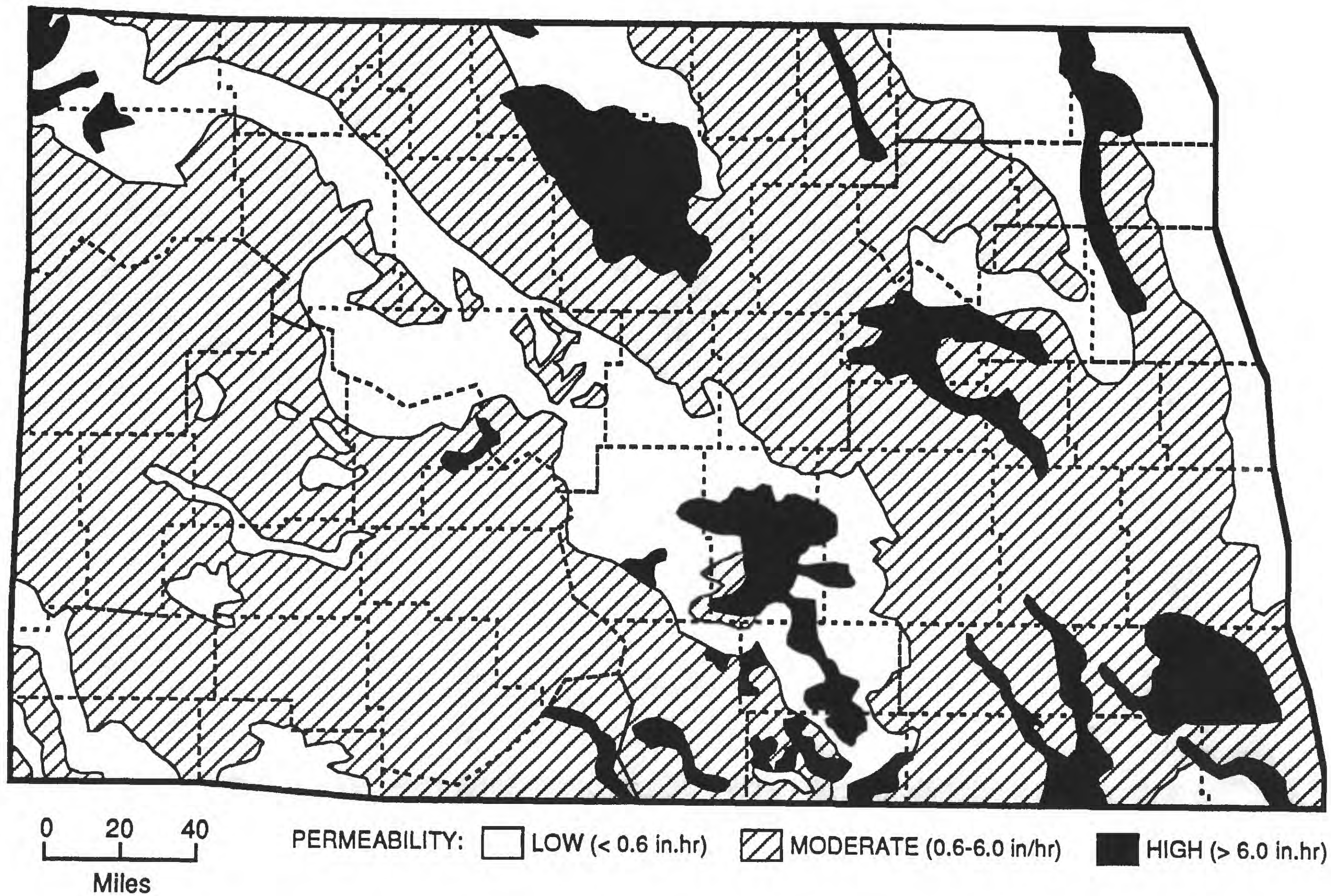


Figure 7. Generalized soil permeability map of North Dakota. Data from Clayton and others (1990b) and U.S. Soil Conservation Service county soil surveys. Compiled by Kevin M. Schmidt, U.S. Geological Survey.

INDOOR RADON DATA

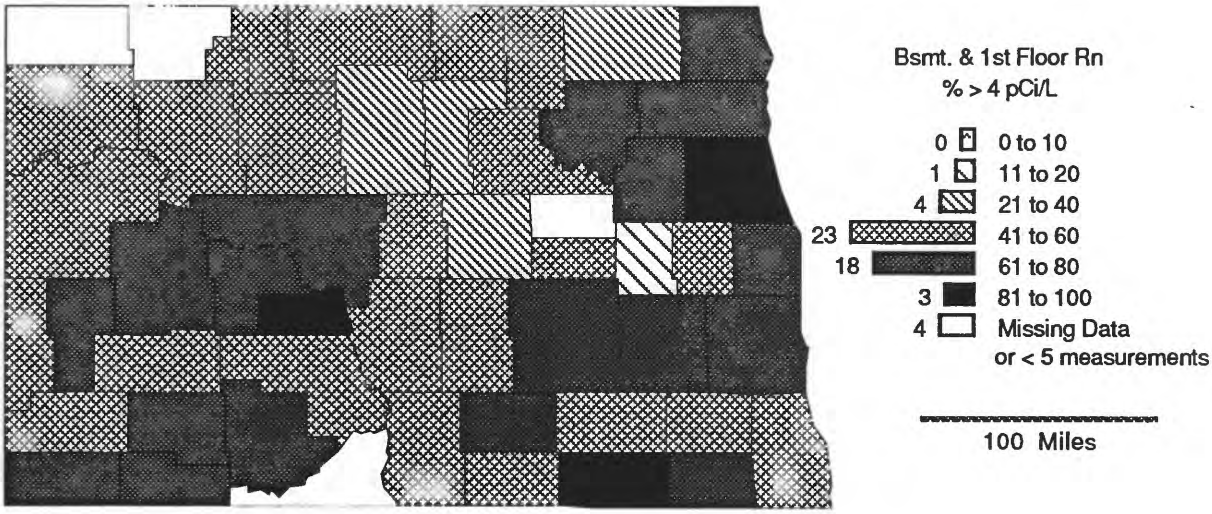
Indoor radon data from the 1987-88 State/EPA Residential Radon Survey of North Dakota are presented in figure 8 and Table 1. Only data from counties with five or more measurements are shown on figure 8. Most of the data are from basements because most of the homes in North Dakota (about 80 percent) have basements. Figure 9 is a map showing county names and locations for reference. Of 1596 homes tested in North Dakota in the State/EPA Residential Radon Survey, 63 percent had screening indoor radon measurements exceeding the EPA's guideline level of 4 pCi/L. The highest indoor radon concentration measured in North Dakota in the State/EPA survey was 184 pCi/L, although measurements higher than 200 pCi/L have been reported by other sources (U.S. Senate, 1987). Three areas of the State have a relatively large proportion of homes with high indoor radon concentrations, as indicated by the percent of homes sampled in each county with screening indoor radon levels greater than 4 pCi/L: The Red River Valley, along the State's eastern border, the southeastern quarter of the State, and the southwestern part of the State (fig. 8). Average screening indoor radon levels are greater than 4 pCi/L across most of the State (fig. 8). Homes with screening indoor radon concentrations between 50 and 100 pCi/L were found in Bottineau, Cass, Grand Forks, Mercer, and Walsh Counties, and homes with screening indoor radon levels exceeding 100 pCi/L were found in Bowman, Stark, and Stutsman Counties (Table 1). In all but two of the counties for which data are presented in figure 8, more than 25 percent of the homes sampled in each county had basement radon levels greater than 4 pCi/L, indicating that elevated radon levels are widespread across the State.

The data indicate that all areas of North Dakota may have a significant number of homes with indoor radon levels exceeding 4 pCi/L. The areas with the highest maximum levels as well as the greatest proportion of homes with elevated radon levels are the Red River Valley and the southwestern quarter of the State. The geologic reasons for this distribution are discussed below.

GEOLOGIC RADON POTENTIAL

Correlations of aerial radioactivity data (fig. 10) with geology and indoor radon data are inconsistent in those areas underlain by glacial deposits. Except for the Lake Agassiz deposits in the Red River Valley, glacial deposits have a surface radioactivity signature that is lower than expected (fig. 10), especially in light of the measured indoor radon levels. Schumann and others (1991) conducted field sampling of soils, soil-gas radon, and surface radioactivity in central and eastern North Dakota and measured surface radioactivities that were consistent with the NURE aerial radiometric data, indicating that the anomalously low surface radioactivity was not due to measurement error. Although the soils exhibit low radioactivity in the upper 30 cm of soil (the typical depth of investigation of the gamma spectrometers), there is obviously sufficient radon parent material (uranium and radium) deeper than 30 cm in the soil, but shallow enough to generate elevated levels of indoor radon in many areas.

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, where they are more easily leached and moved downward through the soil profile with other mobile ions. Calcium carbonate and iron oxides form soil-grain coatings or concretions that sorb or associate with uranium (Hansen and Stout, 1968; Nash and



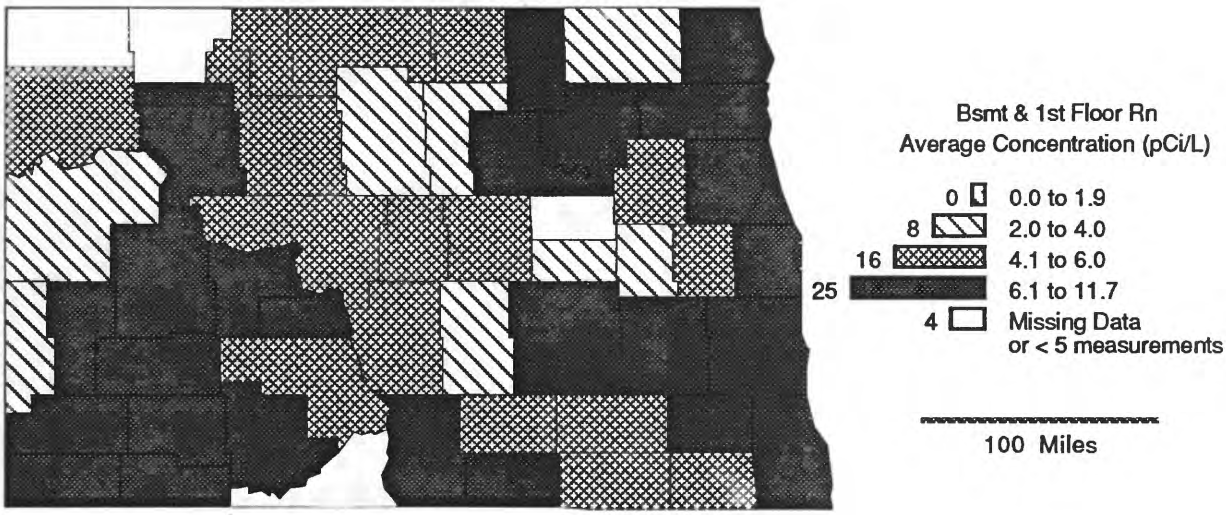


Figure 8. Screening indoor radon data from the EPA/State Residential Radon Survey of North Dakota, 1987-88, for counties with 5 or more measurements. Data are from 2-7 day charcoal canister tests. Histograms in map legends show the number of counties in each category. The number of samples in each county (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 North Dakota 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
ADAMS	23	9.3	7.4	7.3	7.1	27.8	78	13
BARNES	38	8.0	5.6	5.8	8.0	44.1	74	8
BENSON	8	7.2	4.0	4.2	10.5	32.7	50	13
BILLINGS	9	8.7	6.3	9.2	6.1	20.6	78	11
BOTTINEAU	33	6.0	4.0	4.2	8.7	52.6	52	3
BOWMAN	31	10.7	5.5	6.6	22.2	126.6	71	6
BURKE	4	2.6	2.4	2.7	0.9	3.5	0	0
BURLEIGH	101	4.9	4.0	3.8	4.0	32.1	47	1
CASS	171	7.9	5.6	5.4	9.3	85.6	66	6
CAVALIER	14	3.7	1.7	3.1	3.6	14.4	36	0
DICKEY	11	5.5	4.7	5.2	2.7	10.1	82	0
DIVIDE	4	8.8	7.5	8.7	5.3	13.8	100	0
DUNN	28	8.7	6.4	6.7	6.6	25.3	75	11
EDDY	4	4.6	2.3	3.6	4.8	10.7	50	0
EMMONS	15	6.6	4.8	4.1	6.1	25.0	53	7
FOSTER	7	3.7	2.9	4.0	2.3	7.4	43	0
GOLDEN VALLEY	7	4.0	3.6	2.7	2.1	7.2	43	0
GRAND FORKS	172	11.7	9.3	9.5	9.3	77.7	90	10
GRANT	23	8.1	5.8	6.1	7.6	34.9	61	4
GRIGGS	10	3.3	2.8	3.0	2.0	8.0	20	0
HETTINGER	31	7.2	5.4	5.7	5.7	25.4	61	6
KIDDER	8	4.0	3.3	4.0	2.5	9.0	50	0
LA MOURE	5	5.2	5.0	5.6	1.7	7.1	60	0
LOGAN	13	5.7	5.0	4.8	3.3	14.6	69	0
MCHENRY	30	3.6	2.8	2.9	2.7	12.6	33	0
MCINTOSH	9	7.1	2.9	3.6	11.1	35.7	44	11
MCKENZIE	6	3.5	3.0	3.3	2.1	6.1	50	0
MCLEAN	17	5.0	4.6	4.4	2.3	10.6	71	0
MERCER	46	8.1	6.1	6.3	8.1	50.8	72	7
MORTON	99	5.6	4.2	4.4	5.0	32.6	53	3
MOUNTRAIL	20	7.5	5.1	5.3	8.5	38.1	60	10
NELSON	26	5.3	4.6	4.7	3.0	13.9	62	0
OLIVER	19	6.4	5.9	6.1	2.9	14.4	84	0
PEMBINA	59	9.4	6.4	7.1	7.8	35.0	73	14
PIERCE	17	3.8	3.4	3.0	2.3	11.4	24	0
RAMSEY	18	6.6	5.2	5.2	4.7	16.7	78	0
RANSOM	7	8.4	5.9	10.5	6.0	17.4	57	0
RENVILLE	9	5.1	4.8	4.3	2.4	11.4	56	0
RICHLAND	46	7.0	4.5	4.8	8.0	48.7	57	4
ROLETTE	20	5.5	3.6	3.8	4.6	14.5	50	0
SARGENT	10	5.5	4.9	5.7	2.5	9.8	70	0

TABLE 1 (continued). Screening indoor radon data for North Dakota.

COUNTY	NO. OF MEAS.	MEAN	GEOM. MEAN	MEDIAN	STD. DEV.	MAXIMUM	%>4 pCi/L	%>20 pCi/L
SHERIDAN	5	5.0	4.8	5.0	1.3	6.6	60	0
SIOUX	2	4.9	2.7	4.9	5.8	9.0	50	0
SLOPE	7	7.0	4.3	3.3	6.3	15.6	43	0
STARK	122	8.0	5.1	4.8	17.0	184.2	59	4
STEELE	7	5.2	3.7	3.3	5.7	17.8	43	0
STUTSMAN	40	7.8	4.1	4.6	20.7	134.4	63	3
TOWNER	10	8.1	5.2	4.8	10.5	36.8	50	10
TRAILL	26	6.8	4.4	5.3	7.2	38.2	65	4
WALSH	49	10.5	7.3	8.0	9.2	50.6	76	10
WARD	66	4.2	3.2	3.6	3.2	20.6	45	2
WELLS	11	5.6	2.4	2.8	7.8	22.4	27	9
WILLIAMS	23	4.6	3.9	3.8	3.0	13.3	48	0

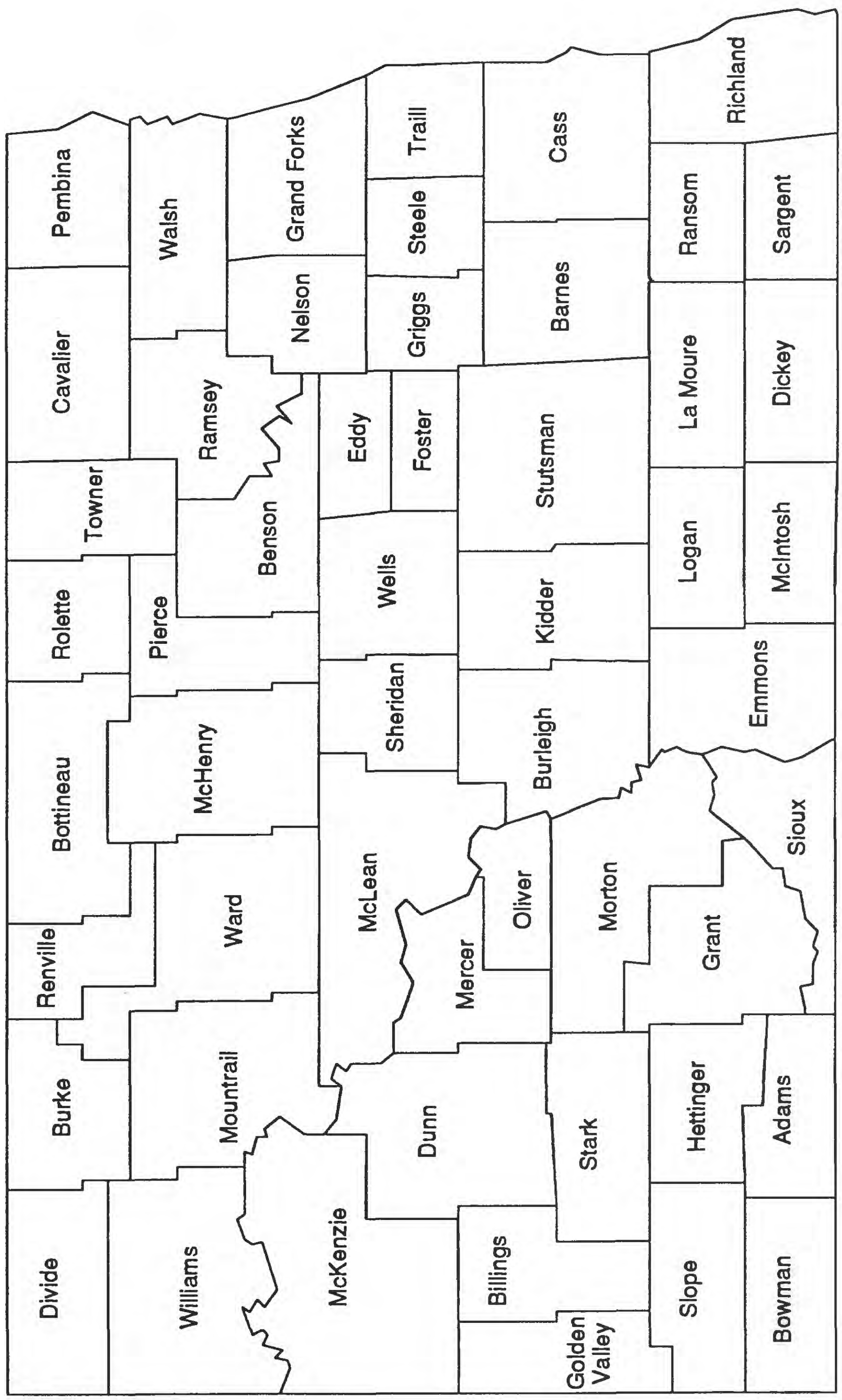


Figure 9. North Dakota counties.

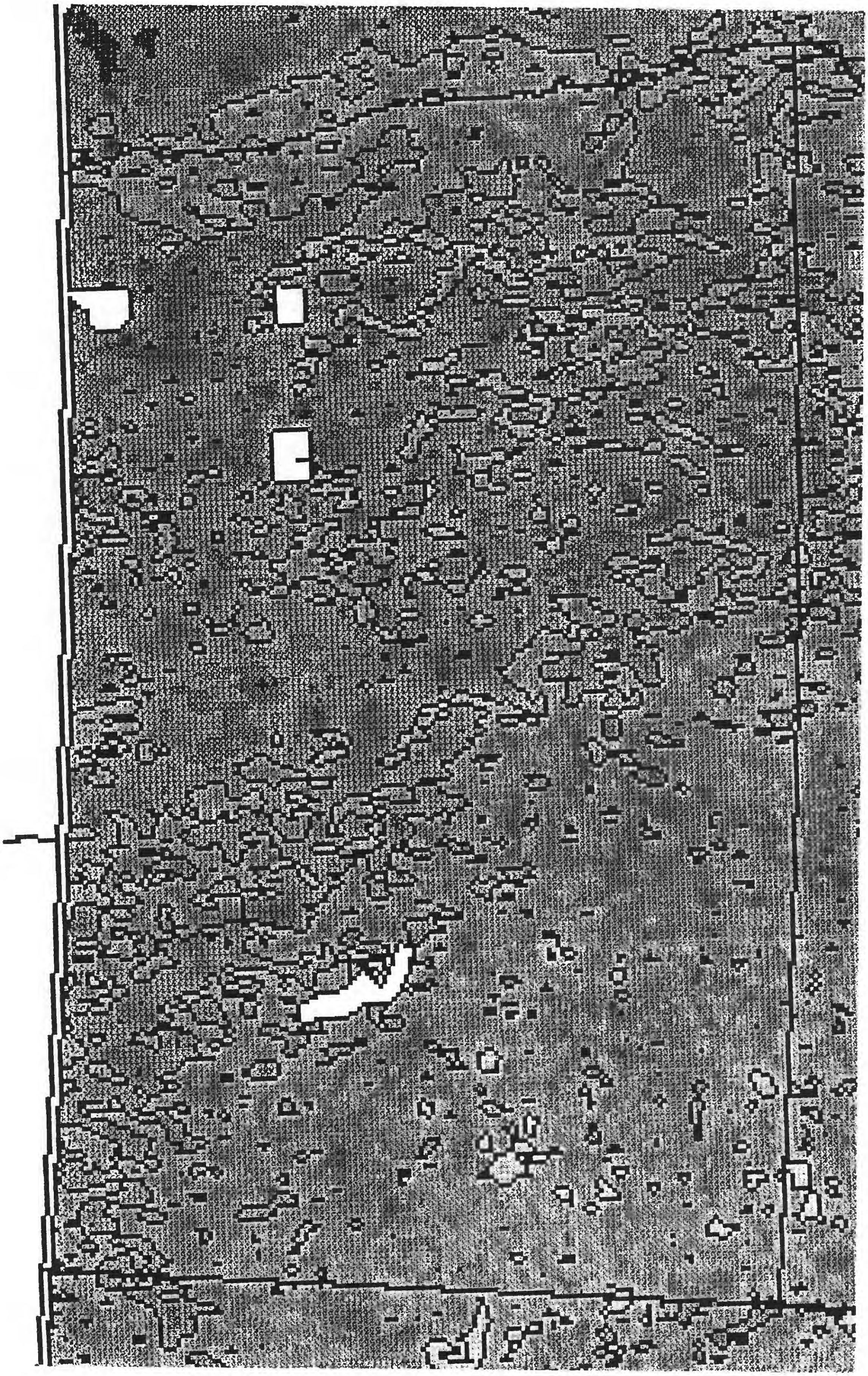


Figure 10. Aerial radiometric map of North Dakota (after Duval and others, 1989). Contour lines at 1.5 and 2.5 ppm equivalent uranium (eU). Pixels shaded from 0 to 6.0 ppm eU at 0.5 ppm eU increments; darker pixels have lower eU values; white indicates no data.

others, 1981), providing a possible mechanism for uranium accumulation and enhanced radon emanation in deeper soil horizons. The low surface radioactivity and comparatively high soil radon concentrations of the glacial soils suggest that radionuclides have been removed from the upper soil layers and are concentrated in deeper horizons, providing a possible explanation for the relatively low measured soil radioactivity and high indoor radon levels in the glaciated areas.

Although many of the soils derived from glacial deposits in North Dakota, including the Lake Agassiz deposits, contain significant amounts of clay, the soils can have permeabilities that are higher than indicated by standard water percolation tests due to gas flow through shrinkage cracks when the soils are dry. In addition, clays tend to have high radon emanation coefficients because clay particles have a high surface-to-volume ratio compared to larger and/or more spherical soil grains. These two factors make areas underlain by glacial deposits derived from the Pierre Shale, and areas underlain by glacial lake deposits, such as the Red River Valley and other areas shown in figure 5, highly susceptible to indoor radon problems. Because two of the State's largest population centers, Grand Forks and Fargo, lie within the Red River Valley, a large number of homes could be affected.

The southwestern quarter of the State, generally including the area southwest of the Missouri River, is underlain primarily by sedimentary rocks of Late Cretaceous and younger age. Tertiary-age rock units including the Cannonball, Slope, Bullion Creek, Sentinel Butte, and Golden Valley Formations, and the White River Group (fig. 4), generally contain higher-than-average amounts of uranium and are known or likely to cause indoor radon problems in some homes built on these units. Buildings constructed using fill from mine spoil are also likely to have elevated indoor radon levels; this is known to have been used in the construction of some homes in the Belfield area (U.S. Senate, 1987). Finally, although it is not known to be a widespread problem in North Dakota, it should be mentioned that water from private wells in virtually any area of the State could contain significant amounts of dissolved radon that could contribute to radon in indoor air when the water is degassed through use in the home.

SUMMARY

Figure 11 shows radon potential areas of North Dakota delineated in this report and assigned Radon Index (RI) and Confidence Index (CI) scores in Table 2. For the purposes of assessing radon potential the State was divided into three areas: the area underlain by bedrock and not covered by glacial deposits, designated the Unglaciated Area; an area underlain by glacial deposits, designated the Glaciated Area; and areas underlain by glacial lake deposits, designated Glacial Lakes (note that each lake is identified individually on figure 11).

The Unglaciated Area has a high radon potential (RI=13) with high confidence (CI=11). Tertiary and Upper Cretaceous sandstones, shales, and locally, coal-bearing units, are potential sources of high radon levels in this area. The Glaciated Area, which covers more than half of the State, has a high radon potential (RI=13) with high confidence (CI=10). Glacial deposits in this area are largely derived from Cretaceous shales containing higher-than-average amounts of uranium. Their low surface radioactivity is misleading because radionuclides are likely concentrated in deeper soil horizons, and many of the soils have higher permeability than indicated by their high clay content because the soils crack when dry. The Glacial Lakes have basically the same source rocks as the other glacial deposits, but have higher surface radioactivity and may have even higher radon emanation coefficients and higher permeability than glacial drift, perhaps due to the better sorting of the silt and clay lake deposits. Some of the highest indoor radon levels in the

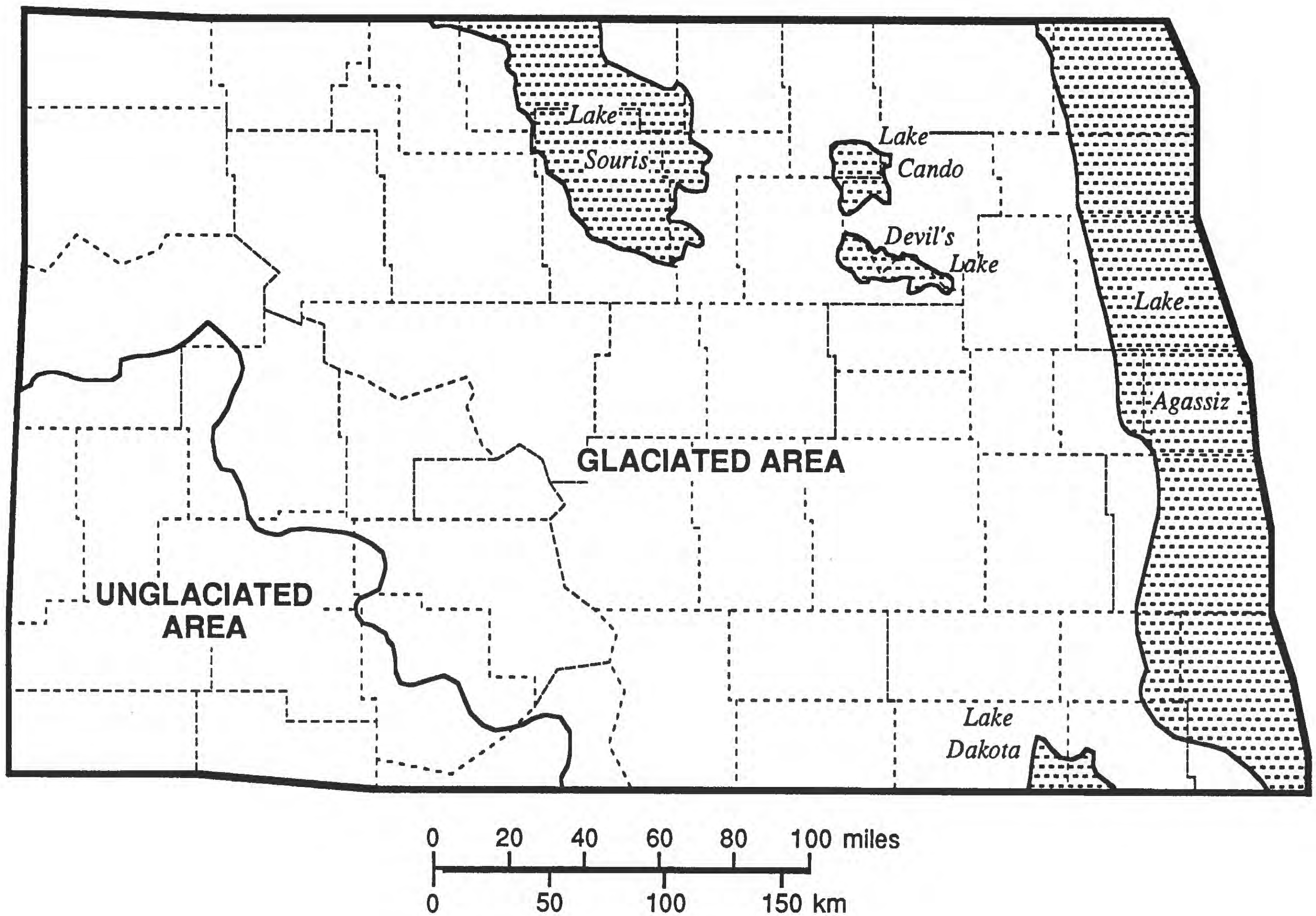


Figure 11. Radon potential areas of North Dakota. See Table 2 for radon potential rankings of areas. Areas covered by glacial lake deposits are indicated by dashed pattern. NOTE: All areas of the state, as depicted on this map, have high radon potential.

State have been measured in homes situated on deposits of Lake Agassiz. The Glacial Lakes areas have a high radon potential (RI=14) and 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 North Dakota. See figure 11 for locations of areas.

	Unglaciated Area		Glaciated Area		Glacial Lakes	
FACTOR	RI	CI	RI	CI	RI	CI
INDOOR RADON	3	3	3	3	3	3
RADIOACTIVITY	2	3	1	2	2	2
GEOLOGY	3	3	3	3	3	3
SOIL PERM.	2	2	1	2	1	2
ARCHITECTURE	3	--	3	--	3	--
GFE POINTS	0	--	2	--	2	--
TOTAL	13	11	13	10	14	10
RANKING	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

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PRELIMINARY GEOLOGIC RADON POTENTIAL ASSESSMENT OF SOUTH DAKOTA

by
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INTRODUCTION

This is a generalized assessment of geologic radon potential of rocks, soils, and surficial deposits of South Dakota. 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

South Dakota lies within two major physiographic provinces—the eastern part of the State falls within the Central Lowlands Province, and the western part is in the Great Plains Province. The Central Lowlands is generally characterized by tall-grass prairie, whereas the Great Plains is covered primarily by short- and medium-grass prairie. Mean annual precipitation ranges from 24 inches (610 mm) in the southeast corner of the State and in the Black Hills, to 14 inches (355 mm) in the northwest part of the State (Hogan and others, 1970). Within the State the physiography is further subdivided into several areas characterized by specific features (fig. 1). Approximately half of the topography of South Dakota is subdued and gently rolling due to the influence of glaciers, which covered approximately the eastern half of the State with Pleistocene-age glacial drift and glacial lake deposits.

The Missouri Coteau is an area of low hills composed of hummocky dead-ice morainal material. The James River Lowland is a large, shallow, flat-floored trough 50-75 miles (80-120 km) wide and about 250 miles (400 km) long (fig. 1). The axis of the James River Lowland lies about 200 feet (60 m) lower than its edges, and the topography is interrupted only by low moraine ridges. In the northern end of the basin, deposits of glacial Lake Dakota form a large, flat, mostly silt-and clay-covered area occupying nearly 1700 mi^2 (4400 km^2) and extending northward into southernmost North Dakota (Rothrock, 1943).

The Coteau des Prairies (Prairie Coteau) is a highland area characterized by rough, knobby hills in the northern and southern parts and long, smooth hills in the central part. It is bordered by escarpments that separate it from the James River Lowland to the west and the Minnesota-Red River Lowland to the east. The Prairie Coteau rises to elevations of as much as 2000 feet (600 m) above sea level, in contrast to the James River at about 1300 ft (400 m) and the Minnesota River at about 1000 ft (300 m). The hills of this area owe their origin primarily to the action of glaciers, which deposited as much as 400-500 ft (120-150 m) of drift and reworked the sands, gravels, and clays to form ridges and hills (Rothrock, 1943).

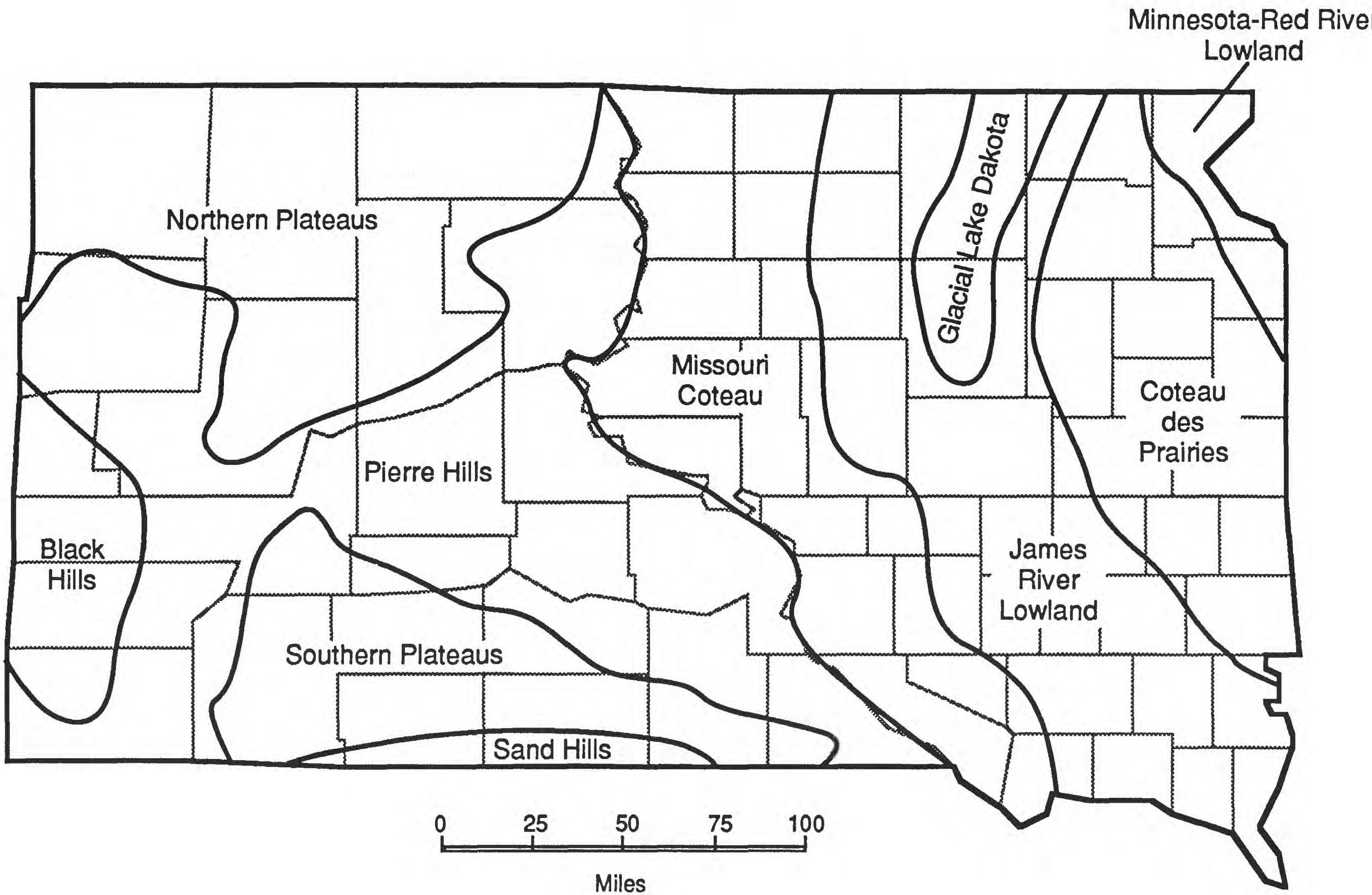


Figure 1. Major Physiographic Divisions of South Dakota (After Hogan and others, 1970 and Rothrock, 1943).

The northeastern corner of the State is occupied by the Minnesota-Red River Lowland. The dominant feature of this area is a valley which forms the eastern boundary of the State and contains Big Stone and Traverse Lakes. This steep-sided trench was a spillway for glacial Lake Agassiz, which drained southward through this channel and the valley of the Minnesota River to the Mississippi River. Beach and lake deposits from Lake Agassiz are found in the northern part of the Minnesota-Red River Lowland.

The Northern Plateaus, Pierre Hills, and Southern Plateaus regions together make up the Missouri Plateaus division of the Great Plains Province in western South Dakota. This area is characterized by butte and mesa topography, with badlands common throughout. The most famous and spectacular badlands occur in the westernmost part of the Southern Plateaus region, just east of the Black Hills. The Pierre Hills are characterized primarily by smooth, rounded hills, in contrast to the more rugged, flat-topped buttes and mesas of the Northern and Southern Plateaus regions. The northernmost extension of the Sand Hills of Nebraska extends into south-central South Dakota. The Black Hills occupy an area of more than 3000 mi^2 (7800 km^2) in the southwestern part of the State. The region's outer edge is delineated by hogbacks that dip away from the core of the Black Hills. The core of the Black Hills is composed of crystalline rocks that form peaks rising to over 7000 ft (2100 m). Harney Peak, in the southern Black Hills near the center of the crystalline basin, is, at 7242 feet (2207 m), the highest point in North America east of the Rocky Mountains (Rothrock, 1943).

Much of South Dakota's population is clustered around the cities of Sioux Falls and Rapid City, in Minnehaha and Pennington Counties, respectively (figs. 2, 3). Brown, Codington, and Brookings Counties also contain major population centers. Most of the State's approximately 696,000 inhabitants (1990 data) live in the eastern third of the State (fig. 2). Indian tribal lands cover about a third of the State's area. Agriculture and livestock are major land uses statewide, with mining, tourism, lumber industry, and energy (oil, gas, and coal) constituting a significant use of land and human resources in the western part of the State.

GEOLOGY

The discussion of geology is divided into three sections: bedrock geology, uranium geology, and glacial geology. "Bedrock" refers to non-glacial rock units, which are exposed at the surface west of the Missouri River and are mostly covered by glacial deposits east of the river. The bedrock geologic map (fig. 4) shows rock units exposed at the surface in the unglaciated area and those which would be at the surface if the glacial deposits were absent. The glacial deposits are composed of material derived from underlying bedrock and from rock units to the north, northwest, and northeast. The discussion of bedrock geology is summarized from U.S. Geological Survey (1975) and Darton (1951). The term "marine" refers to sedimentary rocks that were deposited in a shallow ocean environment; "continental" refers to sedimentary rocks deposited on land by the action of rivers, glaciers, or wind. The section on glacial geology is summarized from Flint (1955), Hammond (1991), Lemke and others (1965), and Tipton (1975).

Bedrock geology: Most of the State is underlain by marine sedimentary rocks, primarily sandstone, siltstone, and shale, of Cretaceous age (fig. 4). These units include, in descending order, the Hell Creek Formation, Fox Hills Sandstone, Pierre Shale, Colorado Group, Skull Creek Shale, and the Inyan Kara Group. They consist of dark gray shale, sandstone, siltstone, and some limestone. The Pierre Shale is the most extensive unit and it contains a uranium-bearing black shale unit known as the Sharon Springs Member. Rocks older than Cretaceous include marine

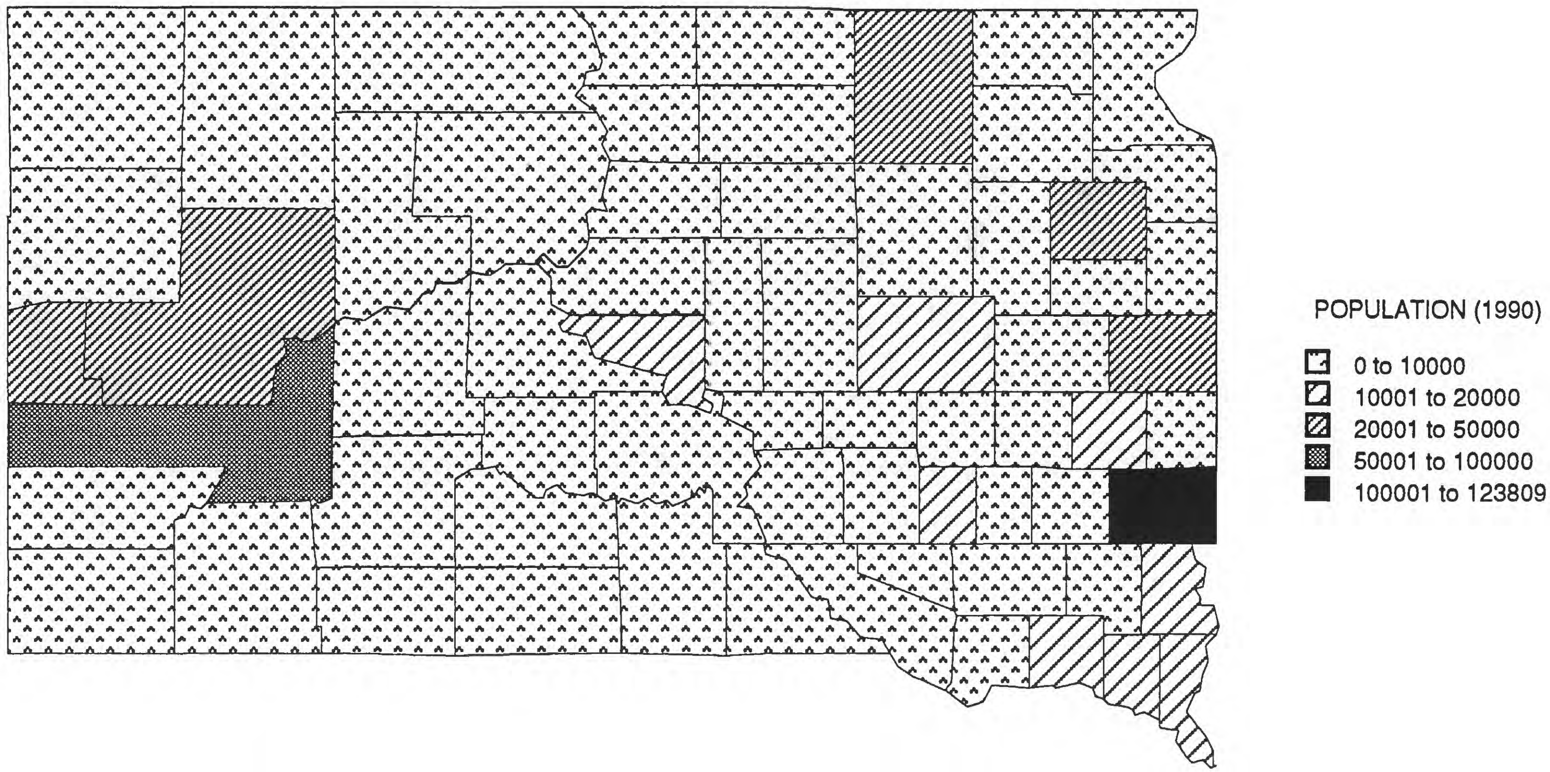


Figure 2. Population of counties in South Dakota (1990 U.S. Census data).

Figure 3. South Dakota counties.

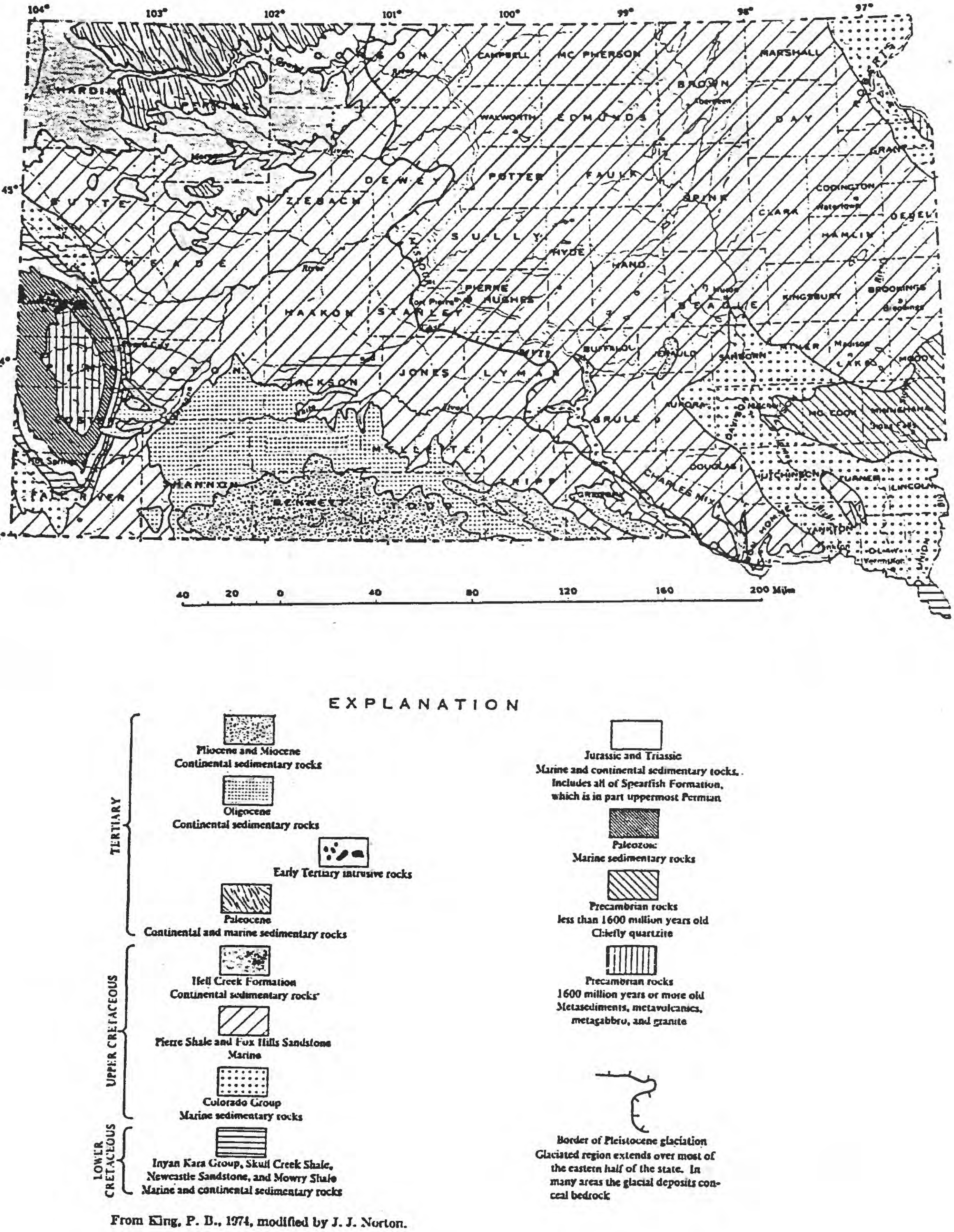


Figure 4. Geologic map of South Dakota (from U.S. Geological Survey, 1975). Mowry Shale is now considered to be Upper Cretaceous in age.

sandstone, limestone, and shale of Paleozoic and Mesozoic age that are exposed in and around the Black Hills, and Precambrian granite and metamorphic rocks forming the core of the Black Hills and underlying glacial deposits in the southern parts of the Minnesota River-Red River Lowland and Prairie Coteau (fig. 4). Rocks younger than Cretaceous include continental sandstones and shales of Tertiary age exposed in the northwest part of the State and in the southern part of the State west of the Missouri River (fig. 4). These rocks include (using the nomenclature of Darton, 1951), the Paleocene Ludlow, Cannonball, and Fort Union Formations, Oligocene White River Group, and the Miocene Arikaree Formation.

Uranium Geology: Uranium deposits occur in sandstones of the Lower Cretaceous Inyan Kara Group in the Edgemont mining district in Fall River County (fig. 5). Near-surface uranium deposits in the Edgemont district are associated mainly with carbonaceous (organic-rich) material or pyrite in the sandstones (Schnabel, 1975). Uranium is also associated with coals, carbonaceous siltstones, and carbonaceous shales in the Fort Union Formation in the northwestern part of the State, particularly in the Slim Buttes and Cave Hills areas of Harding County (fig. 5). Uranium-bearing coals have also been found in the Tertiary Tongue River and Hell Creek Formations in Perkins County, and may be present in other parts of northwestern South Dakota (Curtiss, 1955). Localized uranium deposits occur in pegmatite zones and in granites in the Black Hills. Uranium minerals have also been found in the Deadwood and Minnelusa Formations (which are mapped as Paleozoic rocks on figure 4), Spearfish Formation, Newcastle Sandstone, the Pierre Shale, and several Tertiary formations, including the Brule and Chadron Formations of the White River Group, and the Ogallala and Arikaree Formations, in western South Dakota (Curtiss, 1955). Uranium probably occurs in higher-than-average amounts (average crustal abundance is 2.5 parts per million [Carmichael, 1989]) in much of the Upper Cretaceous sandstone and shale underlying the glacial deposits, especially the Sharon Springs Member of the Pierre Shale. The Pierre Shale as a whole probably contains higher-than-average amounts of uranium, in part because it was deposited under reducing conditions under which uranium is relatively immobile and thus more likely to concentrate at the site of deposition, and because it contains an abundance of organic matter and clay minerals that fix or bond with metals, including uranium.

Glacial Geology: Virtually all of South Dakota east of the Missouri River and a small part west of the river were covered by glaciers at one time. Most of eastern South Dakota is covered by late Wisconsin-age drift. Wisconsin-age glaciers advanced from the north and northwest in two main lobes, the James and the Des Moines lobes. Pre-Wisconsin drift is exposed in southeastern South Dakota and in the north-central part of the state (fig. 6). The age of the deposits labeled "Illinoian" in figure 6 is uncertain, but is known to be early Wisconsin or older, and is assigned an early Wisconsin? age by Hammond (1991). An Illinoian age is assigned to the deposits by G.M. Richmond (personal communication, 1992), and is used in this report for consistency with the Quaternary Geologic Atlas of the United States (for example, Richmond and others, 1991). Late Wisconsin ice reached its maximum extent about 12,500 years ago and retreated from the state about 10,000 years ago (Lemke and others, 1965).

East of the Missouri River, glacial drift is nearly continuous and averages about 100 feet (30 m) in thickness, but some areas, such as the northern part of the Coteau des Prairies, are underlain by as much as 800 feet (250 m) of drift (Tipton, 1975). West of the Missouri River the drift is discontinuous and consists mainly of scattered glacially-rounded boulders. The most common type of glacial deposit is till composed of reworked Cretaceous rocks. The abundance of shale in the source bedrock is reflected in the high clay content of the tills. Till layers are separated by layers of stratified drift and, in some areas, loess (windblown silt) or paleosols (fossil soils),

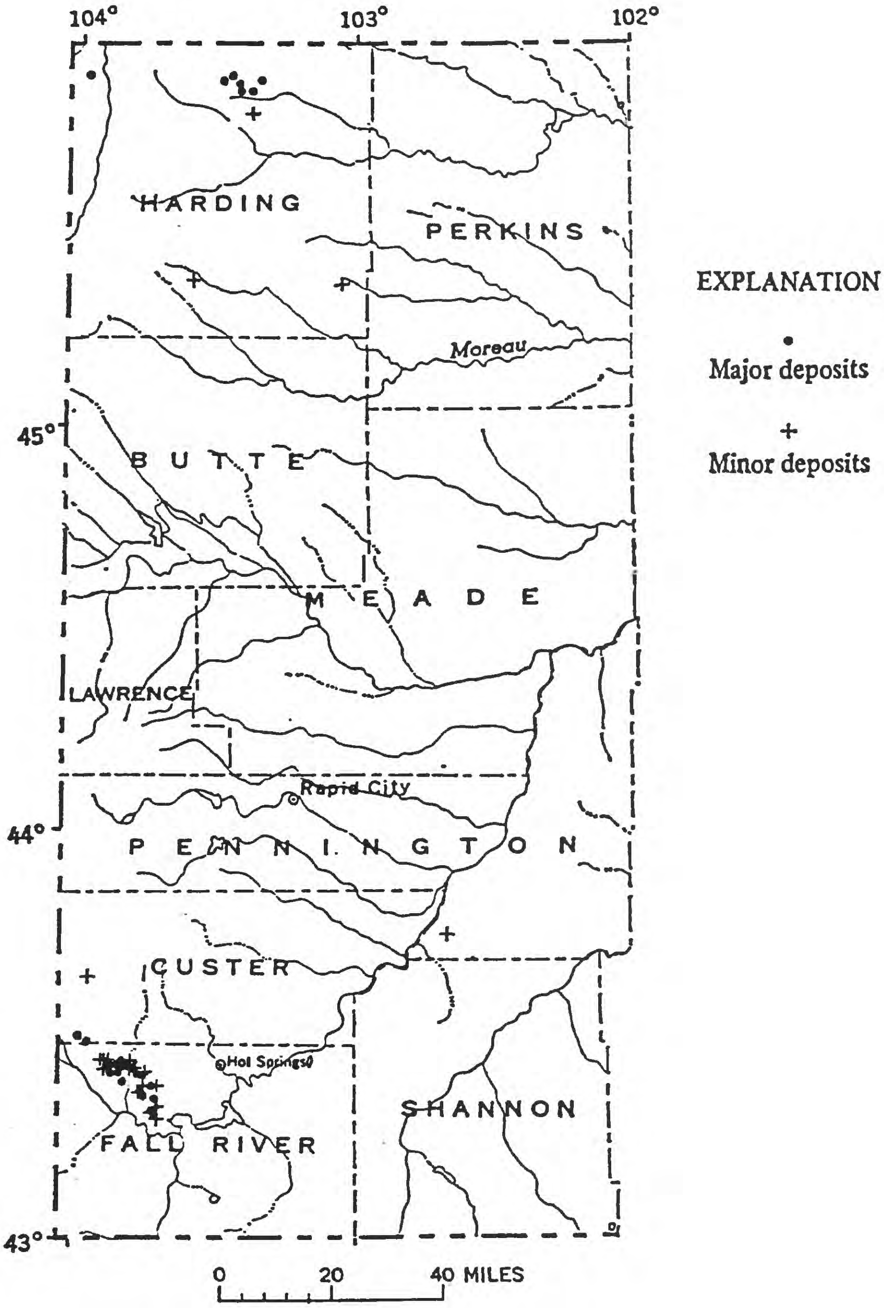


Figure 5. Locations of uranium deposits in western South Dakota (from U.S. Geological Survey, 1975).

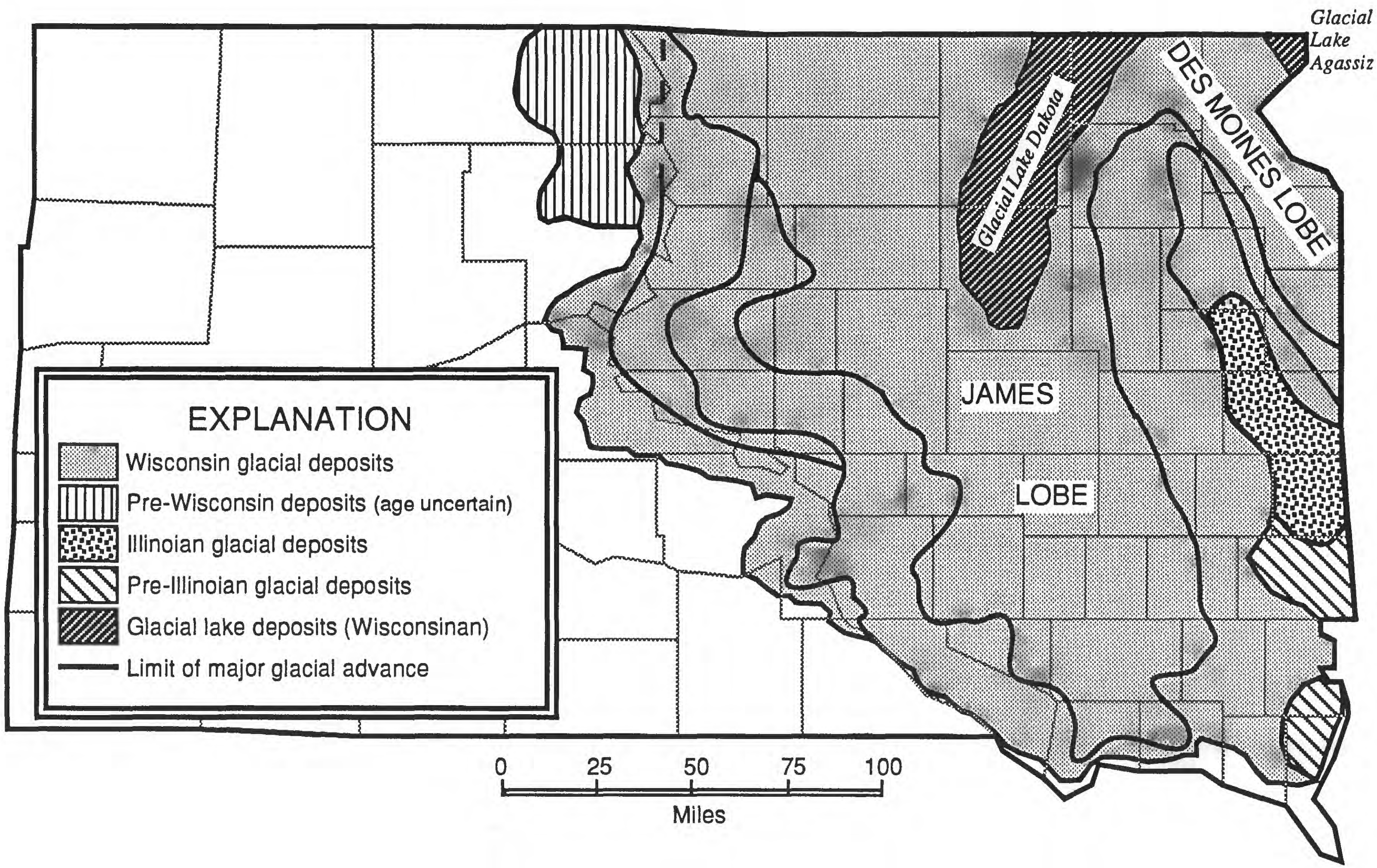


Figure 6. Map showing glacial deposits in South Dakota (after Lemke and others, 1965; Flint, 1955; and G.M. Richmond, personal communication, 1992).

representing individual glacial advances separated by non-glacial periods. Late Wisconsin deposits consist of clay-rich till and fragments of local Cretaceous shale bedrock (Flint, 1955). Pre-late Wisconsin glacial deposits contain significantly fewer shale fragments, reflecting their primary source, Precambrian igneous and metamorphic rocks from northern Minnesota. This indicates that the pre-late Wisconsin glaciers advanced from the northeast rather than from the north and northwest as did the late Wisconsin glaciers (Lemke and others, 1965).

During the last part of the glacial stage, as the glaciers were melting, two glacial lakes existed in South Dakota. Glacial Lake Dakota covered the northern part of the James River Lowland, depositing as much as 40 feet (12 m) of silt with lesser amounts of clay and fine sand (Flint, 1955). Glacial Lake Agassiz occupied the Red River Valley and extended from northern Manitoba to the northeastern corner of South Dakota. At its maximum extent, Lake Agassiz covered more area than all of the present Great Lakes combined (Flint, 1955). Lake Agassiz drained eastward into the ancestral Minnesota River system through a deep trench now occupied by Lake Traverse and Big Stone Lake. Silt and clay lake bed deposits and beach deposits associated with Lake Agassiz are found in the northeastern corner of the State.

SOILS

Major soil types of South Dakota are shown in figure 7A. These include Aridic Borolls—soils of cool, very dry plains; Aridic Ustolls—soils of warm, very dry plains; Typic Borolls—soils of cool, dry plains; Typic Ustolls—soils of warm, dry plains; Udic Borolls—soils of cool, moist prairie; and Udic Ustolls—soils of warm, moist prairie. Soil textures range from clays and clay loams to loams, silty and sandy loams, and sands. Clayey and silty soils are most common, as many soils are derived from shales, siltstones, or glacial deposits derived from these rocks. Some areas, such as the Black Hills, have poorly-formed soils or weathered bedrock at the surface (South Dakota Agricultural Experiment Station, 1971). Soil permeabilities are mostly low (less than 0.6 in/hr in SCS soil percolation tests) to moderate (0.6 to 6.0 in/hr) (fig. 7B). A few soils with high permeability (> 6.0 in/hr) are found in South Dakota but they cover only small areas in river valleys and a few other areas (fig. 7B).

INDOOR RADON DATA

Indoor radon data shown in figure 8 and presented in Table 1 are from The EPA/Indian Health Service Residential Radon Survey and The Radon Project of the University of Pittsburgh. The Radon Project data represent 70 screening measurements in seven counties from homeowners that purchased charcoal canister radon detectors from The Radon Project. Indoor radon data were also collected in a survey of 669 homes conducted during 1988-89 by EPA and the Indian Health Service (IHS) on reservations in the Great Plains (fig. 9). Of these, 378 homes were in South Dakota. Data for Brookings, Brown, Davison, Hughes, Hutchinson, Minnehaha, and Yankton Counties are from The Radon Project; all other counties for which indoor radon data are shown are from the EPA/IHS survey. Although the data are sparse they suggest that most areas of the State have the potential for elevated indoor radon levels. In this report, "elevated" refers to screening indoor radon levels greater than 4 pCi/L.

Overall, more than half the homes tested in reservations in eastern South Dakota had indoor radon levels greater than 4 pCi/L. Taken as a group, the Lower Brule, Pine Ridge, Rapid City, and Rosebud reservations in central and southern South Dakota (fig. 9) had a relatively low percentage of homes (20 percent) with radon levels greater than 4 pCi/L. The Standing Rock and

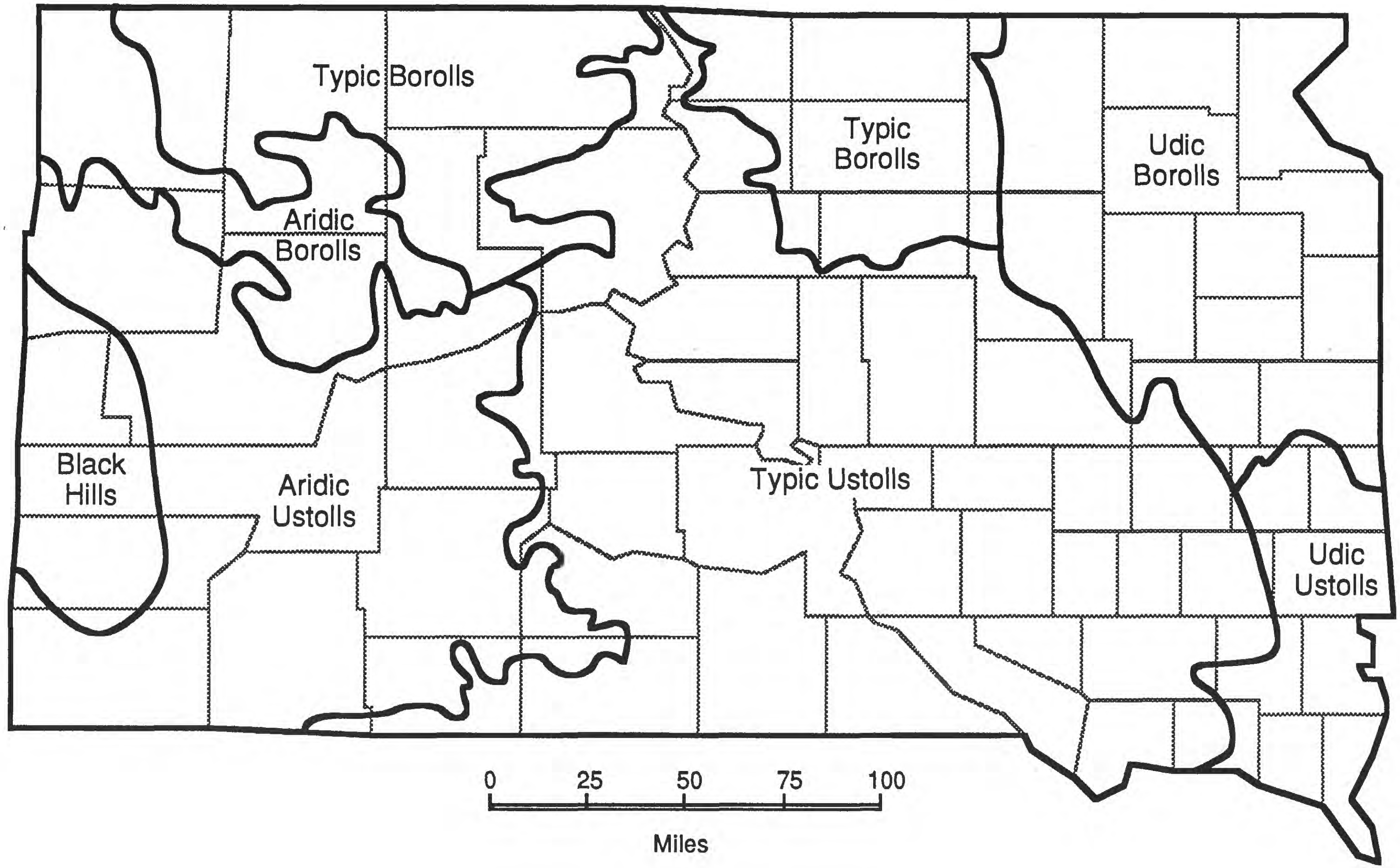


Figure 7A. Generalized map of soil types in South Dakota. After South Dakota Agricultural Experiment Station (1971).

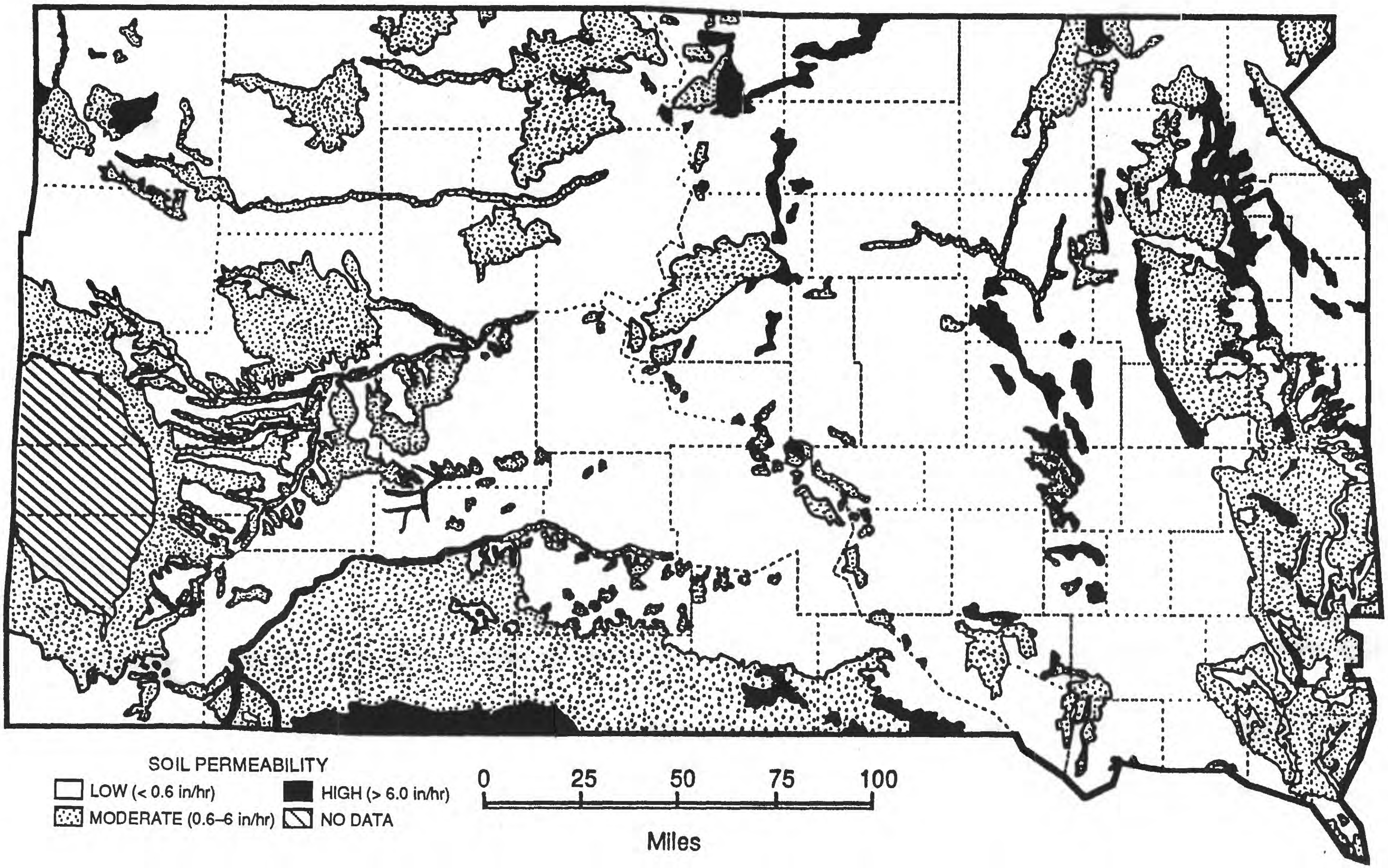
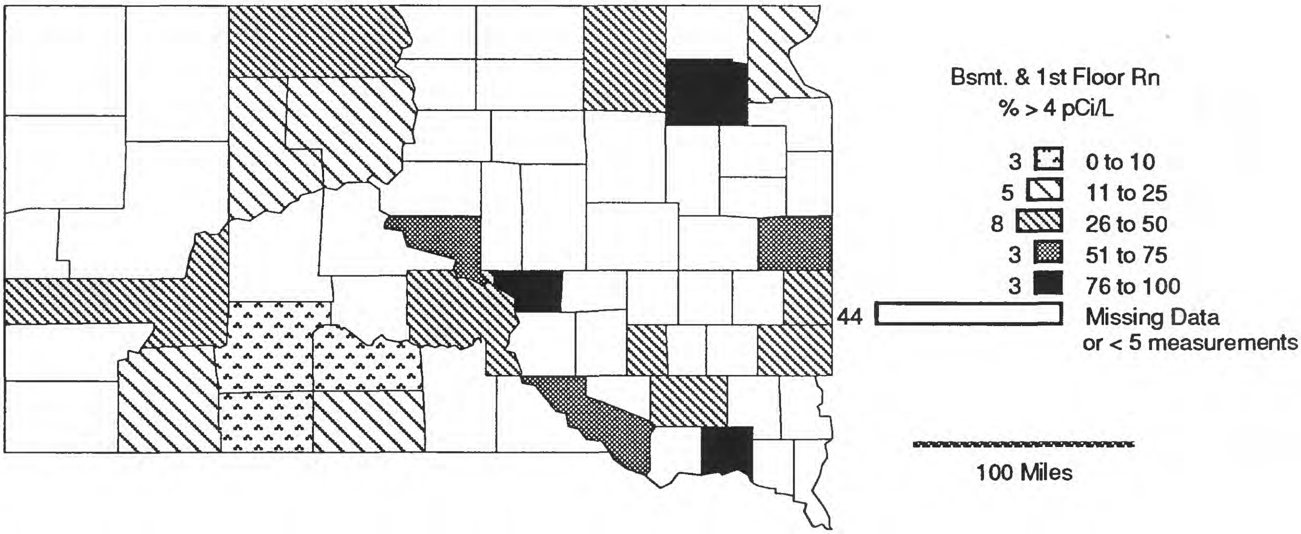


Figure 7B. Generalized soil permeability map of South Dakota. After South Dakota Agricultural Experiment Station (1971) and U.S. Soil Conservation Service soil survey data.



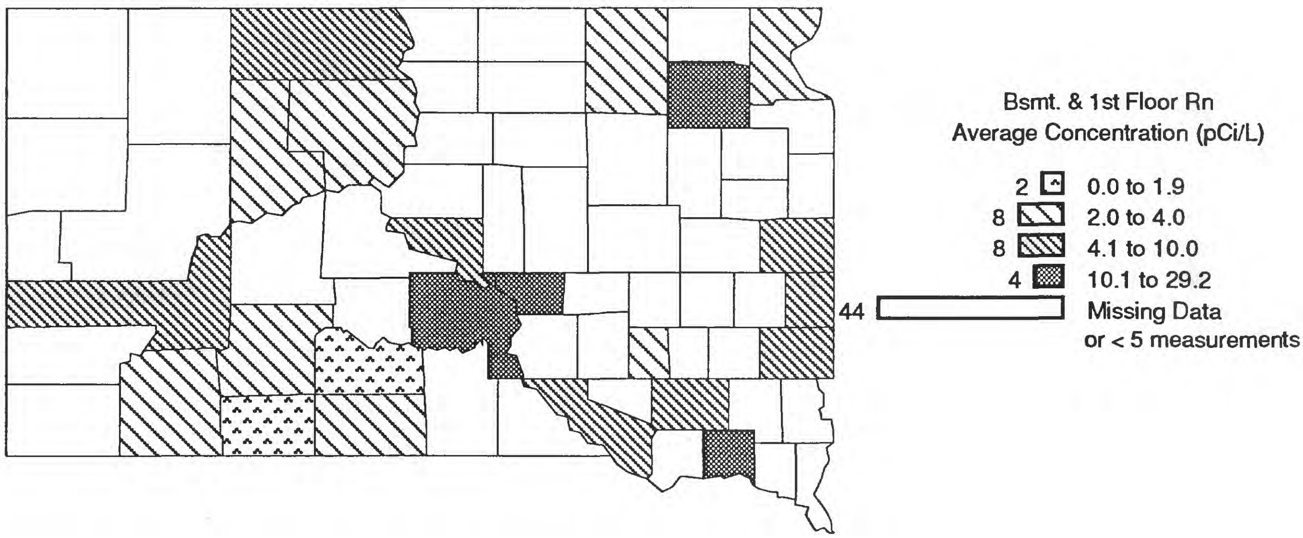


Figure 8. Screening indoor radon data for South Dakota from the EPA/Indian Health Service Indoor Radon Survey (1988-89) and The Radon Project of the University of Pittsburgh, for counties with 5 or more measurements. Data are from 2-7 day charcoal canister tests. Histograms in map legends show the number 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 for South Dakota from the EPA/Indian Health Service Residential Radon Survey and The Radon Project of the University of Pittsburgh. Data represent 2-7 day charcoal canister measurements. * indicates county data from The Radon Project; data for all other counties are from the EPA/IHS survey.
- indicates no data.

COUNTY	NO. OF MEAS.	MEAN	GEOM. MEAN	MEDIAN	STD. DEV.	MAXIMUM	%>4 pCi/L	%>20 pCi/L
Bennett	6	1.6	1.4	1.7	0.7	2.5	0	0
Brookings*	18	6.3	--	--	--	--	61	--
Brown*	8	3.5	--	--	--	--	38	--
Buffalo	15	23.2	13.0	10.9	24.7	73.7	93	33
Charles Mix	26	7.8	5.0	6.2	6.4	22.4	62	4
Corson	37	6.9	4.1	3.8	10.8	64.9	43	5
Davison*	9	3.9	--	--	--	--	33	--
Day	5	11.2	10.5	8.8	4.9	19.0	80	0
Dewey	47	2.1	1.6	1.5	2.1	12.3	11	0
Gregory	3	2.7	2.6	2.1	1.1	4.0	33	0
Hughes*	8	6.8	--	--	--	--	63	--
Hutchinson*	4	8.4	--	--	--	--	50	--
Jackson	12	2.0	1.7	1.6	1.0	3.9	0	0
Lyman	15	29.2	5.4	3.3	80.2	315.7	40	20
Marshall	2	5.6	3.6	5.6	6.0	9.8	50	0
Mellette	10	1.6	1.4	1.5	0.7	3.1	0	0
Minnehaha*	18	4.2	--	--	--	--	39	--
Moody	8	4.4	2.6	2.5	4.5	12.9	38	0
Pennington	17	5.0	3.8	3.7	3.9	14.4	47	0
Roberts	17	3.7	2.1	2.0	5.5	23.0	24	6
Shannon	62	3.1	2.3	3.0	2.2	8.8	24	0
Todd	73	2.0	1.4	1.4	1.7	7.1	14	0
Tripp	4	2.0	1.8	1.7	0.9	3.3	0	0
Yankton*	5	16.2	--	--	--	--	100	--
Ziebach	17	3.5	2.2	2.2	4.1	16.2	18	0

Figure 9. Map of Indian reservations participating in the Aberdeen area EPA/Indian Health Service Indoor Radon Survey during 1988-89.

Cheyenne River reservations in north-central South Dakota had 25 percent of homes with indoor radon levels greater than 4 pCi/L. The Crow Creek, Flandreau, Sisseton, and Yankton reservations together had 57 percent of homes with screening radon levels greater than 4 pCi/L. The Crow Creek and Lower Brule reservations (fig. 9) had the highest maximum indoor radon levels, with one reading as high as 316 pCi/L in the Lower Brule reservation in Lyman County. Notable counties include Buffalo County, with an indoor radon average of 23.2 pCi/L and a maximum reading of 73.7 pCi/L of 15 measurements, and Lyman County, with an average of 29.2 pCi/L for 15 readings (the average is skewed toward the 315.7 pCi/L reading, as indicated by the geometric mean of 5.4 pCi/L and the median of 3.3 pCi/L for the county). The seven counties with data from The Radon Project had average indoor radon levels ranging from 3.5 to 16.2 pCi/L. Five of the seven counties had average indoor radon levels exceeding 4 pCi/L (the exceptions are Brown and Davison Counties).

GEOLOGIC RADON POTENTIAL

Aerial radioactivity, shown on an equivalent uranium (eU) map of South Dakota (fig. 10), correlates fairly well with exposures of uranium-bearing rocks in the unglaciated western part of the State. Areas with high eU (defined here as > 2.5 parts per million, or ppm) are associated with the granite core of the Black Hills and with the Cretaceous Inyan Kara and Colorado Groups surrounding the Black Hills (see figure 4). Although they have high radioactivity, Precambrian igneous and metamorphic rocks are considered to be primarily moderate to locally high in radon potential. Rock types of the Black Hills core with high radon potential include conglomeratic metasedimentary rocks near Nemo and pegmatites (Chadima, 1989). High radioactivity is also associated with Tertiary sediments in Custer and Pennington Counties and with the Tertiary Ludlow and Fort Union Formations and White River Group in the Northern Plateaus. Cretaceous and Tertiary sandstones host uranium deposits in the northwestern and southwestern parts of the State, and contain higher-than-average amounts of uranium in many areas. These rocks have an overall high radon potential. Tertiary rocks in the Southern Plateaus region have a moderate radon potential but are likely to generate locally high indoor radon levels.

An area of high eU (about 3 ppm) located in the central part of the State just north of Pierre, between Blunt and Gettysburg and west to the Missouri River, appears to be associated with Wisconsinan glacial deposits. With this exception, virtually all of the glaciated part of South Dakota has an anomalously low eU signature. The glacial drift, which is derived mainly from Cretaceous shale, contains sufficient uranium to generate radon at levels of concern. However, most of the uranium and radium has probably been leached from the near-surface soil layers and transported downward in the soil profile (Schumann and others, 1991). The glacial deposits likely contain significantly more uranium than is indicated by the eU map, but the gamma-ray spectrometer, which obtains most of its signal from the upper 30 cm of soil, cannot detect these higher levels of uranium and radium in the deeper soil horizons.

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 and the radon emanation coefficient in the soils by exposing uranium and radium at grain surfaces. Poorly-sorted glacial drift may also have somewhat higher permeability than the shale bedrock from which it is derived due to mixing with coarser materials. In addition, cracking of the clayey glacial soils during dry periods can create sufficient permeability for radon transport. Desiccation cracking is

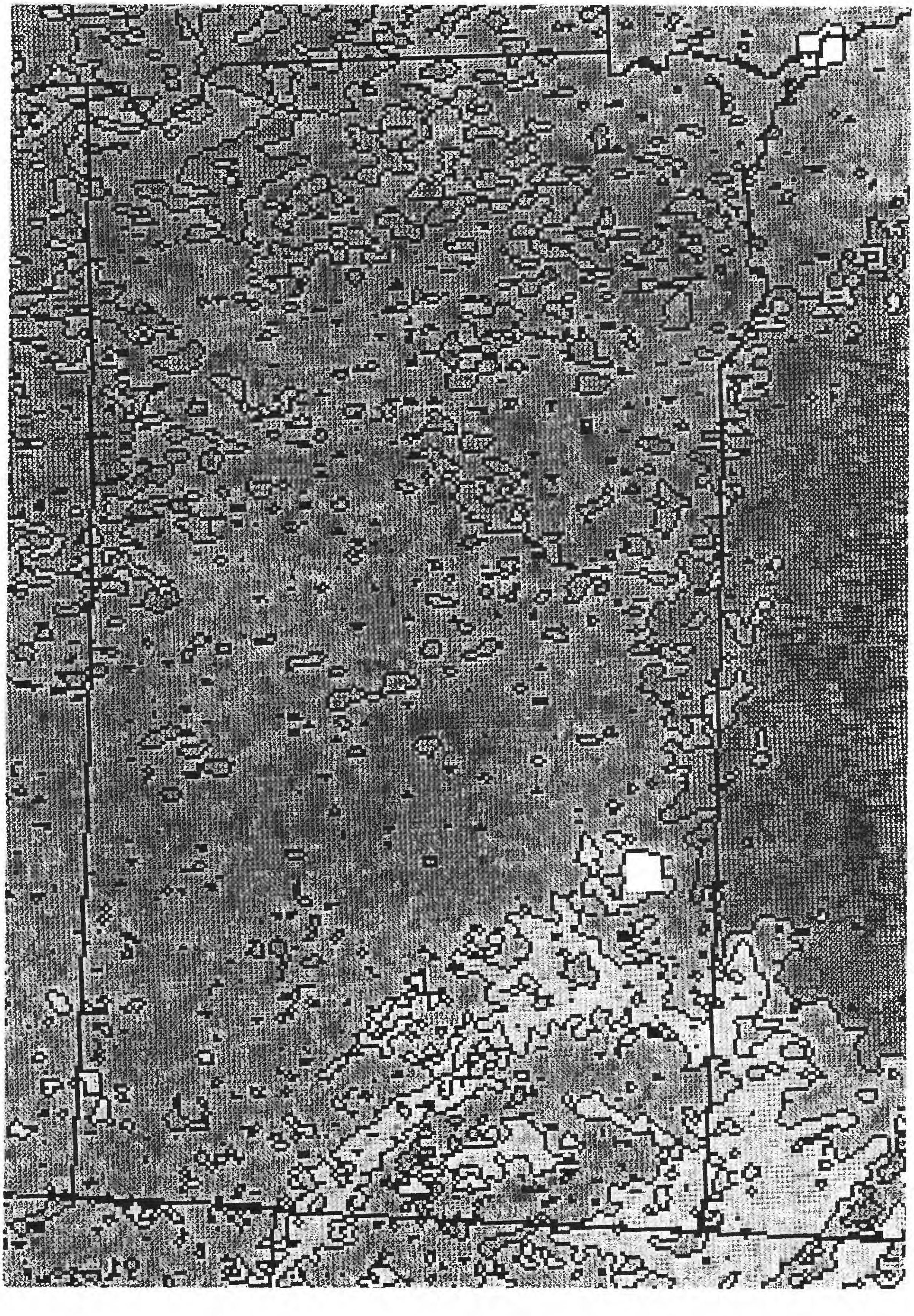


Figure 10. Aerial radiometric map of South Dakota (after Duval and others, 1989). Contour lines at 1.5 and 2.5 ppm equivalent uranium (eU). Pixels shaded from 0 to 6.0 ppm eU at 0.5 ppm eU increments; darker pixels have lower eU values; white indicates no data.

an important factor causing elevated radon levels in areas underlain by clayey glacial deposits. Deposits of glacial Lakes Dakota and Agassiz are likely to generate elevated indoor radon levels. The lake clays and silts have a relatively high radon emanation coefficient and are known to generate elevated radon in homes and in soil gas in Manitoba (Grasty, 1989) and North Dakota (Schumann and others, 1991). Unglaciated areas underlain by shale bedrock have a moderate radon potential due to their combination of above-average uranium content and low permeability, but locally elevated radon levels are likely to occur in areas where weathering of the shale has produced fractured, relatively more permeable soils.

SUMMARY

Figure 11 shows radon potential areas of South Dakota delineated in this report and assigned Radon Index (RI) and Confidence Index (CI) scores in Table 2. Area BH, the Black Hills, has a moderate radon potential (RI=11) and moderate confidence (CI=8). The granite core of the Black Hills has a high radiometric signature and may produce locally elevated indoor radon levels, particularly in areas underlain by pegmatites. Area KS, underlain by sandstones and shales of Cretaceous age that surround the Black Hills, has a high radon potential (RI=14) and moderate confidence (CI=9). Of particular concern in this area is the Inyan Kara Group, which is known to host uranium deposits, especially in the area between Edgemont and Hot Springs. Area ETS, Early Tertiary sandstones, mostly equivalents of the Fort Union Formation of Paleocene age but locally including the White River Group and Arikaree Formation, has a high radon potential (RI=14) and moderate (CI=9) confidence. Of special note are outcrops of the Arikaree Formation in the Slim Buttes and Cave Hills areas in Harding County, which host uranium deposits and thus may be of particular concern. Area LTS, Late Tertiary Sandstones, includes outcrops of the White River Group and Arikaree Formation in the southwestern part of the State. This area has an overall moderate radon potential (RI=11) with moderate confidence (CI=9), but some locally elevated indoor radon levels may be found. Area SH along the South Dakota-Nebraska border includes part of the Sand Hills of Nebraska and has an overall low (RI=8) radon potential with moderate confidence (CI=9). The Pierre Hills area (area PH on figure 11) is underlain primarily by Pierre Shale and Fox Hills Sandstone. This area has an overall moderate radon potential (RI=11) with moderate confidence (CI=9). Areas underlain by Pierre Shale are likely to have locally elevated indoor radon levels, particularly in areas where the shale-derived soils are relatively permeable or in areas underlain by the Sharon Springs or other organic-rich members of the Pierre Shale. The eastern part of the state underlain by glacial drift (area GC) has a high radon potential (RI=14, CI=9). Of particular note are glacial lake deposits (areas denoted by GL) which cause some of the highest indoor radon levels in adjacent states. These areas also have an RI of 14 and CI of 9, and may be areas of locally very high indoor radon levels.

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.

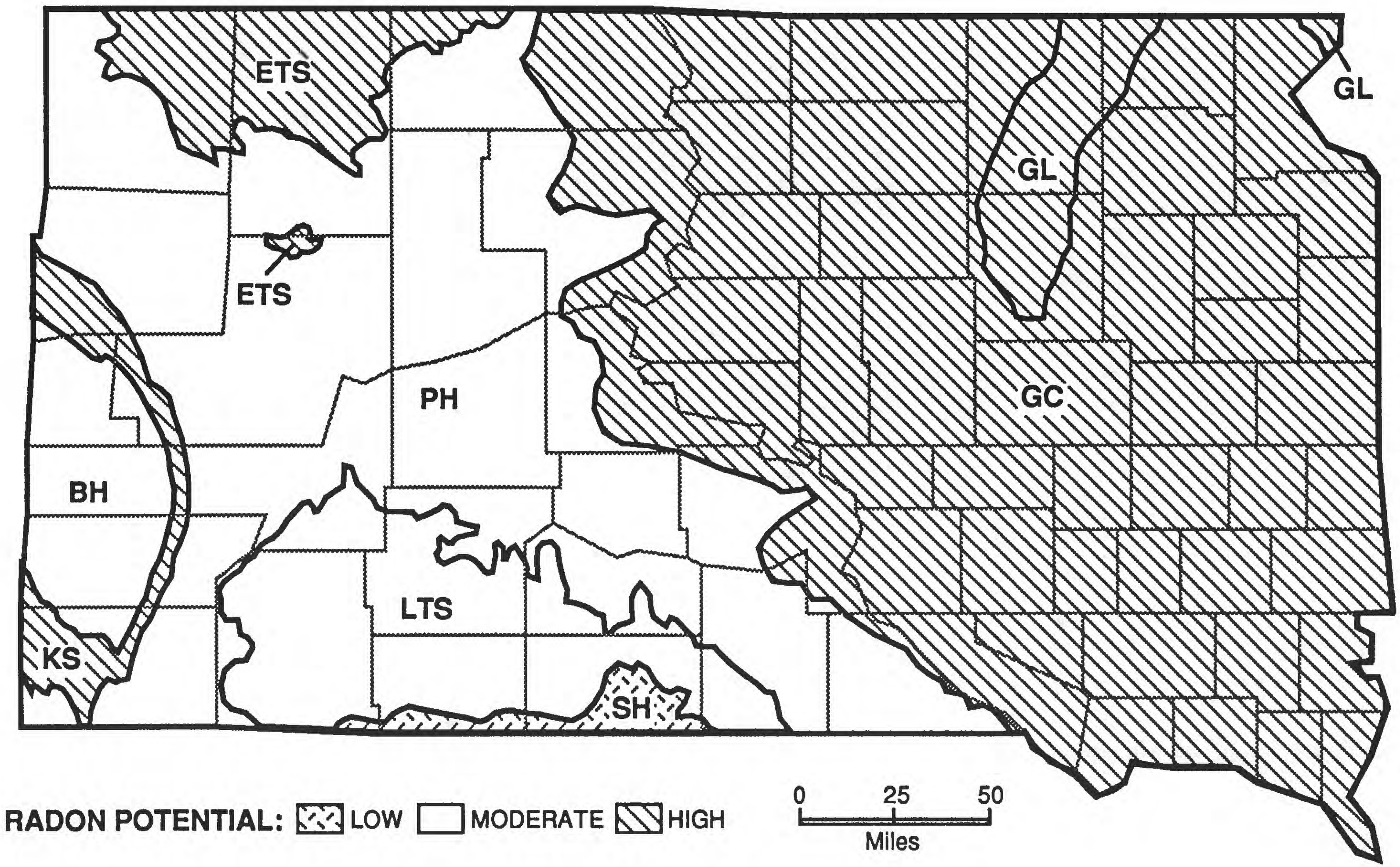


Figure 11. Radon potential areas of South Dakota; boundaries are approximate. BH, Black Hills; KS, Cretaceous sandstones/shales surrounding the Black Hills; PH, Pierre Hills area; ETS, Early Tertiary sandstones (Paleocene); LTS, Late Tertiary sandstones (Oligocene, Miocene, Pliocene); SH; Sand Hills; GC, area of glacial cover; GL, glacial lake deposits.

TABLE 2. Radon Index (RI) and Confidence Index (CI) scores for geologic radon potential areas of South Dakota. See figure 11 for locations and abbreviations of areas.

	BH		KS		ETS		LTS	
FACTOR	RI	CI	RI	CI	RI	CI	RI	CI
INDOOR RADON	2	1	3	1	3	1	2	1
RADIOACTIVITY	2	3	3	3	3	3	2	3
GEOLOGY	2	2	3	3	3	3	2	3
SOIL PERM.	2	2	2	2	2	2	2	2
ARCHITECTURE	3	--	3	--	3	--	3	--
GFE POINTS	0	--	0	--	0	--	0	--
TOTAL	11	8	14	9	14	9	11	9
RANKING	MOD	MOD	HIGH	MOD	HIGH	MOD	MOD	MOD

	SH		PH		GC		GL	
FACTOR	RI	CI	RI	CI	RI	CI	RI	CI
INDOOR RADON	1	1	2	1	3	1	3	1
RADIOACTIVITY	1	3	2	3	1	3	1	3
GEOLOGY	1	2	2	2	3	3	3	3
SOIL PERM.	2	2	1	2	2	2	2	2
ARCHITECTURE	3	--	3	--	3	--	3	--
GFE POINTS	0	--	0	--	+2	--	+2	--
TOTAL	8	8	10	8	14	9	14	9
RANKING	LOW	MOD	MOD	MOD	HIGH	MOD	HIGH	MOD

RADON INDEX SCORING:

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

Possible range of points = 3 to 17

CONFIDENCE INDEX SCORING:

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

Possible range of points = 4 to 12

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PRELIMINARY GEOLOGIC RADON POTENTIAL ASSESSMENT OF UTAH

by
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INTRODUCTION

Uranium ore was discovered in southwestern Utah in 1900, and since that time uranium deposits have been mined as an energy resource and as a source of vanadium and radium, primarily in southeastern Utah (Smith, 1987). Uranium in Utah occurs in rocks of many ages and lithologies (Doelling, 1974), and in 1980 Utah ranked third in domestic uranium production behind New Mexico and Wyoming (Chenoweth, 1980). Because the uranium- and radium-bearing bedrock and the soils and alluvium derived from those rocks are widespread in Utah, and because radon is a daughter product of uranium decay, many areas in the State have the potential to generate and transport radon in sufficient concentrations to be of concern in indoor air. However, even in areas underlain by rocks known to contain uranium, other mitigating factors such as soil porosity and permeability or ground-water levels may locally interact to produce an environment that does not have elevated indoor radon levels.

Recently, several studies have investigated the potential for indoor radon in Utah. Parts of the discussion of radon potential in Utah in the present report are summarized from comprehensive papers on indoor radon data and the potential for radon hazards in Utah (Sprinkel, 1987, 1988; Sprinkel and Solomon, 1990a, 1990b). Preliminary indoor radon measurements suggested that parts of Utah locally may be susceptible to elevated radon levels (Woolf, 1987; Lafavore, 1987). Additional studies investigated outdoor radon occurrences in soil and water (Rogers, 1956, 1958; Tanner, 1964; Horton, 1985). The Utah Geological and Mineral Survey has conducted statewide studies to identify geologic features that have the potential to produce elevated indoor radon levels (Sprinkel, 1987, 1988). Subsequent indoor radon studies (Sprinkel and others, 1989; Sprinkel and Solomon, 1990b) were conducted on the basis of that research, and additional geologic studies have updated the discussion of radon hazards in Utah (Solomon and others, 1991).

This is a generalized assessment of geologic radon potential of rocks, soils, and surficial deposits of Utah. 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

Five major physiographic provinces (fig. 1A) extend into Utah, three of which occupy large areas of the state, and they result in considerable topographic variety that reflects the

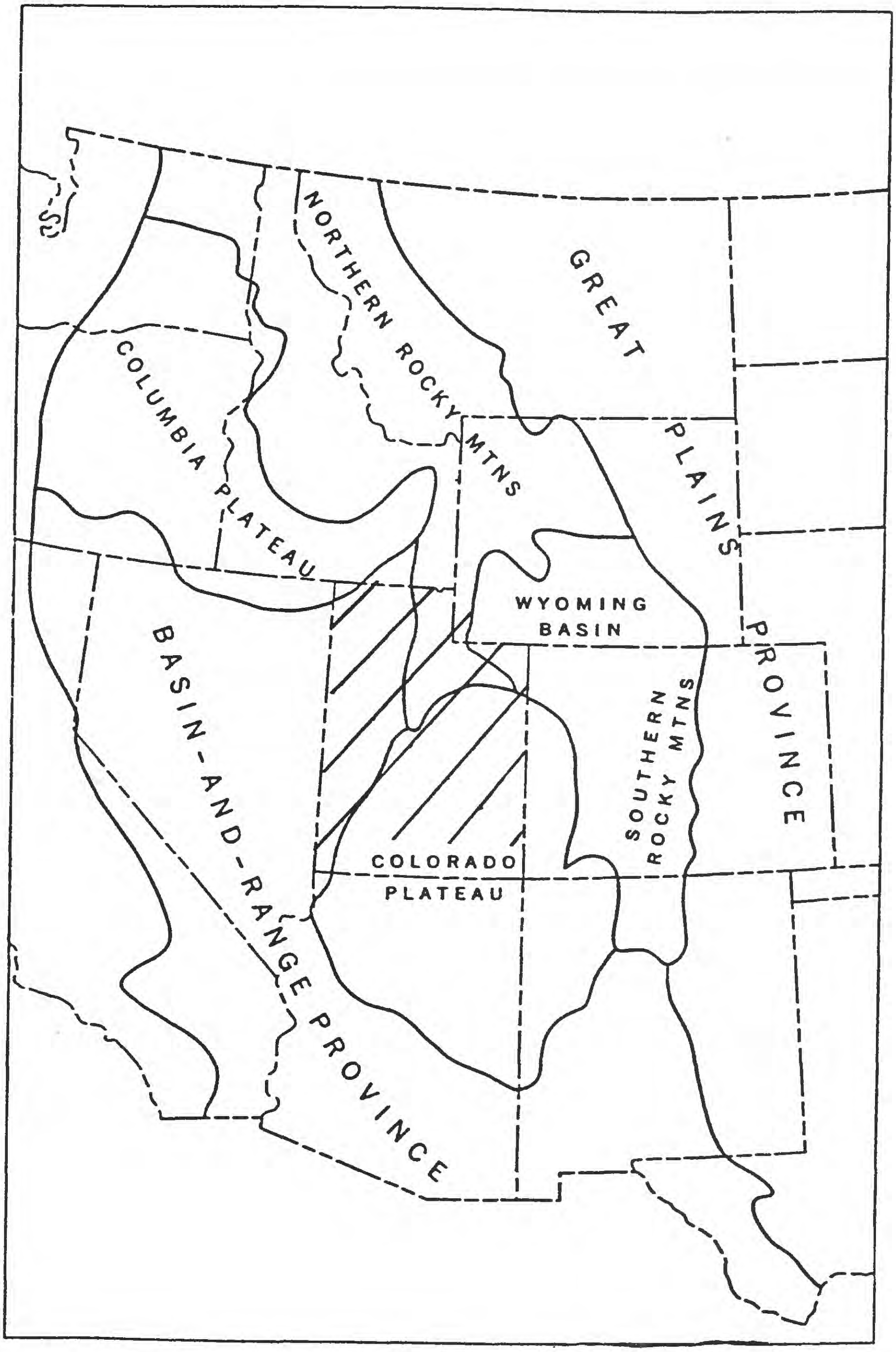

Figure 1A. Map showing major physiographic features in the western United States (modified from Mallory, 1972).

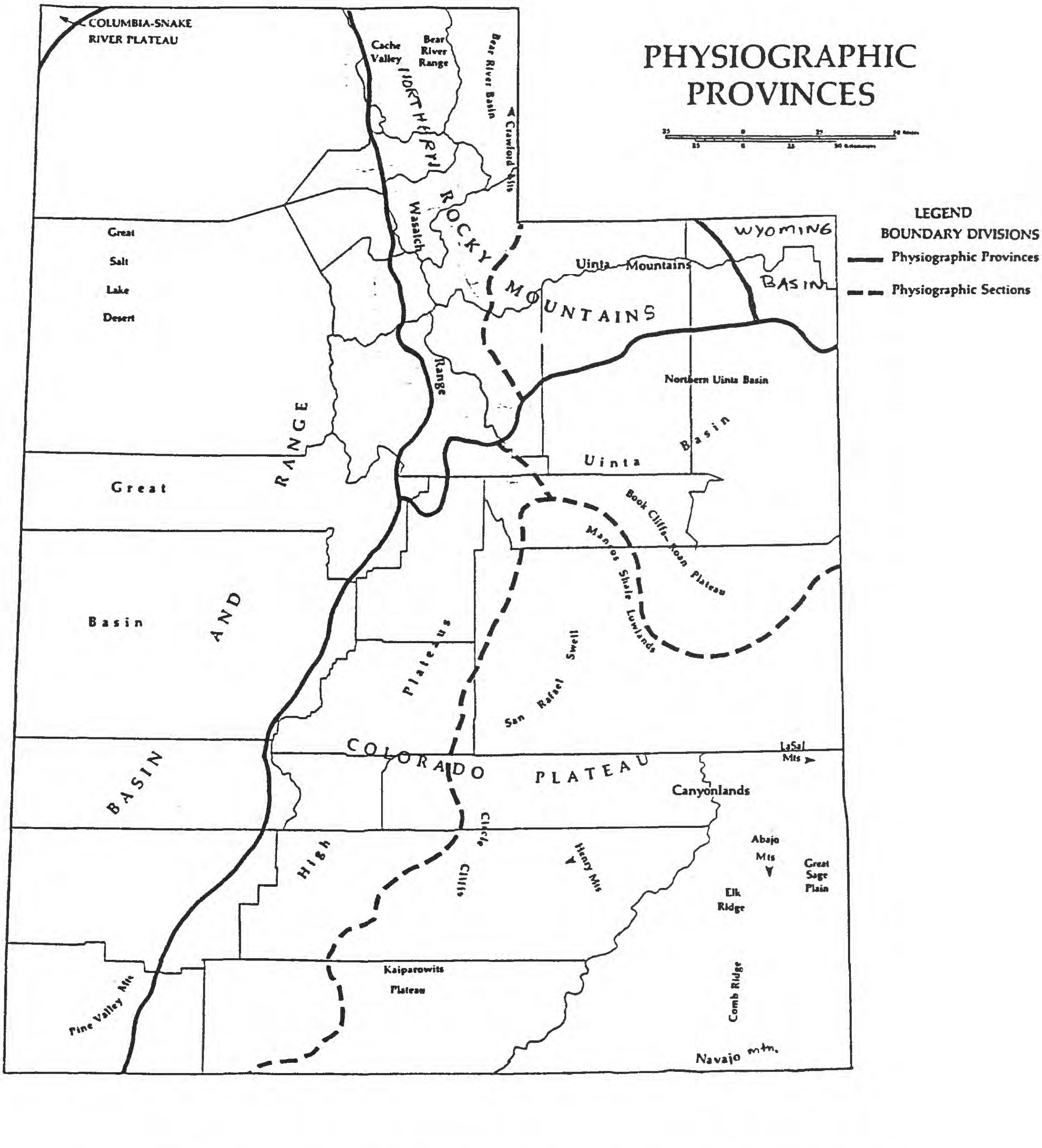

Figure 1B. Physiographic features in Utah (modified from Wahlquist, 1981).

underlying bedrock geology (fig. 2) (Mallory, 1972; Hintze, 1980, 1988). The Great Basin section of the Basin and Range encompasses the western part of Utah, whereas the Wasatch Range and the Uinta Mountains in the north and northeast are part of the Northern Rocky Mountains. The Colorado Plateau, a roughly circular area centered about the Four Corners region of Utah, Colorado, Arizona, and New Mexico, covers a large part of the southeastern half of Utah (Wahlquist, 1981).

The Colorado Plateau consists of highly dissected plateaus and mesas ranging in elevation from about 5,000 ft to high mountains of about 11,000 ft, and lower elevations in the deepest river canyons. On the Colorado Plateau, the bedrock geology consists primarily of Paleozoic, Mesozoic, and Cenozoic flat-lying to gently folded sedimentary rocks that are locally interrupted by Cenozoic intrusive plutonic and extrusive volcanic rocks.

In Utah, the Colorado Plateau is subdivided into three subsections (fig. 1B): the Uinta Basin, Canyonlands, and High Plateaus. The Uinta Basin lies south of the Uinta Mountains in northeastern Utah. Elevations rise to over 9,000 ft on the Roan Plateau at the southern rim of the basin. Although the basin consists predominantly of gently rolling terrain, the Green River and its tributaries have cut numerous spectacular canyons and deep ravines into the easily eroded Tertiary rocks that are prominent in the basin. Canyonlands dominate the southeastern quarter of Utah. The Colorado River and its tributaries have sculpted extensive canyons, cliffs, mesas, buttes, and badlands. Within Canyonlands, the Abajo, Henry, and La Sal Mountains form rugged highlands eroded from Tertiary igneous intrusions that tower over the surrounding canyon country. Large structural upwarps, such as the Monument uplift and the San Rafael Swell, expose domed and folded Paleozoic and Mesozoic sedimentary rocks. The Kaiparowits Plateau is a high mesa that is transitional from the Canyonlands to the High Plateaus. The High Plateaus form a series of gently rolling uplands locally capped by basalt flows and glacial deposits. The western edge of the High Plateaus are marked by impressive escarpments that resulted from large normal faults. The Hurricane fault separates the High Plateaus from the Basin and Range in southwestern Utah.

The Basin and Range covers most of the western half of Utah and includes the Great Basin, which is located in western Utah and eastern Nevada. The Basin and Range is characterized by uplifted and tilted high mountain ranges separated by flat, low-lying basins. In the Basin and Range, mountain ranges vary in width from less than a mile to more than 15 miles, and they vary in length from a few miles to more than 60 miles. Uplifted rocks in the ranges consist primarily of Precambrian metamorphic, igneous, and sedimentary rocks, Paleozoic to Cenozoic sandstone and limestone, and Tertiary plutonic and volcanic rocks. The intervening basins are filled by fluvial, lacustrine, colluvial, and alluvial-fan deposits. Many of the basins exhibit internal drainage. The basin fills are generally quite thick and consist of gravel, sand, silt, clay, marl, gypsum, and halite.

In northeastern Utah, the Uinta Mountains and the Wasatch Range are the southernmost part of the Northern Rocky Mountains Province. The east-west trending Uinta Mountains were created by anticlinal upwarping, with sedimentary rocks dipping outward on all flanks of the range. The north-south trending Wasatch Range extends from east of Nephi northward into Idaho. The western flank of the range is steep and straight, reflecting displacement on the still-active Wasatch fault.

The Snake River-Columbia Plateau Province extends from the northwest into the extreme northwestern corner of Utah, and the Wyoming Basin Province extends into the extreme northeastern part of Utah. Both areas are so small compared to the remainder of the State that they do not warrant additional discussion.

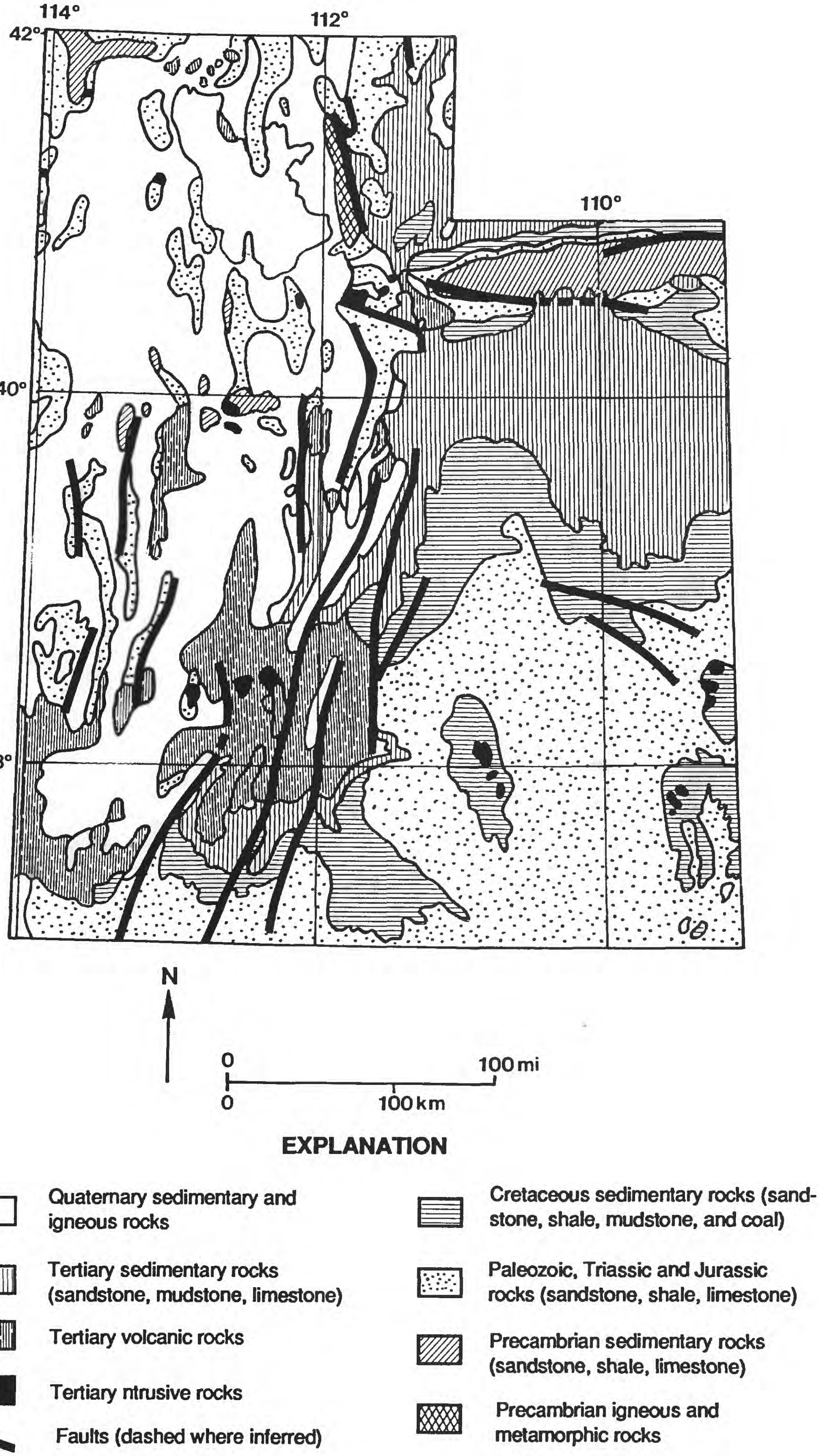

Figure 2. Map showing generalized geology of Utah (modified from Mallory, 1972).

Population density (fig. 3A,B) and land use in Utah reflect the geology, topography, climate, and early immigration history of the State. Utah is a very sparsely populated state and has a mean population density of 12.9 persons per square mile (Wahlquist, 1981). The population has a very uneven distribution: some mountainous and desert tracts have virtually no residents, and only a few ranching and farming communities can be found in large areas of both the Colorado Plateau and the Basin and Range provinces. Only 8 percent of Utah's population lies within 15 counties that account for 70 percent of Utah's land area. On the other end of the scale, the four Wasatch Front counties of Salt Lake, Weber, Davis, and Utah account for only 4 percent of Utah's land area but 77 percent of its population. Salt Lake County has only one percent of the State's area but contains 42 percent of its population (Wahlquist, 1981).

Urban areas are concentrated along the Wasatch Front on the western flank of the Wasatch Mountains and extend from Brigham City and Perry on the north through Ogden and Salt Lake City to Sandy and Provo on the south. This population concentration along the Wasatch Front reflects Utah's early settlement by Mormon pioneers. Many of the small ranching and farming communities scattered throughout the State also started as early Mormon settlements. Outside the Wasatch Front, fairly dense concentrations of Mormon settlements developed in Cache Valley, Sanpete Valley, and the St. George area.

GEOLOGY

Utah's geology is complex and varies widely from place to place, but in general the bedrock geology (fig. 2) is characteristic of the major physiographic provinces (fig. 1B). The following discussion of the geology of Utah is condensed from Mallory (1972), Hintze (1975, 1980, 1988), and Wahlquist (1981). Detailed maps of the geology of Utah are presented by Hintze (1975, 1980).

The Colorado Plateau in southeastern Utah and the small part of the Wyoming Basin in extreme northeastern Utah are underlain by uplifted, primarily flat-lying to locally folded, deeply incised sedimentary rocks ranging in age from Pennsylvanian to Tertiary. Pennsylvanian and Permian rocks are predominantly arkosic conglomerates, fluvial and eolian sandstones, and minor marine limestones. Triassic strata comprise marine sandstone, shales, and limestones and extensive continental fluvial and lacustrine sandstones, mudstones, and limestones. Jurassic rocks consist of laterally extensive eolian sandstones, marine limestones, evaporites, and shales, and continental lacustrine and fluvial sandstones and mudstones. Cretaceous strata form a thick sedimentary section in Utah and consist of marine shales, sandstones, limestones, and coals that interfinger with nonmarine fluvial sandstones and shales. Tertiary sedimentary rocks are dominantly lacustrine carbonates and mudstones and include minor fluvial sandstones. Tertiary igneous intrusions locally dome the sedimentary section in the La Sal, Henry, and Abajo Mountains on the Colorado Plateau. Tertiary volcanic rocks formed by extrusive lava flows, tuffs, breccias, and conglomerates along with rhyolitic intrusives are exposed in the Marysvale volcanic field along the central part of the margin between the Colorado Plateau and the Basin and Range.

In the Wasatch Range, Precambrian metasedimentary, metamorphic, and crystalline rocks form the cores of the mountains. Uplifted sedimentary and volcanic rocks ranging in age from Cambrian through Tertiary ring the mountains and locally crop out within them. Along the Wasatch Front, uplift of the mountains along faults has produced erosion and subsequent deposition of Pleistocene lacustrine deltas and Holocene alluvial fans and gravels. Tertiary crystalline rocks in southeast Salt Lake County provided clastic material to uranium-enriched

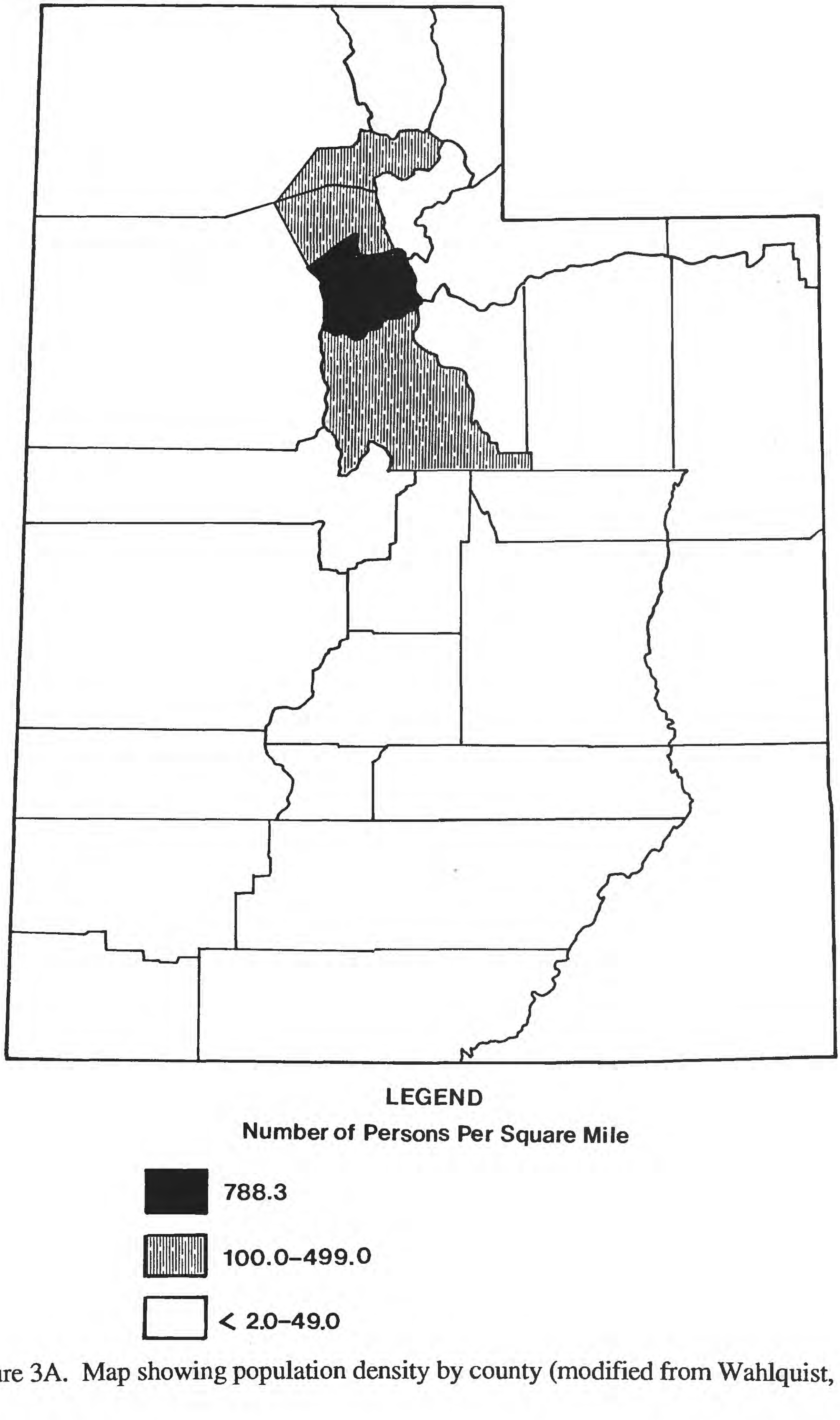

Figure 3A. Map showing population density by county (modified from Wahlquist, 1981).

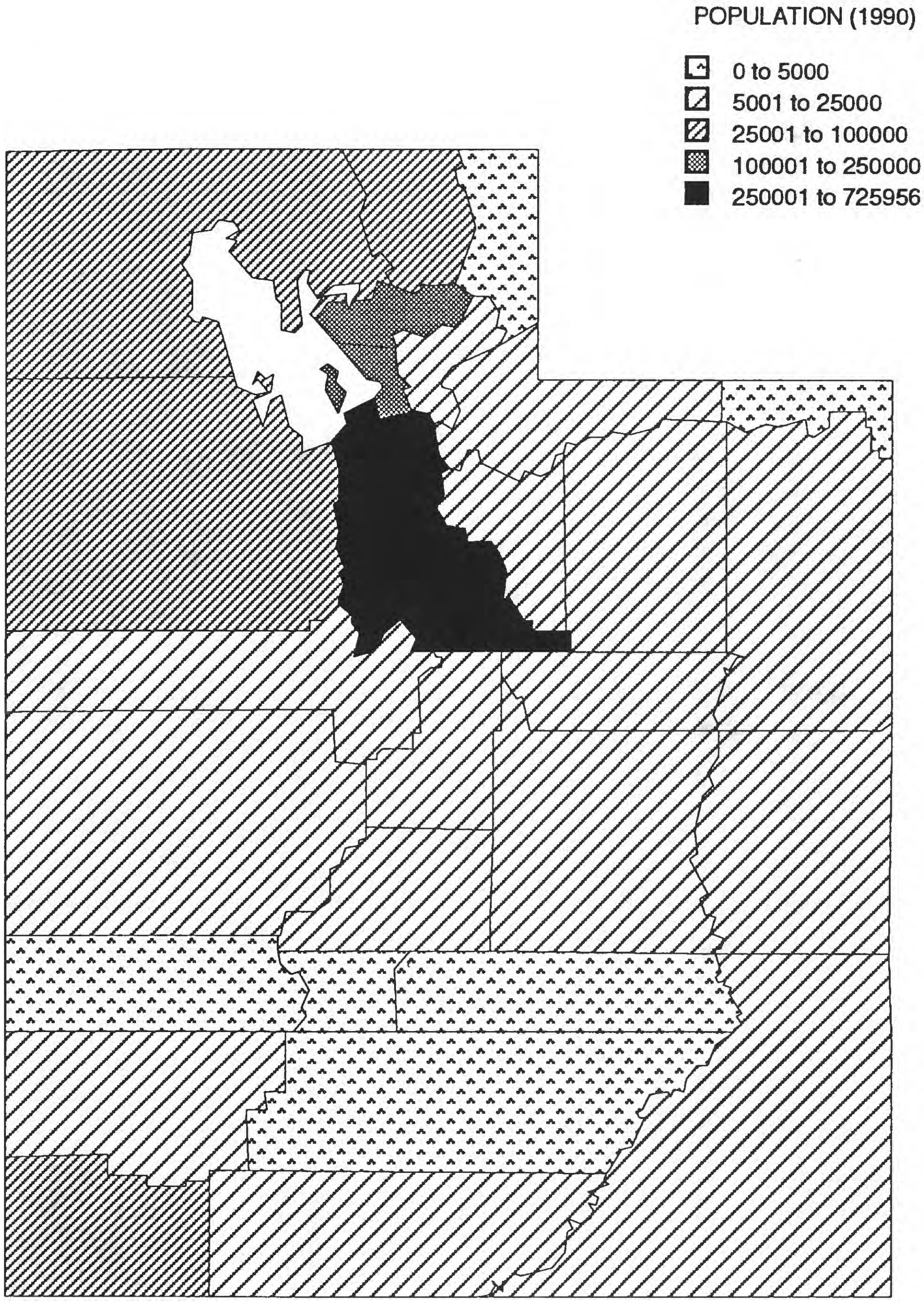

Figure 3B. Population of counties in Utah (1990 U.S. Census data).

sediments in eastern Salt Lake Valley (Stokes, 1986). In the Uinta Mountains, the core of the anticline is formed by Precambrian quartzites, and the rocks on the flanks of the range include upper Paleozoic and Mesozoic limestones, sandstones, and shales.

In the Basin and Range, Tertiary tectonism uplifted and faulted to the surface rocks ranging in age from Precambrian through Cenozoic. Deformation during the Late Cretaceous to early Tertiary Laramide orogeny created scattered mountain ranges with NE-SW trends. In the late Oligocene, tensional faulting associated with extrusive volcanic activity was initiated and continued into the Miocene, a time characterized by intense normal faulting and crustal extension. In the late Miocene, renewed tectonism produced block-fault mountain ranges that trend NW-SE. This episode of tectonism continues today. Basin filling was dominant in the earlier stages of this episode, but more recent geologic activity is dominated by stream downcutting, development of alluvial terraces, and erosion by the major rivers in the region.

The Basin and Range province exposes a wide variety of rocks of different ages and lithologies (fig. 2). Precambrian igneous plutonic rocks and metasedimentary, metavolcanic, and metamorphic rocks are scattered throughout the region. Paleozoic rocks exposed in the uplifted mountains range in age from Cambrian to Permian. Mesozoic and Cenozoic sedimentary and volcanic rocks occur in small outcrops in the ranges. Major basins in the region were filled by Paleocene through Pleistocene and Holocene fluvial and lacustrine systems that deposited sandstones, mudstones, and limestones.

Uranium ore has been produced from several provinces in Utah. The Colorado Plateau hosts the majority of Utah's significant uranium ore deposits, although major deposits also occur in the Marysvale volcanic field, at Topaz Mountain, near Wah Wah, and at Silver Reef (fig. 4). The Colorado Plateau has produced the majority of Utah's total uranium production, principally from sandstone-hosted ore bodies in two settings: 1) the Upper Triassic Chinle Formation and 2) the Upper Jurassic Morrison Formation. The Shinarump, Monitor Butte, and Moss Back Members of the Chinle Formation and the Cutler Formation host significant uranium ore bodies in many areas of southern Utah, including Monument Valley, White Canyon (Red Canyon, Fry Canyon, Deer Flat, Elk Ridge), Lisbon Valley, Canyonlands (Cane Creek, Inter-River, Seven Mile, Indian Creek, Lockhart Canyon, Mineral Canyon), Circle Cliffs, Capitol Reef, Orange Cliffs, Temple Mountain, San Rafael Swell, Paria, and Silver Reef. The Morrison Formation hosts significant uranium ore deposits in several areas of Utah including Montezuma Canyon, Bluff (Butler Wash), Dry Valley, Paradox Valley, Thompsons, La Sal Montains, Henry Mountains, and Green River. Uranium also occurs in Tertiary volcanic rocks of the Marysvale volcanic field and Wah Wah Mountains and in Tertiary sedimentary strata of the Uinta Basin near Myton.

In addition to known deposits in Utah where uranium has been concentrated as ore, uranium also occurs in several rock types at concentrations too low to be considered economic but in amounts that may still generate radon at levels considered to be a problem in indoor air. For example, the black, organic-rich deposits of the Upper Mississippian and Lower Pennsylvanian Manning Canyon Shale and the Upper Cretaceous Mancos Shale contain low-level concentrations of uranium; Precambrian crystalline rocks exposed along the Wasatch Front have consistent uranium concentrations and may contain locally higher concentrations along fractures, faults, and shear zones; Tertiary volcanic rocks and ash-flow tuffs surrounding calderas in the Marysvale volcanic field have low-level uranium concentrations; and many alluvial and lacustrine deposits and soils reworked from uranium-bearing igneous and sedimentary parent rocks, particularly along the Wasatch Front, have significant potential to generate radon.

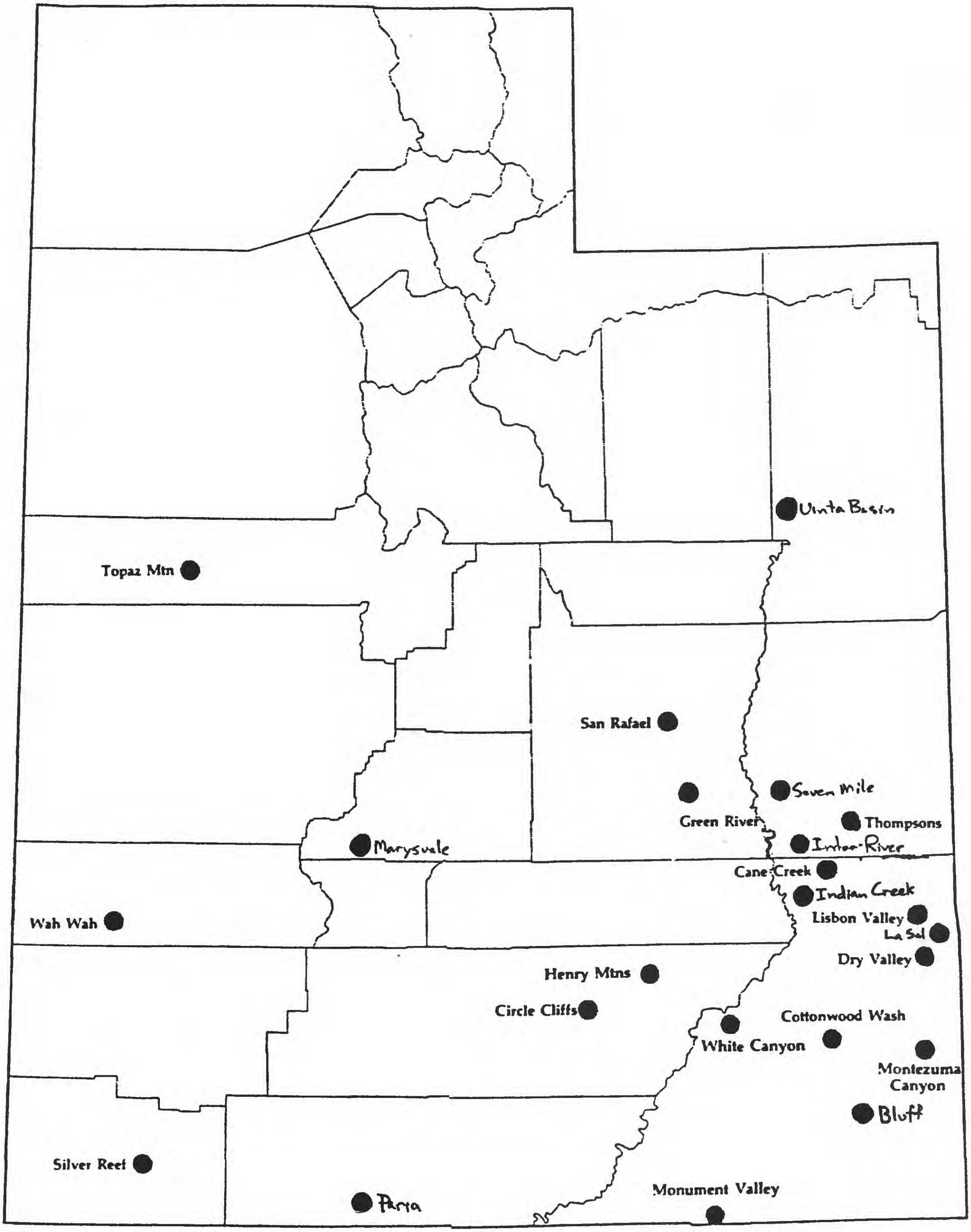

Figure 4. Map showing uranium districts in Utah (modified from Wahlquist, 1981, and from W.J. Finch, written comm., 1990).

SOILS

A generalized soils map of Utah (fig. 5) complied from Agriculture Experiment Station (1964), Soil Conservation Service (1973), and Wilson and others (1975) indicates that soils in Utah in general consist of Mollisols, Aridisols and Entisols. Mollisols are dark, relatively fertile soils formed under grasslands and in grass-covered forests. Mollisols are generally found in central Utah from the Idaho border south almost to Arizona. They occur where average annual precipitation exceeds 12 to 14 inches and elevations are mainly above 5,000 ft. Aridisols are thin, light-colored soils that occur where average annual precipitation is less than 12 to 14 inches and comonly is less than 10 inches. They are found throughout the Great Basin, the Bear River Valley of Rich County, the southern part of the Uinta Basin, and the northern part of the Colorado River drainage system in Utah. Entisols are incipient soils that lack discernable horizons. Entisols are unevenly distributed around the Uinta Mountains in northeastern Utah and in scattered valleys in southern Utah. Many parts of Utah display no soil development in areas of rock outcrops, sand dunes, and playa lake beds. It should be noted that the soil associations shown on the map are very generalized due to the scale of the map, and the reader is referred to Soil Conservation Service (1973) and Wilson and others (1975) for more detailed descriptions of the soils and their permeabilities.

INDOOR RADON DATA

Indoor radon data from the State of Utah radon study (fig. 6, Table 1) are included in the following discussion. Data from these radon studies in Utah are published and discussed in Sprinkel and Solomon (1990a, 1990b) and Sprinkel (1988). The data are from track-etch indoor radon detectors that were placed in the homes for approximately one year. A map showing the counties in Utah (fig. 7) is provided for reference. In this discussion, "elevated" indoor radon refers to indoor radon levels greater than 4.0 pCi/L.

Box Elder, Sevier, Beaver, Garfield, and Washington Counties had average indoor radon levels greater than 4.1 pCi/L; Rich, Weber, Morgan, Wasatch, Sanpete, Uintah, and Grand Counties had average indoor radon levels from 3.1 to 4.0 pCi/L; Piute, Utah, Salt Lake, Summit , and Cache Counties had average indoor radon levels of 2.1 to 3.0 pCi/l; Davis, Duschene, Iron, and Kane Cunties had average indor radon levels of 1.1 to 2.0 pCi/l; and Toole, Millard, and Carbon Counties had average indoor radon levels from 0 to 1.1 pCi/L. (fig. 6). In these counties, the average concentration was from 3.1 to 4 pCi/L (fig. 6). Daggett, Juab, Emery, Wayne, and San Juan Counties had no data.

GEOLOGIC RADON POTENTIAL

A comparison of the geology (fig. 2) with aerial radiometric data (fig. 8) and indoor radon data (fig. 6, Table 1) provides preliminary indications of rock types and geologic features suspected of having the potential to generate elevated indoor radon levels. An overriding factor in the geologic evaluation is the location and distribution of known uranium-producing outcrops in Utah (figs. 2, 4), coupled with the distribution of uranium occurrences and areas with concentrations of uranium that are suspected of producing elevated indoor radon levels (Sprinkel, 1987, 1988; Sprinkel and Solomon, 1990b). In addition to identifying uranium-bearing rocks and uranium occurrences, Sprinkel (1988) and Solomon and others (1991) also indicated that the

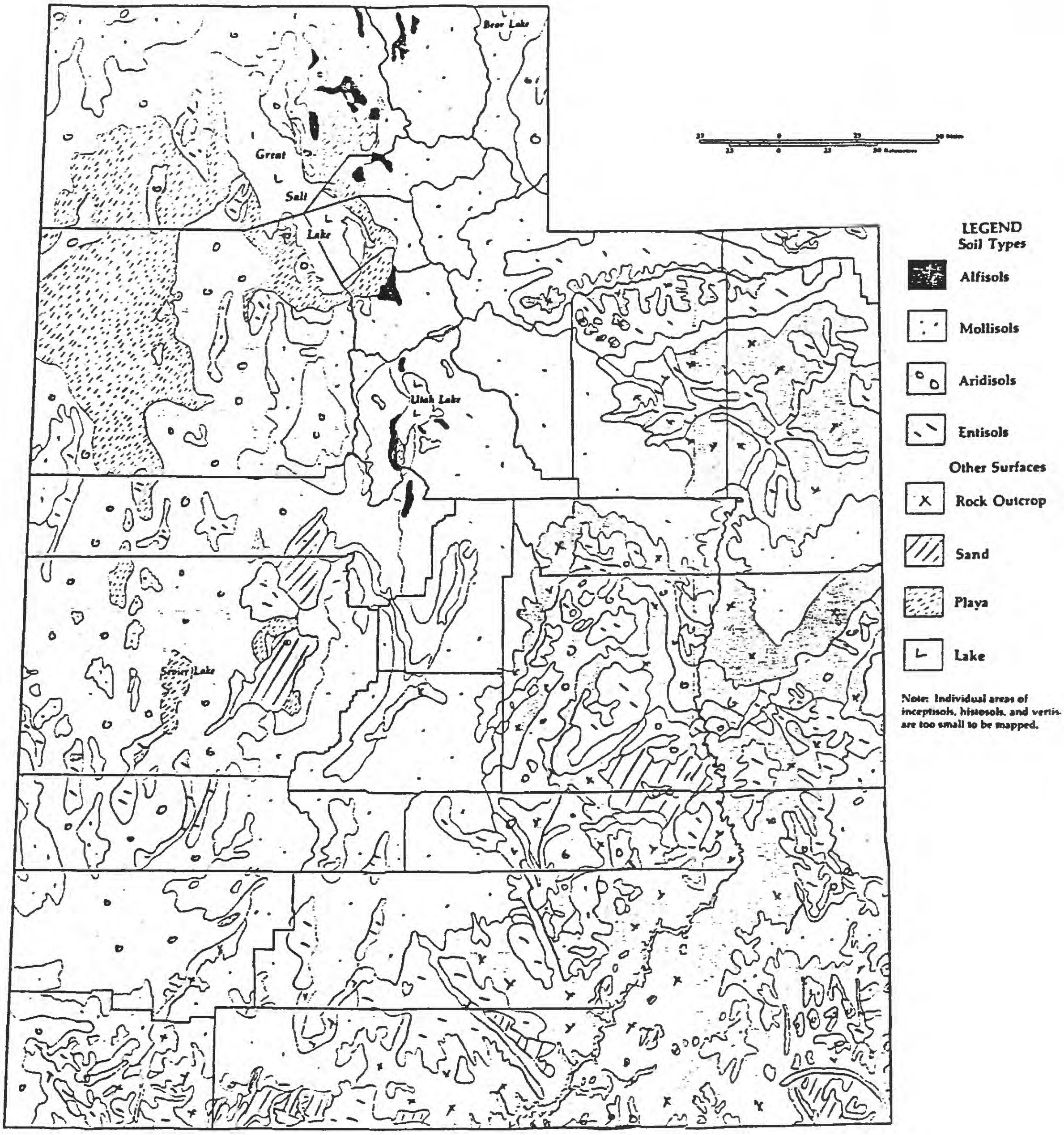

Figure 5. Map showing generalized soils in Utah (modified from Wahlquist, 1981).

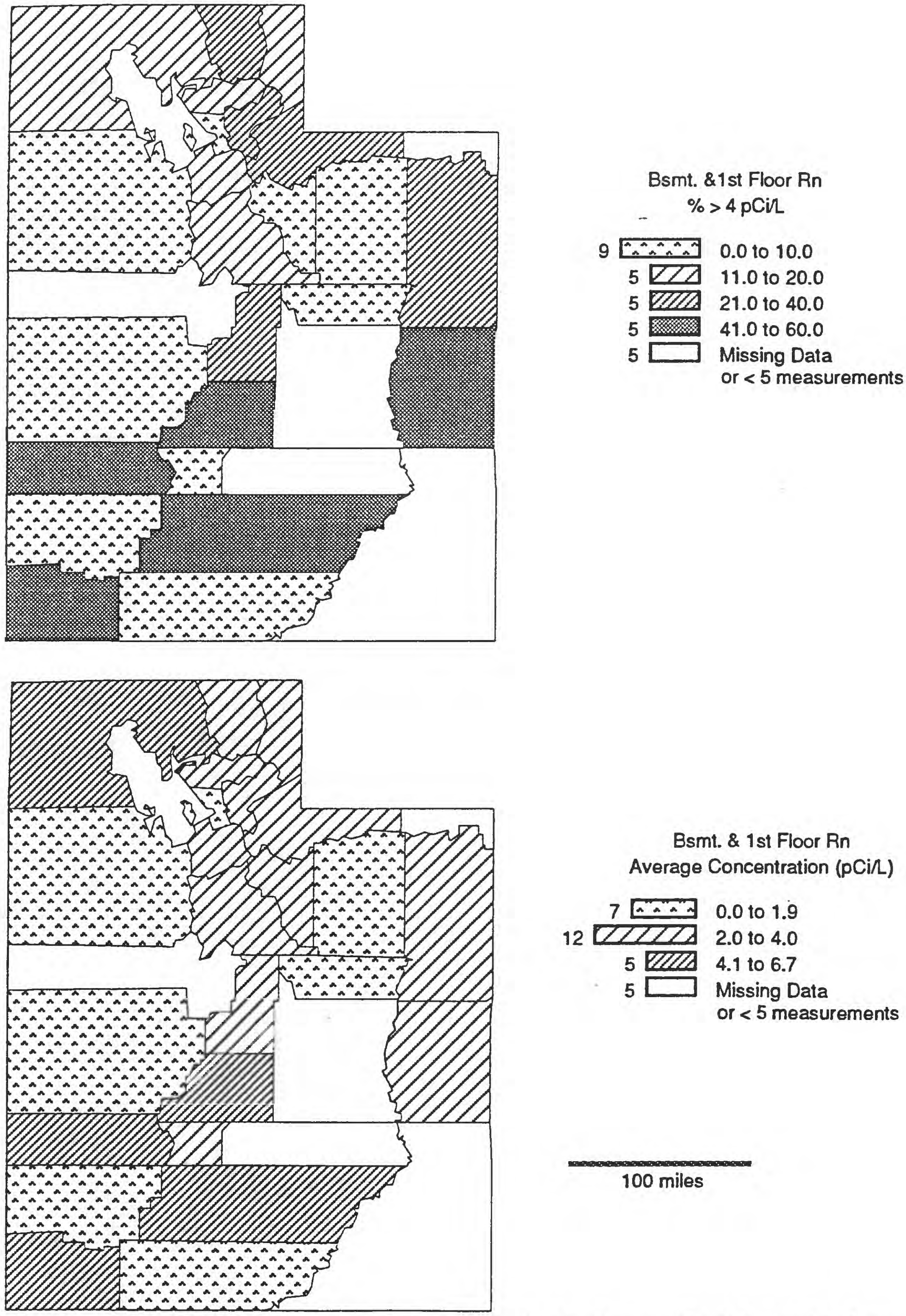

Figure 6. Indoor radon data from the State of Utah Radon Survey (Sprinkel and Solomon, 1990b), for counties with 5 or more measurements. Data are from 1-year alpha-track detector tests conducted during 1987-88. Histograms in map legends show the number of counties in each category. The number of samples in each county (see Table 1) may not be sufficient to statistically characterize the radon levels of the counties, but they do suggest general trends. Unequal category intervals were chosen to provide reference to decision and action levels.

TABLE 1. Screening indoor radon data from the State of Utah's indoor radon survey. Data represent long-term alpha-track detector readings collected during 1987-88. Compiled from data in Sprinkel and Solomon (1990).

COUNTY	NO. OF MEAS.	MEAN	STD. DEV.	MEDIAN	GEO. MEAN	MAXIMUM	%>4 pCi/L	%>20 pCi/L
BEAVER	2	6.7	5.4	6.7	5.5	10.5	50	0
BOX ELDER	16	5.9	12.4	2.2	2.9	52.0	19	6
CACHE	17	2.6	1.9	2.2	2.0	7.1	24	0
CARBON	1	0.4	***	0.4	0.4	0.4	0	0
DAVIS	38	1.5	1.0	1.2	1.2	4.3	3	0
DUCHESNE	14	1.8	1.5	1.4	1.2	5.7	7	0
GARFIELD	2	4.8	2.3	4.8	4.5	6.4	50	0
GRAND	2	3.2	3.5	3.2	2.0	5.6	50	0
IRON	6	1.8	1.1	1.7	1.6	3.8	0	0
KANE	2	1.2	1.0	1.2	1.0	1.9	0	0
MILLARD	2	0.7	0.5	0.7	0.5	1.0	0	0
MORGAN	3	3.7	1.8	3.3	3.5	5.7	33	0
PIUTE	1	2.1	***	2.1	2.1	2.1	0	0
RICH	10	3.5	3.4	2.2	2.7	12.1	20	0
SALT LAKE	268	2.4	2.5	1.7	1.7	26.2	13	0
SANPETE	6	3.1	1.2	2.9	2.9	4.6	33	0
SEVIER	14	5.8	7.2	2.4	3.3	22.4	43	14
SUMMIT	14	3.0	1.5	3.2	2.6	4.9	29	0
TOOELE	2	0.8	0.3	0.8	0.8	1.0	0	0
UINTAH	10	3.4	3.0	2.2	2.3	8.5	30	0
UTAH	127	2.7	2.3	2.1	2.0	13.6	14	0
WASATCH	1	3.6	***	3.6	3.6	3.6	0	0
WASHINGTON	8	4.5	4.7	2.8	2.7	14.3	50	0
WEBER	65	3.5	8.9	1.3	1.6	68.2	12	2

Figure 7. Map showing counties in Utah.

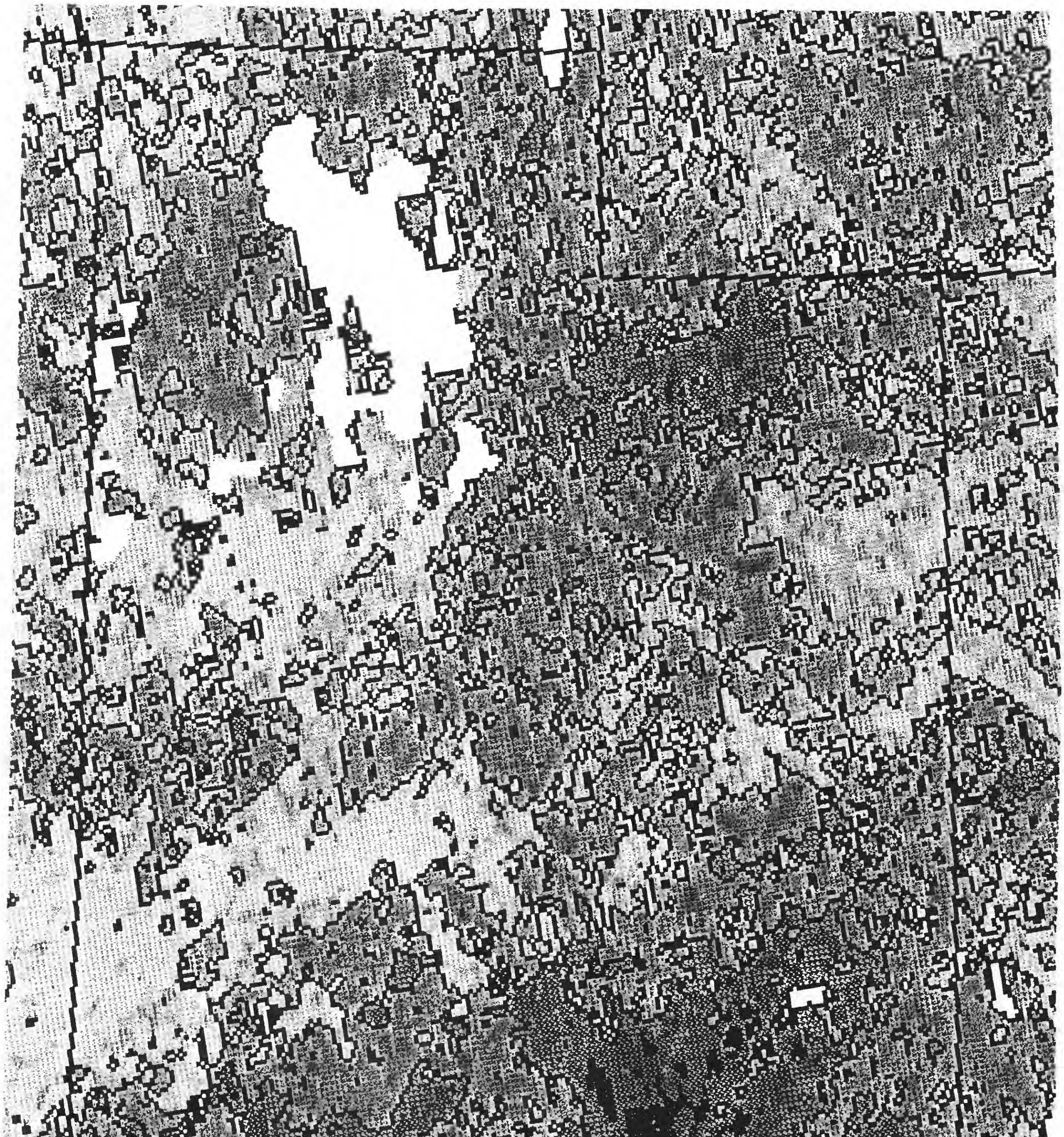

Figure 8. Aerial radiometric map of Utah (after Duval and others, 1989). Contour lines at 1.5 and 2.5 ppm equivalent uranium (eU). Pixels shaded from 0 to 6.0 ppm eU at 0.5 ppm eU increments; darker pixels have lower eU values; white indicates no data.

Wasatch fault zone, which generally runs north-south at the foot of the Wasatch Range, and small geothermal areas also have the potential to produce elevated indoor radon. However, even in areas underlain by rocks known to contain uranium, other mitigating factors such as soil porosity and permeability or ground-water levels locally may interact to produce an environment that does not have elevated indoor radon levels.

On the Colorado Plateau, aerial radiometric data (fig. 8) and indoor radon data (fig. 6) suggest that several rock formations have the potential to contribute to elevated indoor radon levels. Outcrops of the Lower Permian Cutler Formation, Upper Triassic Chinle Formation, and the Upper Jurassic Morrison Formation, all of which contain significant uranium ore deposits, have the potential to generate elevated levels of indoor radon even in areas that do not contain uranium at economic concentrations. In addition to these known uranium-producing formations, several other formations warrant consideration. Dark marine strata of the Upper Mississippian and Lower Pennsylvanian Manning Canyon Shale along the Wasatch Range; marine phosphatic limestones of the Lower Permian Phosphoria Formation on the southeastern flank of the Uinta Mountains; Cretaceous marine shales that occur on the southern flank of the Uinta Basin, on the northern rim of the San Rafael Swell, in the northern Henry Basin, and on the southeastern flank of the Uinta Mountains; Jurassic sedimentary rocks at the northern end of the Henry Basin; Tertiary continental rocks in the southern Uinta Basin; Tertiary volcanic rocks in the Marysvale volcanic field and smaller adjacent volcanic areas that trend from the Colorado Plateau to the Basin and Range, all are known to contain uranium in concentrations above background and have the potential to generate elevated indoor radon concentrations. Although these rock units are not specifically labelled on the geologic map (fig. 2), the areas identified by Sprinkel (1987, 1988) and by Sprinkel and Solomon (1990a, 1990b) that contain these units are shown on figure 9 and can be compared to more detailed geologic maps of Utah (Hintze, 1975, 1980).

In the Wasatch Range and the Uinta Mountains, the aerial radiometric data (fig. 8) indicate relatively low eU (equivalent uranium) readings. However, along the Wasatch Front, the aerial radiometric data indicate several anomalies that may be attributable to the proximity of uranium-bearing quartz monzonite bedrock, to porous and permeable Pleistocene to Holocene lacustrine, lacustrine-deltaic, and alluvial fan deposits shed from steep mountain canyons and eroded from uranium-bearing bedrock such as the quartz monzonite, the Manning Canyon Shale, or Permian Phosphoria Formation, or to the proximity of the Wasatch fault zone.

In the Basin and Range, much of the area has an anomalously high eU signature on the aerial radiometric map (fig. 8). Small areas associated with Precambrian granites and Tertiary volcanic rocks and granites have very high eU signatures, as do many of the Tertiary and Quaternary basin fills. Locally, individual rock formations may contribute to elevated indoor radon, but the scale of the maps and available geologic and aerial radiometric data, coupled with the lack of indoor radon data from this region, are not sufficient to characterize individual rock units.

Each of the three major physiographic provinces in Utah contain areas underlain by rocks that potentially could generate elevated indoor radon levels. Particular attention should be paid to rocks discussed in this section (fig. 9) and to areas previously identifed in other reports (Sprinkel, 1987, 1988; Sprinkel and Solomon, 1990b) as having the potential to generate elevated indoor radon levels. Areas with high uranium contents in soils, particularly in areas where the sediments are derived from rocks with high uranium contents or with relatively low, but uniform uranium contents such as Pleistocene to Holocene lacustrine deposits, Precambrian rocks, and Mississippian to Pennsylvanian black shales, should be regarded as having the potential to produce increased indoor radon levels (Solomon and others, 1991).

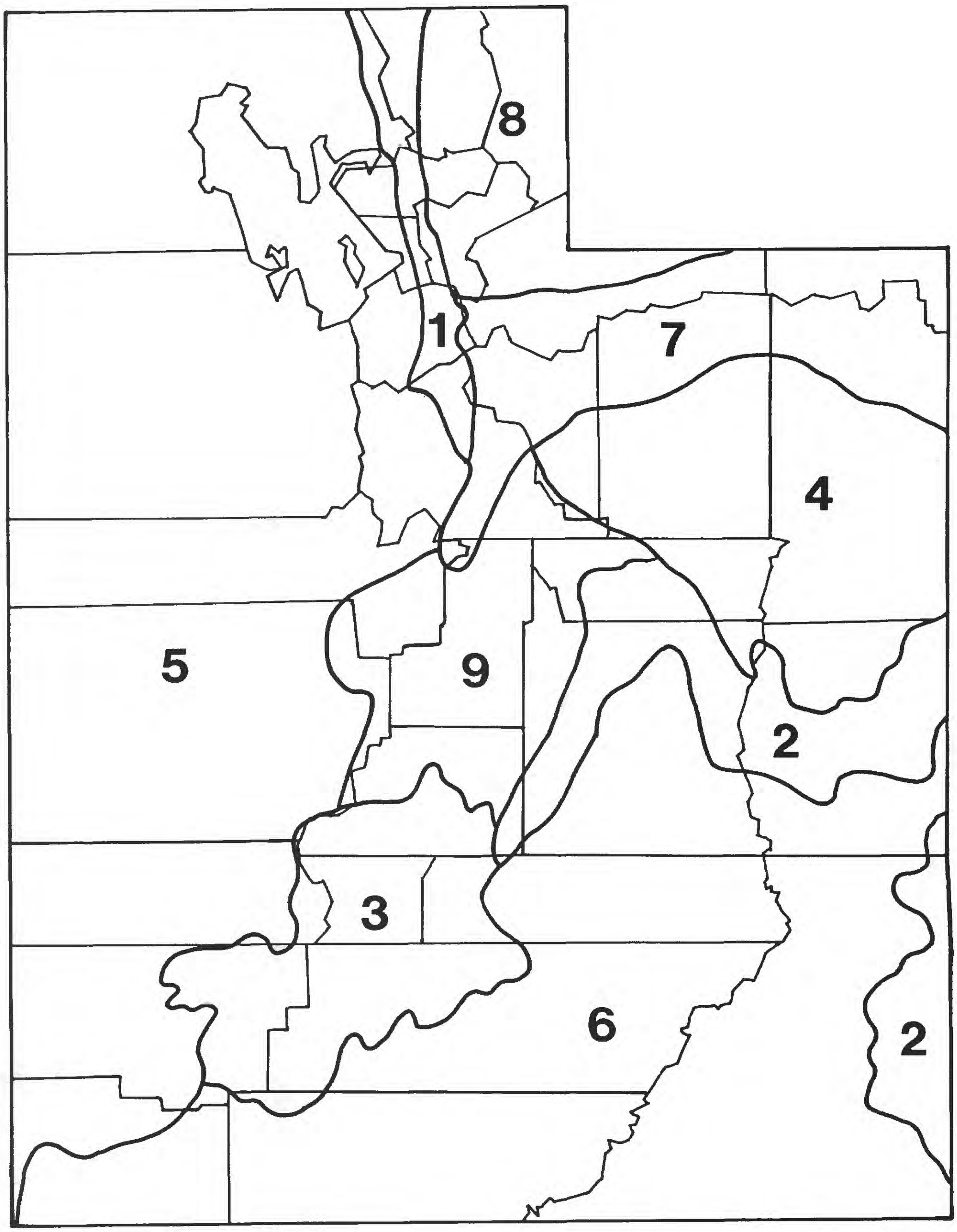

Figure 9. Map showing radon potential areas in Utah (see text and Table 1 for discussion of numbered areas).

SUMMARY

For purposes of assessing the radon potential of the state, Utah is divided into nine general areas (termed Area 1 through Area 9; see fig. 9 and Table 2) and scored with a Radon Index (RI), a semi-quantitative measure of radon potential, and an associated Confidence Index (CI), a measure of the relative confidence of the assessment based on the quality and quantity of data used to make the evaluations. For further details on the ranking schemes and the factors used in the evaluations, refer to the Introduction chapter to this booklet.

Areas 1, 2, 3, and 4 each have high radon potential (RI=14, 13, 13, and 13, respectively) associated with a high confidence index (CI=11) on the basis of high to moderate indoor radon measurements, high surface radioactivity as evidenced by the aerial radiometric data, and the presence of rocks that are known to contain uranium. Area 1 encompasses the Wasatch Range, which contains Precambrian granite and gneiss, Tertiary igneous rocks that have low but consistent uranium concentrations, and major shear zones and faults that can contribute radon. Area 2 is underlain by marine rocks of the Mancos Shale that contain low but consistent concentrations of uranium, and a small area in southeastern Utah that is an extension of the Uravan uranium belt which lies primarily in Colorado. Area 3 is underlain by Tertiary volcanic rocks that have a high aerial radiometric signature. Area 4 is the southern part of the Uinta Basin that contains uranium-bearing Tertiary sedimentary rocks.

Areas 5 through 8 each have moderate radon potential (RI=11, 9,10, and 11, respectively) associated with a high confidence index (CI=10). These areas exhibit low to moderate indoor radon measurements, have low to high surface radioactivity, and contain rocks known to contain little uranium or rocks that are variable in lithology. Area 5 encompasses a part of the Great Basin of the Basin and Range province, and contains variable geology. While many of the mountain ranges have high radiometric signatures, each of the intervening valleys or basins has a characteristically low radiometric signature. The indoor radon data is sparse and generally low, and coupled with the variable geology, the area is rated as moderate. Area 6 includes part of the Colorado Plateau. Both the indoor radon values and the aerial radiometric values are low, and the variable geology indicates a moderate radon potential, although there are small areas of known uranium-bearing and uranium-producing rocks within the area. Area 7 includes the Uinta Mountains. The moderate indoor radon values, coupled with the low aerial radioactivity, and the variable sedimentary geology indicates a moderate radon potential. Area 8 in northeastern Utah is adjacent to the Wyoming Basin province and has moderate indoor radon values, moderate aerial radiometric signatures, and variable geology, indicating a moderate radon potential.

Area 9 has high radon potential (RI=12) associated with a high confidence interval (CI=10). This area exhibits high indoor radon measurements, moderate aerial radioactivity, and variable geology, including Tertiary and Cretaceous sedimentary rocks.

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 <u>not</u> 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 Utah . See figure 9 for locations of areas.

	Area 1		Area 2		Area 3	
FACTOR	RI	CI	RI	CI	RI	CI
INDOOR RADON	3	3	2	3	2	3
RADIOACTIVITY	3	3	3	3	3	3
GEOLOGY	3	3	3	3	3	3
SOIL PERM.	2	2	2	2	2	2
ARCHITECTURE	3	--	3	--	3	--
GFE POINTS	0	--	0	--	0	--
TOTAL	14	11	13	11	13	11
RANKING	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH

	Area 4		Area 5		Area 6	
FACTOR	RI	CI	RI	CI	RI	CI
INDOOR RADON	2	3	2	3	1	3
RADIOACTIVITY	3	3	3	3	1	3
GEOLOGY	3	3	3	2	2	2
SOIL PERM.	2	2	2	2	2	2
ARCHITECTURE	3	--	1	--	3	--
GFE POINTS	0	--	0	--	0	--
TOTAL	13	11	11	10	9	10
RANKING	HIGH	HIGH	MOD	HIGH	MOD	HIGH

	Area 7		Area 8		Area 9	
FACTOR	RI	CI	RI	CI	RI	CI
INDOOR RADON	2	3	2	3	3	3
RADIOACTIVITY	1	3	2	3	2	3
GEOLOGY	2	2	2	2	2	2
SOIL PERM.	2	2	2	2	2	2
ARCHITECTURE	3	--	3	--	3	--
GFE POINTS	0	--	0	--	0	--
TOTAL	10	10	11	10	12	10
RANKING	MOD	HIGH	MOD	HIGH	HIGH	HIGH

RADON INDEX SCORING:

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

Possible range of points = 3 to 17

CONFIDENCE INDEX SCORING:

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

Possible range of points = 4 to 12

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PRELIMINARY GEOLOGIC RADON POTENTIAL ASSESSMENT OF WYOMING

by
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INTRODUCTION

Rocks and soils in many areas of Wyoming have the potential to generate and transport radon in sufficient concentrations to be of concern in indoor air. This radon is a by-product of uranium decay from uranium- and radium-bearing bedrock and the soils and alluvium derived from those rocks. In addition to uranium-bearing bedrock, other factors, such as shears, fractures, and faults in bedrock, alluvial deposits in river valleys derived from bedrock highlands, soil permeability, and the nature and occurrence of groundwater and geothermal areas also have the potential to affect the generation and movement of radon in local areas.

This is a generalized assessment of geologic radon potential of rocks, soils, and surficial deposits of Wyoming. 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

Parts of four major physiographic provinces (fig. 1A) are found in Wyoming: the Southern Rocky Mountains, the Northern Rocky Mountains, the Wyoming Basin, and the Great Plains (Mallory, 1972). The Southern Rocky Mountains extend only into the southeastern part of Wyoming, whereas the Northern Rocky Mountains cover the northwestern quarter of Wyoming (Roberts, 1989). The Wyoming Basin covers one third of south and central Wyoming, and the Great Plains account for about the eastern third of the state (Roberts, 1989). The Great Divide Basin forms a large area of internal drainage within the Wyoming Basin province. The Great Plains province contains a small highland area in northeastern Wyoming that is part of the Black Hills (fig. 1B,C).

Much of Wyoming consists of either mountains, high plains, or basins. The physiography of Wyoming reflects the underlying geology and the effects of erosion and accumulation of sediments. In general, the mountain areas are underlain by large uplifts of igneous and metamorphic rocks, while the small basins and the extensive plains east of the Rocky Mountains are downdropped areas in which great thicknesses of sedimentary rocks and recent sediments have accumulated. Large volumes of volcanic rocks were deposited in and around the Yellowstone Plateau and the Absaroka Mountains in northwestern Wyoming.

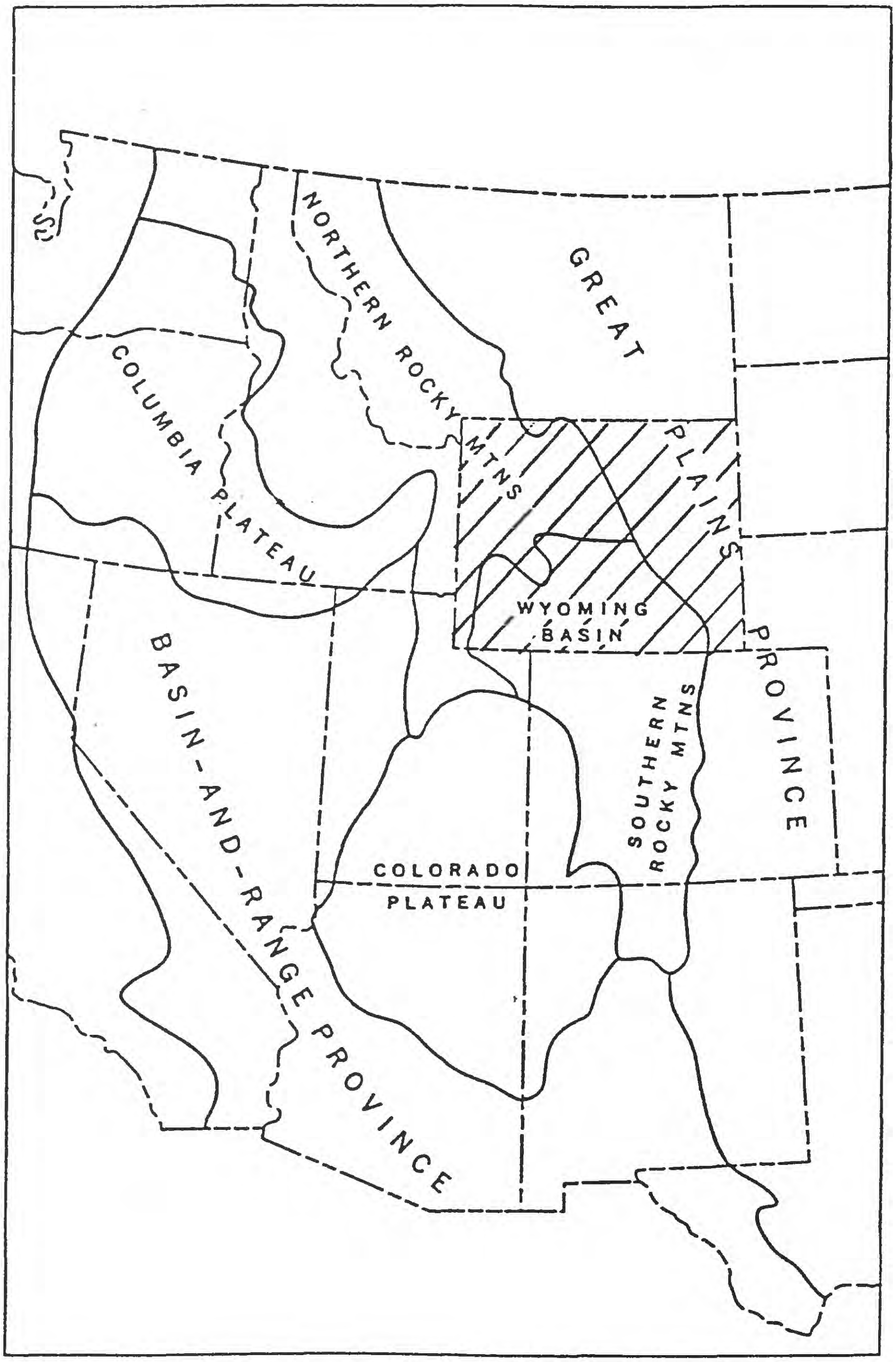


Figure 1A. Major physiographic provinces of the western United States (modified from Mallory, 1972).

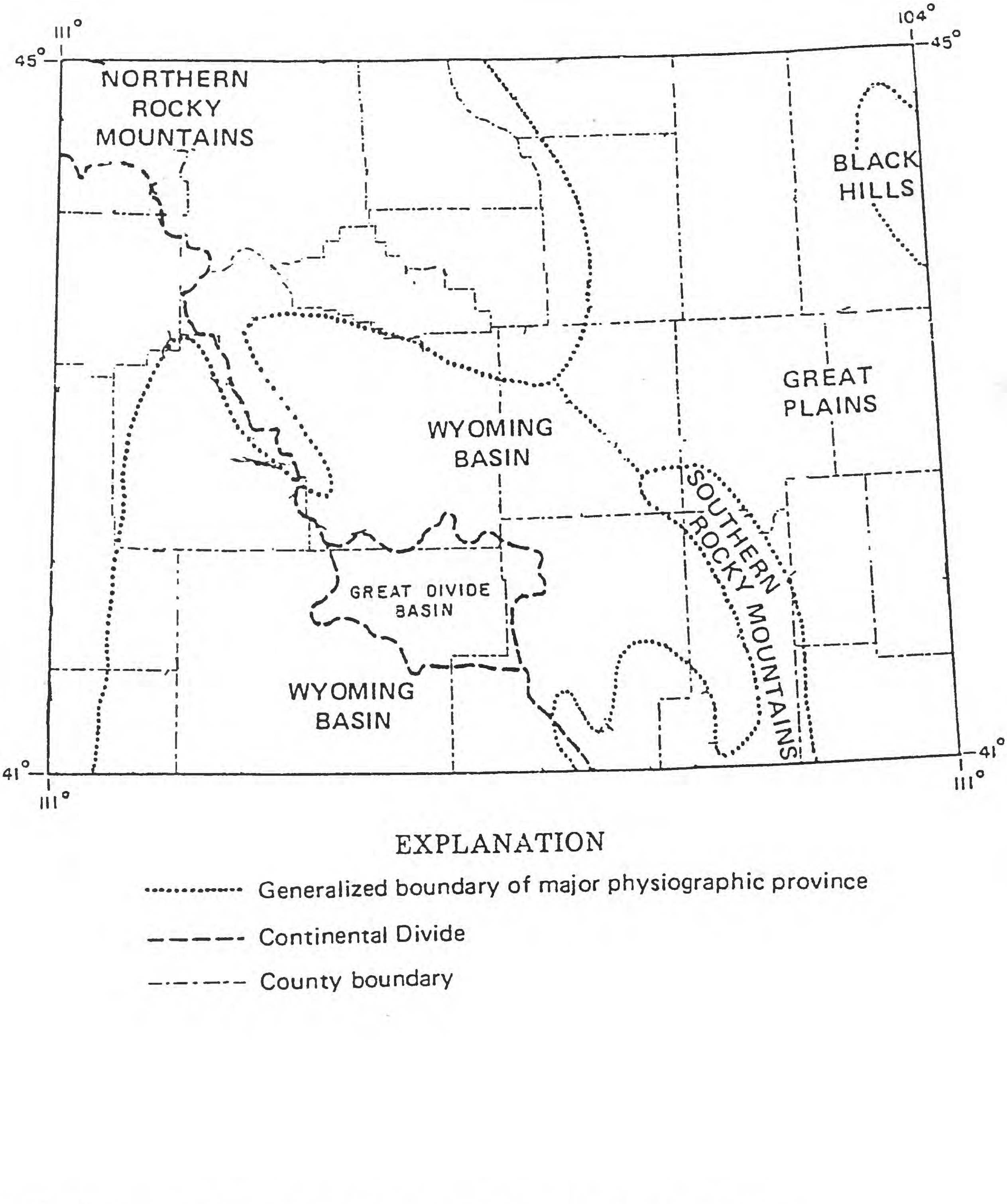


Figure 1B. Physiographic provinces of Wyoming (modified from Roberts, 1989).

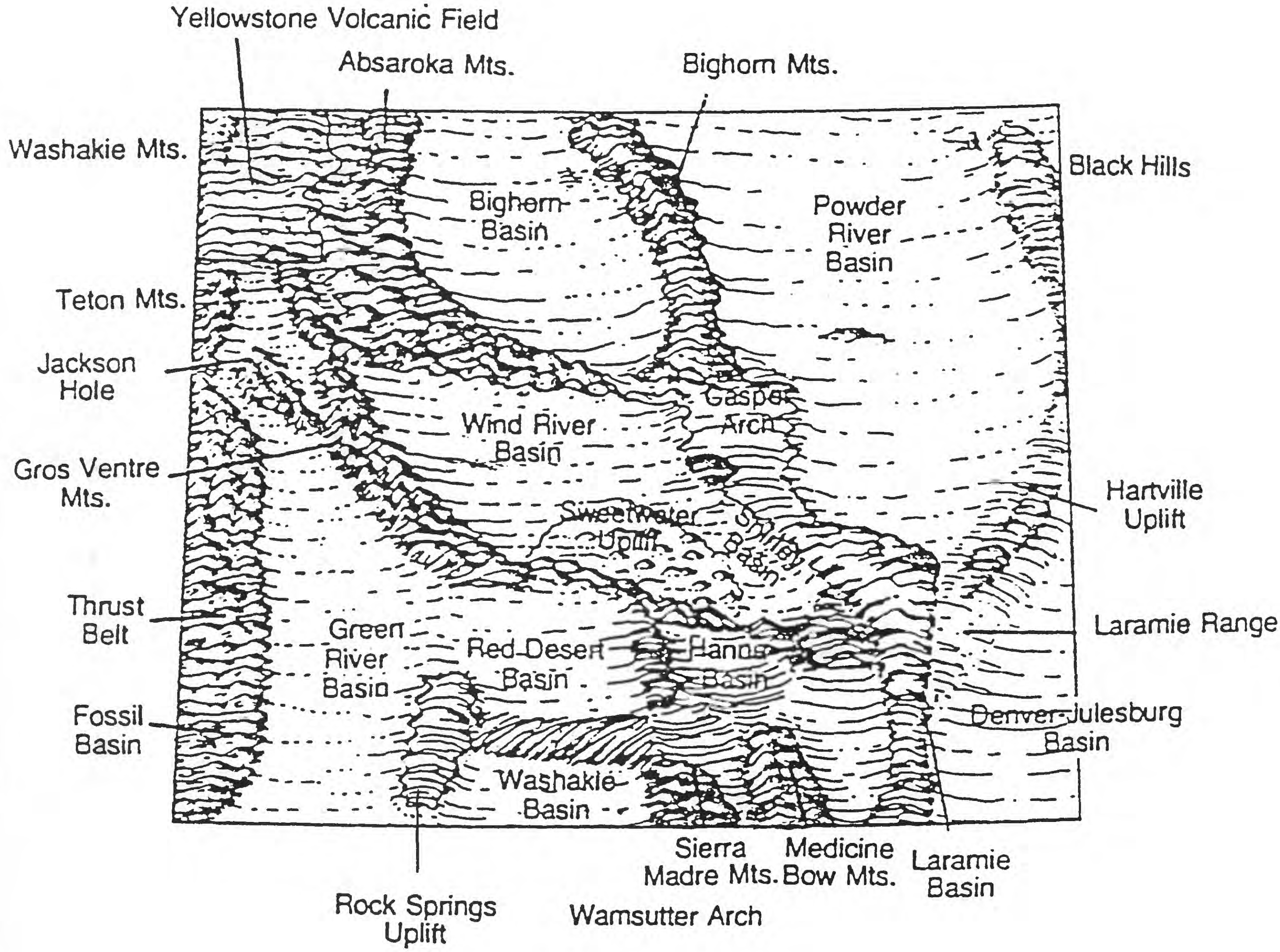


Figure 1C. Basins and uplifts in Wyoming (modified from Lageson and Spearing, 1988).

Wyoming is a very sparsely populated state (fig. 2), with the population centered in a few major cities that are located along the routes of rivers and early exploration. In 1990, Wyoming was the least populated state, with 453,000 people. Land use in Wyoming reflects the geology, topography, climate, and early exploration and settlement in the State. Major industries in Wyoming include grazing, mining, forestry, and recreation. Ranchland is the most widespread land use in the State. Other agricultural uses include non-irrigated and minor irrigated cropland. Mineral and energy resource production have a diverse history in Wyoming. Coal, oil and gas, and uranium production are significant industries in the State. Recreation is a major industry and is shared by both winter activities at ski areas, parks, and mountain recreation sites and by summer recreation and tourism throughout the State.

GEOLOGY

Wyoming's topography and physiography is generally reflected in the geology of the State (fig. 3). The following discussion of the geology of Wyoming is condensed from Mallory (1972), Love and Christiansen (1985), Christiansen (1986), Lageson and Spearing (1988), and Roberts (1989). A detailed geologic map of Wyoming is presented by Love and Christiansen (1985); the reader is encouraged to consult this or other publications for more detailed information.

Rocks ranging in age from Precambrian to Quaternary are exposed in Wyoming (fig. 3). Precambrian rocks in Wyoming are exposed primarily in the cores of mountain ranges in the Rocky Mountains and in the Black Hills. Precambrian rocks include both intrusive igneous and metamorphic rocks. The basins formed between the mountain uplifts expose relatively undeformed Paleozoic to Cenozoic sedimentary rocks, Tertiary through Quaternary extrusive volcanic rocks, and minor Tertiary intrusive rocks.

Paleozoic rocks in Wyoming include Cambrian, Ordovician, Devonian, Mississippian, Pennsylvanian, and Permian strata. Paleozoic sedimentary rocks are generally exposed as bands of uplifted strata around the Precambrian cores of the mountain ranges, which were uplifted during the Laramide orogeny in the Late Cretaceous to Eocene. The Paleozoic rocks dip below the surface into the intermontane basins, and are commonly present at great depths in the basins. Paleozoic rocks are predominantly marine limestone, sandstone, and shale that were deposited in shallow seas, but they also include locally significant conglomerate, sandstone, mudstones, shale, and coal that were deposited in non-marine settings on alluvial fans, within rivers and on floodplains, in swamps and marshes, and as eolian sand dunes.

Mesozoic sedimentary rocks crop out around the margins of the sedimentary basins in a pattern similar to the Paleozoic rocks, having also been uplifted along with the cores of the mountains during the Laramide orogeny. Mesozoic rocks generally underlie the sedimentary basins at moderate depths. Mesozoic strata include Triassic, Jurassic, and Cretaceous rocks. Triassic rocks include marine sandstone and limestone, and extensive continental sandstone, siltstone, and shale. Jurassic rocks consist of primarily eolian, lacustrine, and fluvial sandstone and mudstone. Cretaceous rocks form a thick sedimentary section in Wyoming and include marine shale, sandstone, and limestone that are interspersed with nonmarine sandstone, shale, and coal.

The Cenozoic Era in Wyoming was characterized by extensive continental deposition in nonmarine sedimentary basins and by abundant volcanic activity that had begun in the latest Cretaceous and that continued into the Quaternary. Tertiary and Quaternary sedimentary rocks include conglomerate, sandstone, shale, and coal deposited in alluvial fans, rivers and floodplains, and in scattered marshes and lakes. Intrusive and extrusive volcanic rocks were emplaced in the

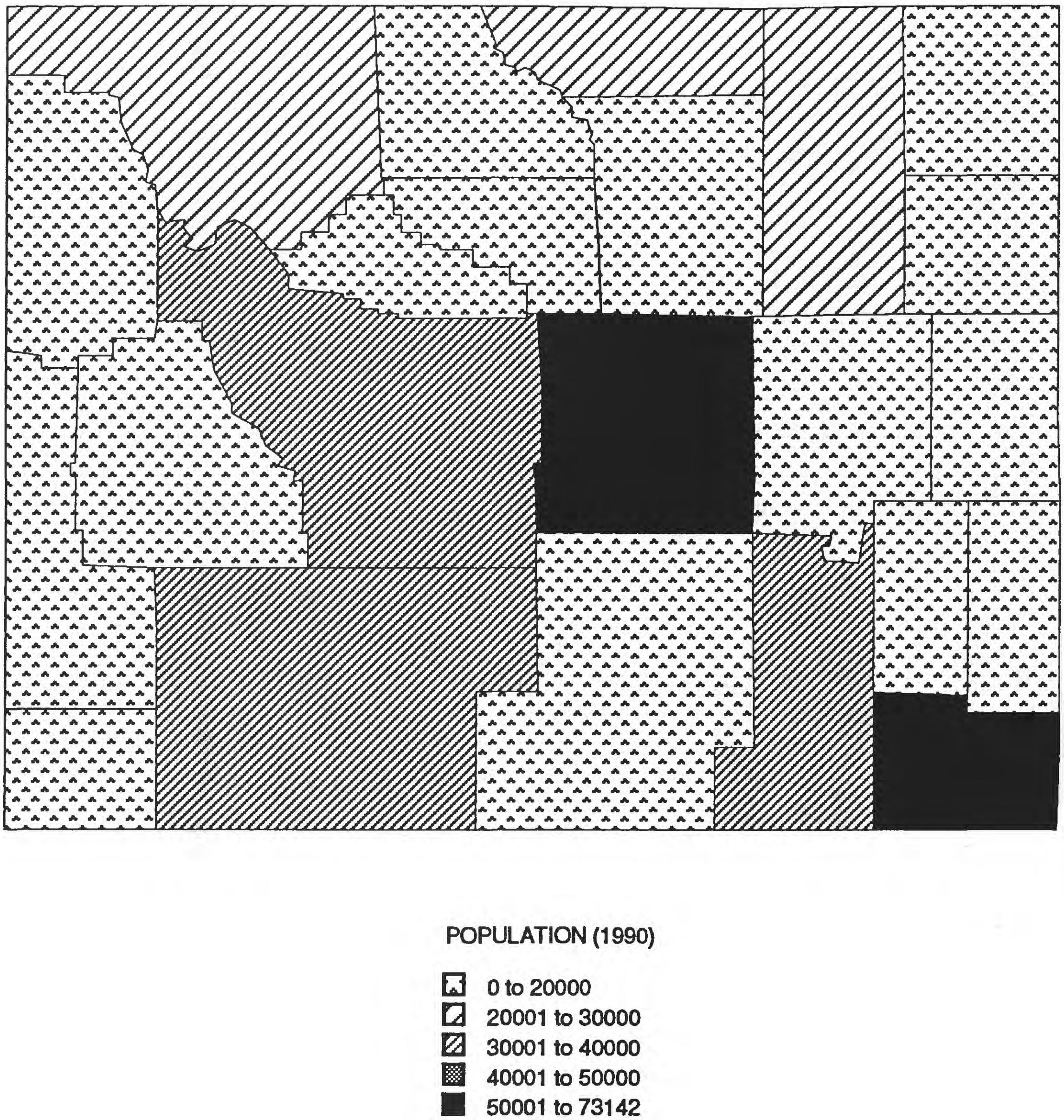


Figure 2. Population of counties in Wyoming (1990 U.S. Census data).

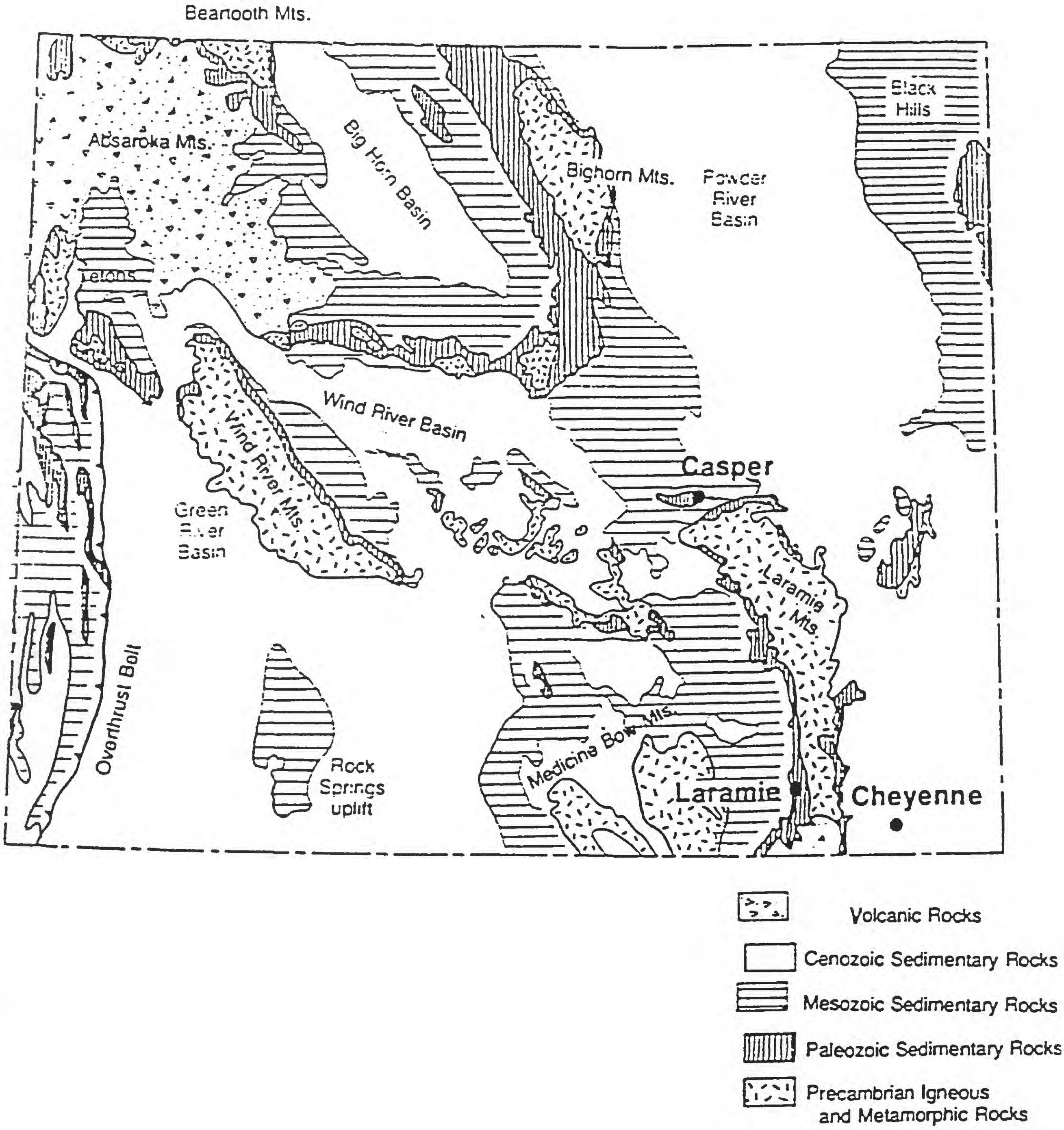


Figure 3. Map showing generalized geology of Wyoming (modified from Lageson and Spearing, 1988).

Black Hills, the Beartooth Mountains, the Absaroka Mountains, and in the vicinity of Yellowstone Plateau and the Teton Mountains.

Several areas of Wyoming contain known uranium deposits or occurrences (fig. 4), and the State has had a variable history of uranium production based on discoveries and fluctuations in the uranium market. Wyoming contains the second largest amount of uranium resources in the United States (U.S. Department of Energy, 1990). Uranium was first documented in Wyoming in 1918 at the Silver Cliff mine near Lusk (Harris, 1985; Lageson and Spearing, 1988; Roberts, 1989). In 1951, J.D. Love of the U.S. Geological Survey discovered uranium at Pumpkin Buttes in northeastern Wyoming. Discoveries in Tertiary sedimentary rocks were exploited to satisfy the price and market guarantees of the U.S. Atomic Energy Comission (AEC). Demand in the late 1960s and 1970s increased in response to the growing nuclear power industry, and production slumped in the 1980s and 1990s paralleling the decrease in demand (Roberts, 1989; J.K. King, Geological Survey of Wyoming, written comm., 1991).

Uranium in Wyoming is present in a variety of rocks. The Fort Union Formation of Paleocene age, the Wasatch and Battle Spring Formations of Paleocene and Eocene age, and the Wind River Formation of early Eocene age host most of the major uranium deposits in Wyoming. The deposits are present in carbonaceous, arkosic, fluvial conglomerate in Crooks Gap, Gas Hills, Powder River Basin, Great Divide Basin, and Shirley Basin.

Several other areas in Wyoming contain significant, but smaller, uranium deposits. In the southern Powder River Basin, uranium deposits in the Teapot Sandstone Member of the Upper Cretaceous Mesaverde Formation are present in fluvial to marginal-marine sandstone. In the Black Hills, uranium occurs in fluvial sandstones of the Paleocene Fort Union Formation and in the underlying Upper Cretaceous Lance Formation. In the Washakie and Sand Wash Basins, uranium is hosted in eolian sandstones of the Oligocene and Miocene Browns Park Formation.

Several other rock units are known to contain minor amounts of uranium in Wyoming (U.S. Department of Energy, 1980), including the Middle Cambrian Flathead Sandstone, Middle and Upper Cambrian Gros Ventre Formation, Middle and Upper Ordovician Bighorn Dolomite, Mississippian Madison Limestone, Middle Pennsylvanian to Lower Permian Tensleep Sandstone, Upper Triassic Crow Mountain Sandstone, Middle and Upper Jurassic Sundance Formation, Upper Jurassic Morrison Formation, Lower Cretaceous Cloverly Formation and Inyan Kara Group, Upper Cretaceous Frontier Fomation and Ericson Sandstone, and Paleocene Hanna Formation. In addition, other rock types such as granites, marine black shales, and phosphates commonly contain low but uniform uranium concentrations. In Wyoming, these rocks include the granitic cores of many of the uplifted Laramide mountain ranges, the Lower Permian Phosphoria Formation, and the Upper Cretaceous Pierre and Cody Shales (in part from J.K. King, Geological Survey of Wyoming, written comm., 1991).

Other geologic settings also may contain uranium. Alluvium and stream sediment derived from granite mountain cores and deposited in river valleys may contain low levels of uranium. Faults and shear zones (Witkind, 1975; Case, 1986; Roberts, 1989) have concentrations of uranium as precipitated minerals or provide pathways for subsequent radon migration from uranium decay. Abnormally radioactive thermal springs are present in Wyoming (Roberts, 1989; J.K. King, Geological Survey of Wyoming, written comm., 1991). The largest concentration of hot springs is in Yellowstone National Park in northwestern Wyoming, where thermal springs and geysers are localized over an intrusion of molten rock in the subsurface.

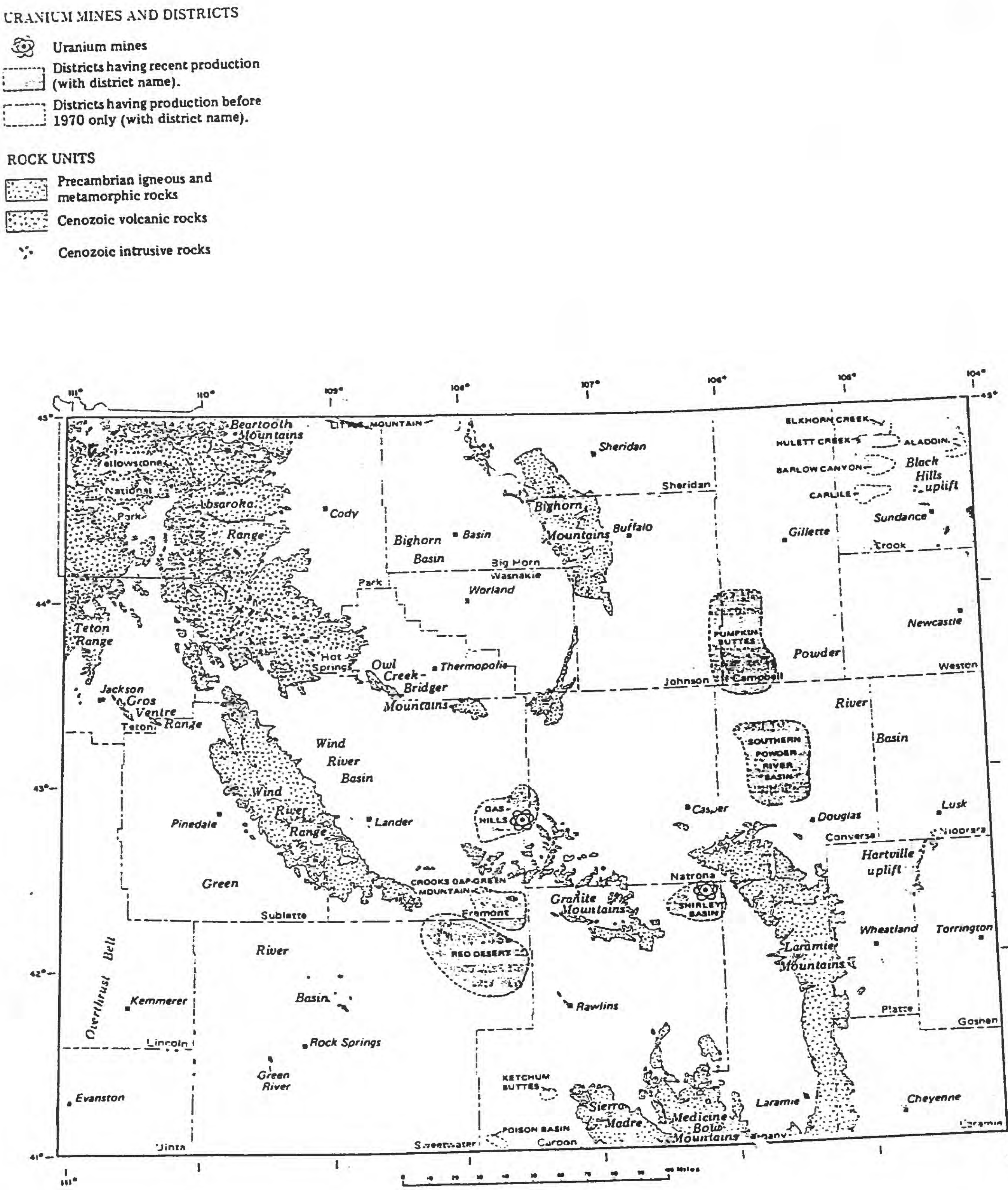


Figure 4. Map showing uranium mines and districts in Wyoming (modified from Roberts, 1989).

SOILS

A generalized soil map of Wyoming (fig. 5) compiled from data in Young and Singleton (1977) and Roberts (1989) shows that soils can be grouped into three general associations. Mountains and mountain valleys contain soils formed from residual materials, alluvium, and glacial deposits or other transported materials. They are generally dark, but some are light colored. Soils in this group are typically assigned to Inceptisols, Mollisols, and Entisols. The second group consists of soils formed in intermontane basins and foothills formed from residual or transported materials in basins, on terraces, or on fans. They are dominantly light colored and are classified as Entisols. The third group includes soils of the eastern Wyoming Plains formed on rolling to steep uplands, terraces, and fans. They are dark to light colored and are classified as Entisols, Aridisols and Mollisols. Data on soil permeability and clay content was not readily available at the scale of the map used in figure 5, but an inspection of typical soil associations and their properties (Young and Singleton, 1977) indicates that many soils in the state have moderate permeability. Soils that formed from alluvium and other transported materials (such as in Star Valley, North Platte River valley, Sake River valley, etc.) tend to have moderate to high permeability; these soils are present in each of those three groups. For the purposes of estimating the radon potential of areas in the State later in this report, each area was considered to have moderate soil permeability.

INDOOR RADON DATA

Screening indoor radon data for Wyoming from the State/EPA Residential Radon Survey (fig. 6, Table 1) was collected during the winter of 1986-87. Data is shown in figure 6 only for those counties in which five or more measurements were made. A map showing the counties in Wyoming (fig. 7) is provided to facilitate discussion of correlations among indoor radon data (fig. 6), geology (fig. 3), aerial radiometric data (fig. 8), and soils (fig. 5). In this discussion, "elevated" indoor radon levels refers to average indoor radon levels greater than 4.0 pCi/L. Of the counties that have more than five measurements, Albany, Goshen, Lincoln, Niobrara, Sheridan, and Weston Counties have county average screening indoor levels greater than 4.0 pCi/L. In Lincoln and Weston Counties, more than 50 percent of the homes tested had screening indoor radon levels greater than 4 pCi/L (Table 1).

Elevated indoor radon averages correlate reasonably well with the geology and physiography of several areas. Counties with the highest indoor radon averages generally coincide with outcrops of sedimentary rocks and alluvium in Laramide basins, and locally with areas of granitic rocks in mountains, and with volcanic rocks, such as the area around Yellowstone National Park. Each of these areas has a corresponding high radiometric signature on the aerial radiometric map (fig. 8).

GEOLOGIC RADON POTENTIAL

A comparison of geology (fig. 3) with aerial radiometric data (fig. 8) and other information provides preliminary indications of rocks, alluvium, and geologic features suspected of producing elevated indoor radon levels. This evaluation parallels the identification of generalized areas for the production of radon by Cannia and Case (1986), and the present study identifies areas based on specific geologic terranes, although at a more general scale than their map. An important consideration is that counties in Wyoming are very large, and major geologic features cut across county boundaries. Wyoming's population is very sparse, and it is concentrated in cities and

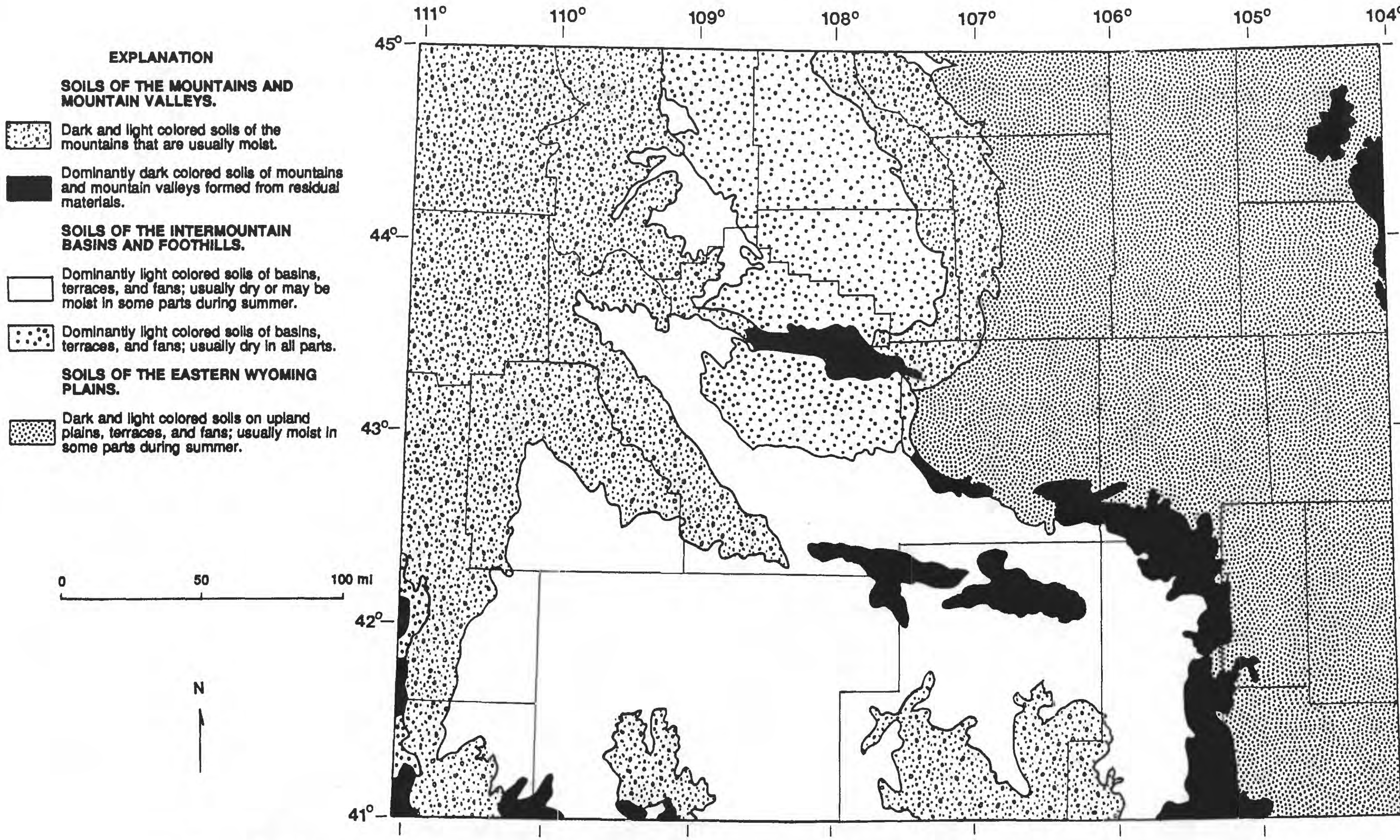
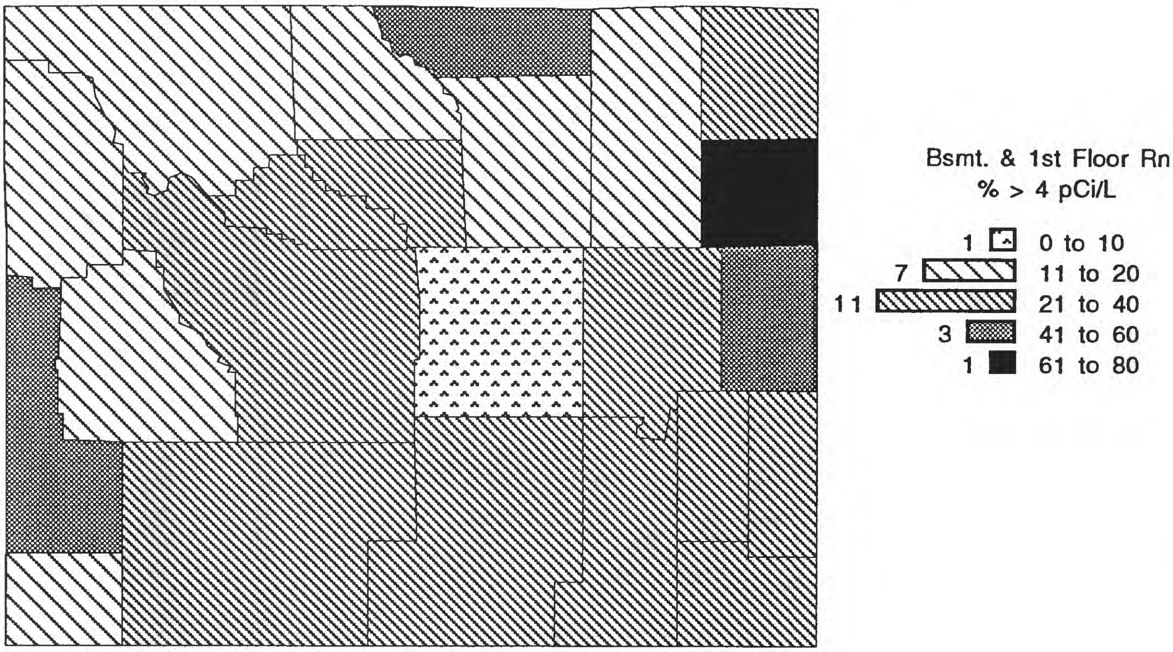


Figure 5. Map showing generalized soils of Wyoming (modified from Roberts, 1989).



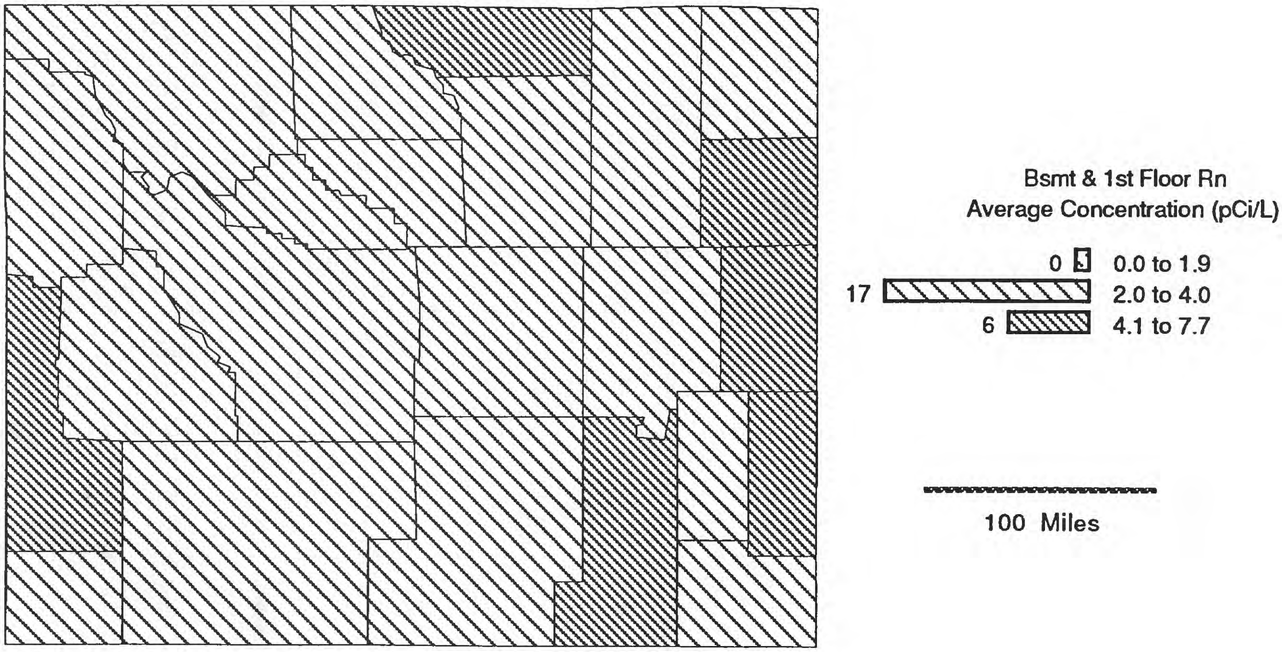


Figure 6. Screening indoor radon data from the EPA/State Residential Radon Survey of Wyoming, 1987-88, for counties with 5 or more measurements. Data are from 2-7 day charcoal canister tests. Histograms in map legends show the number of counties in each category. The number of samples in each county (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 Wyoming 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
ALBANY	52	4.3	2.8	3.0	4.4	26.2	37	2
BIG HORN	26	2.2	1.8	1.8	1.6	6.8	12	0
CAMPBELL	76	3.1	2.0	1.9	3.7	21.6	18	3
CARBON	48	3.2	2.2	2.3	3.2	13.5	21	0
CONVERSE	28	3.6	2.9	3.0	2.5	12.6	36	0
CROOK	20	3.4	2.5	2.5	2.9	12.0	25	0
FREMONT	50	3.6	2.1	2.0	4.3	17.7	24	0
GOSHEN	28	6.1	3.2	3.2	10.7	54.6	36	7
HOT SPRINGS	5	2.6	2.2	1.5	1.7	4.9	40	0
JOHNSON	25	3.1	2.2	1.8	3.1	15.2	20	0
LARAMIE	67	2.9	2.0	2.0	2.9	20.3	22	1
LINCOLN	35	7.7	3.9	4.5	8.6	34.1	51	9
NATRONA	31	2.2	1.8	1.8	1.7	7.8	10	0
NIOBRARA	15	4.9	4.3	3.2	2.7	10.8	47	0
PARK	41	3.0	1.7	1.8	4.6	26.8	12	2
PLATTE	14	2.5	1.5	1.8	2.5	9.3	21	0
SHERIDAN	69	4.3	3.0	3.9	3.3	18.2	49	0
SUBLETTE	21	2.1	1.1	0.9	2.9	12.6	14	0
SWEETWATER	67	3.9	2.6	2.6	4.5	23.3	27	3
TETON	18	3.9	2.0	1.9	6.7	30.0	17	6
UINTA	7	2.0	1.1	0.9	3.2	9.3	14	0
WASHAKIE	18	3.6	1.7	1.5	6.8	30.1	22	6
WESTON	16	5.9	3.9	4.8	6.1	24.4	63	6

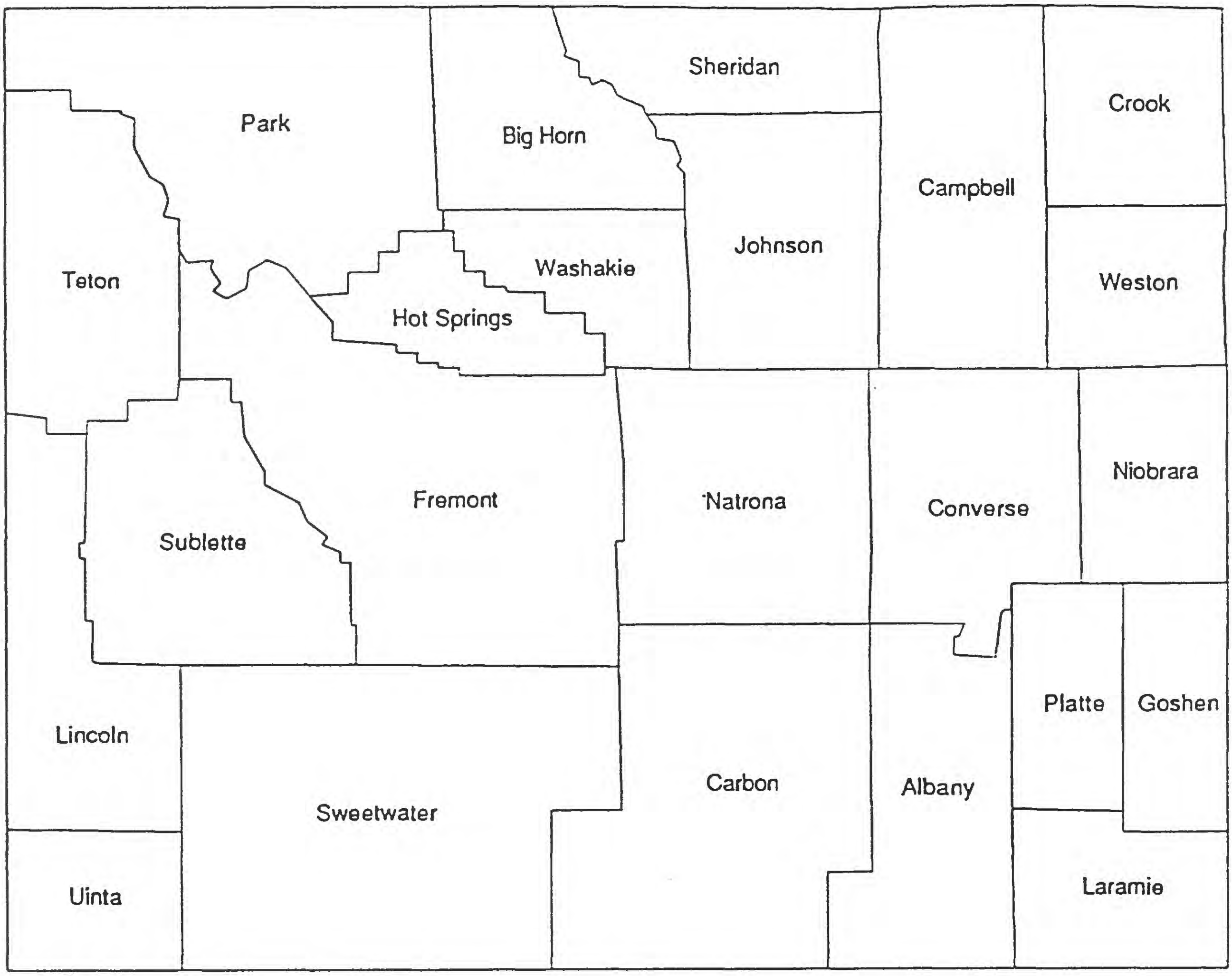


Figure 7. Map showing counties in Wyoming.

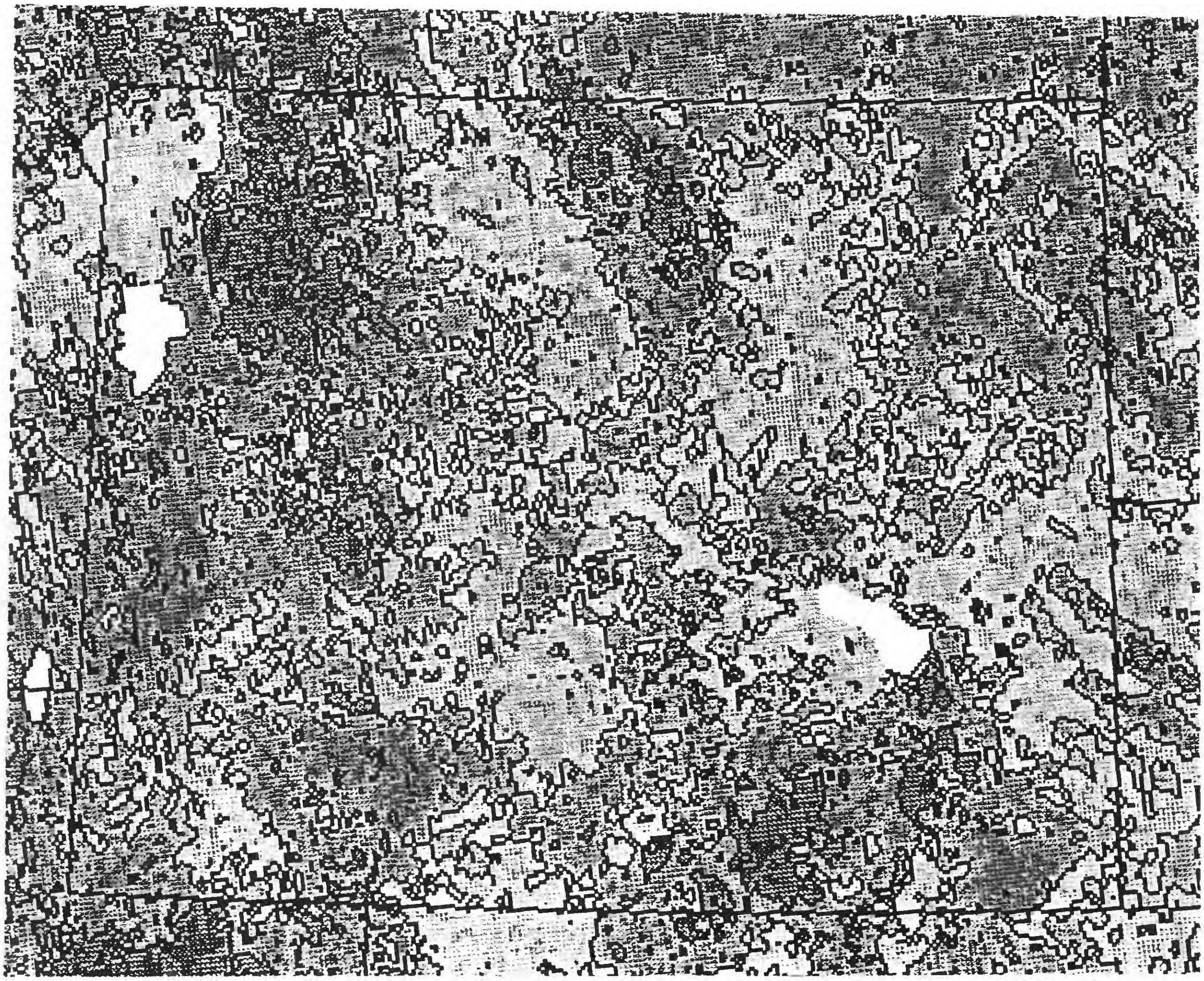


Figure 8. Aerial radiometric map of Wyoming (after Duval and others, 1989). Contour lines at 1.5 and 2.5 ppm equivalent uranium (eU). Pixels shaded from 0 to 6.0 ppm eU at 0.5 ppm eU increments; darker pixels have lower eU values; white indicates no data.

towns; thus the sampling points are widely distributed. This population density and distribution must be considered in evaluating indoor radon data (fig. 6), which are grouped by county.

An overriding factor in the geologic evaluation is the abundance and widespread outcrops in local areas of known uranium-producing and uranium-bearing rocks in Wyoming (figs. 3, 4) (Harris, 1985; Cannia and Case, 1986). Rocks known to contain significant uranium deposits, occurrences, or reserves, in addition to rocks such as granites, marine shales, or phosphates that are known to typically contain low but uniform concentrations of uranium, all have the potential to generate elevated levels of indoor radon. In Wyoming, these rocks include Precambrian metamorphic rocks, granite and gneiss; Cretaceous marine shale and marginal-marine sandstone; Tertiary fluvial sandstone; and Tertiary volcanic rocks.

In Wyoming, uranium deposits and ocurrences are found in the Miocene North Park and Ogallala Formations, the Miocene and Oligocene Browns Park and Arikaree Formations; the Oligocene White River and Chadron Formations, the Eocene Wagon Bed, Green River, and , Wind River Formations; the Eocene and Paleocene Wasatch and Battle Spring Formations; Tertiary volcanic and intrusive igneous rocks; the Paleocene Hanna, Hoback, and Fort Union Formations; the Paleocene and Upper Cretaceous Evanston Formation; the Upper Cretaceous Lance Formation, Fox Hills Sandstone, the Teapot Sandstone Member of the Mesaverde Formation, Frontier Formation, and Ericson Sandstone; the Lower Cretaceous Cloverly Formation, Newcastle Sandstone, and Inyan Kara Group; the Lower Jurassic Morrison Formation; the Upper and Middle Jurassic Sundance Formation; Upper Triassic Crow Mountain Sandstone; the Upper and Lower Triassic Chugwater Formation; the Lower Permian to Middle Pennsylvanian Casper Formation and Tensleep Sandstone; the Lower Permian to Lower Pennsylnanian Minnelusa and Hartville Formations; the Upper and Middle Pennsylvanian Fountain Formation; the Middle Pennsylvanian to Upper Mississippian Amsden Formation; the Upper MIssissippian to Upper Devonian Madison Limestone; the Lower Mississippian Guernsey Formation and Pahasapa Limestone; and the Middle Cambrian Flathead Sandstone. In addition, Precambrian granites in the core of the Laramide mountain ranges, and marine black shales such as the Upper Cretaceous Pierre and Cody Shales; and the Lower Permian Phosphoria Formation commonly contain low but uniform uranium concentrations.

Several areas of Wyoming contain outcrops of one or more of these rock units (figs. 1C, 3, 4) that may contribute to elevated radon levels. The Powder River Basin, Bighorn Basin, Wind River Basin, Shirley Basin, Hanna Basin, Red Desert Basin, Green River Basin, Washakie Basin, Laramie Basin, and Denver-Julesburg Basin all contain extensive outcrops of Cretaceous to Tertiary sedimentary rocks that are known to contain uranium deposits or that exhibit high radiometric signatures on the aerial radiometric map (fig. 8). Precambrian granitic rocks are exposed in the Bighorn Mountains, Teton Mountains, Wind River Mountains, Sierra Madre Mountains, Medicine Bow Mountains, Laramie Range, and the Black Hills. Although granites typically contain low but uniform concentrations of uranium, these granite outcrops do not have a high radiometric signature on the aerial radiometric map (fig. 9). Volcanic rocks of the Yellowstone area have a high aerial radiometric signature, but the volcanic rocks of the Absaroka Mountains do not. In addition, alluvial deposits derived from uranium-bearing bedrock in mountain ranges commonly contribute to elevated radon levels (Duval and others, 1989).

SUMMARY

For the purposes of assessing the geologic radon potential of the State, Wyoming can be divided into seven (7) general areas (termed Area 1 through Area 7; see fig. 9 and Table 2) and scored with a Radon Index (RI), a semi-quantitative measure of radon potential, and an associated Confidence Index (CI), a measure of the relative confidence of the assessment based on the quality and quantity of data used to make the evaluations. For further details on the ranking schemes and the factors used in the evaluations, refer to the Introduction chapter to this booklet. Note that in any specific area, smaller areas of either higher or lower radon potential than that assigned to the entire area may exist because of local factors influencing the generation and transport of radon.

Laramide sedimentary basins (Area 1) collectively have a high geologic radon potential (RI=12) associated with a moderate confidence index (CI=11) on the basis of moderate to high indoor radon measurements, high surface radioactivity as evidenced by aerial radiometric data, and the presence of Cretaceous and Tertiary uranium-bearing and uranium-producing marginal-marine and fluvial sandstones. Laramide uplifts (Area 2) generally have a high radon potential (RI=12) associated with a moderate confidence index (CI=9) on the basis of moderate indoor radon measurements but very sparse data, low aerial radiometric signatures, which are relatively low only as compared to the generally very high readings in the adjacent basins, and the presence of Precambrian granite, which typically has low but consistent uranium concentrations. The Yellowstone volcanic field (Area 3) has a high geologic radon potential (RI=13) and an associated high confidence index (CI=11) on the basis of moderate radon measurements, high surface radioactivity on the aerial radiometric map, the widespread distribution of extrusive volcanic rocks, and an abundance of thermal springs and geysers. Area 4 includes the overthrust belt in western Wyoming and the core of the Black Hills uplift in northeastern Wyoming, both of which expose Late Paleozoic sedimentary or Precambrian igneous rocks; indoor radon measurements are high, but aerial radiometric data is low. Area 4 has a moderate radon potential (RI=11) and an associated high confidence index (CI=10). Area 5 includes Upper Cretaceous marine rocks and has a moderate geologic radon potential (RI=11) associated with a high confidence index (CI=10). Area 6 in southeastern Wyoming includes primarily Tertiary sedimentary rocks with moderate indoor radon and aerial radioactivity data; the area has a moderate radon potential (RI=11) associated with a high confidence index (CI=10). The Absaroka volcanic field (Area 7) has a moderate radon potential (RI=10) and an associated moderate confidence index (CI=7) on the basis of moderate indoor radon measurements but very sparse data, and low aerial radiometric signatures, which may not accurately reflect the average uranium content of the extrusive volcanic rocks.

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 <u>not</u> 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 Wyoming. See figure 9 for locations of Areas. See text for discussion.

FACTOR	Area 1 RI	Area 1 CI	Area 2 RI	Area 2 CI	Area 3 RI	Area 3 CI
INDOOR RADON	2	3	2	3	2	3
RADIOACTIVITY	3	3	2	1	3	3
GEOLOGY	2	3	3	3	3	3
SOIL PERM.	2	2	2	2	2	2
ARCHITECTURE	3	--	3	--	3	--
GFE POINTS	0	--	0	--	0	--
TOTAL	12	11	12	9	13	11
RANKING	HIGH	HIGH	HIGH	MOD	HIGH	HIGH

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

FACTOR	Area 7 RI	Area 7 CI
INDOOR RADON	2	3
RADIOACTIVITY	1	1
GEOLOGY	2	3
SOIL PERM.	2	2
ARCHITECTURE	3	--
GFE POINTS	0	--
TOTAL	10	9
RANKING	MOD	MOD

RADON INDEX SCORING:

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

Possible range of points = 3 to 17

CONFIDENCE INDEX SCORING:

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

Possible range of points = 4 to 12

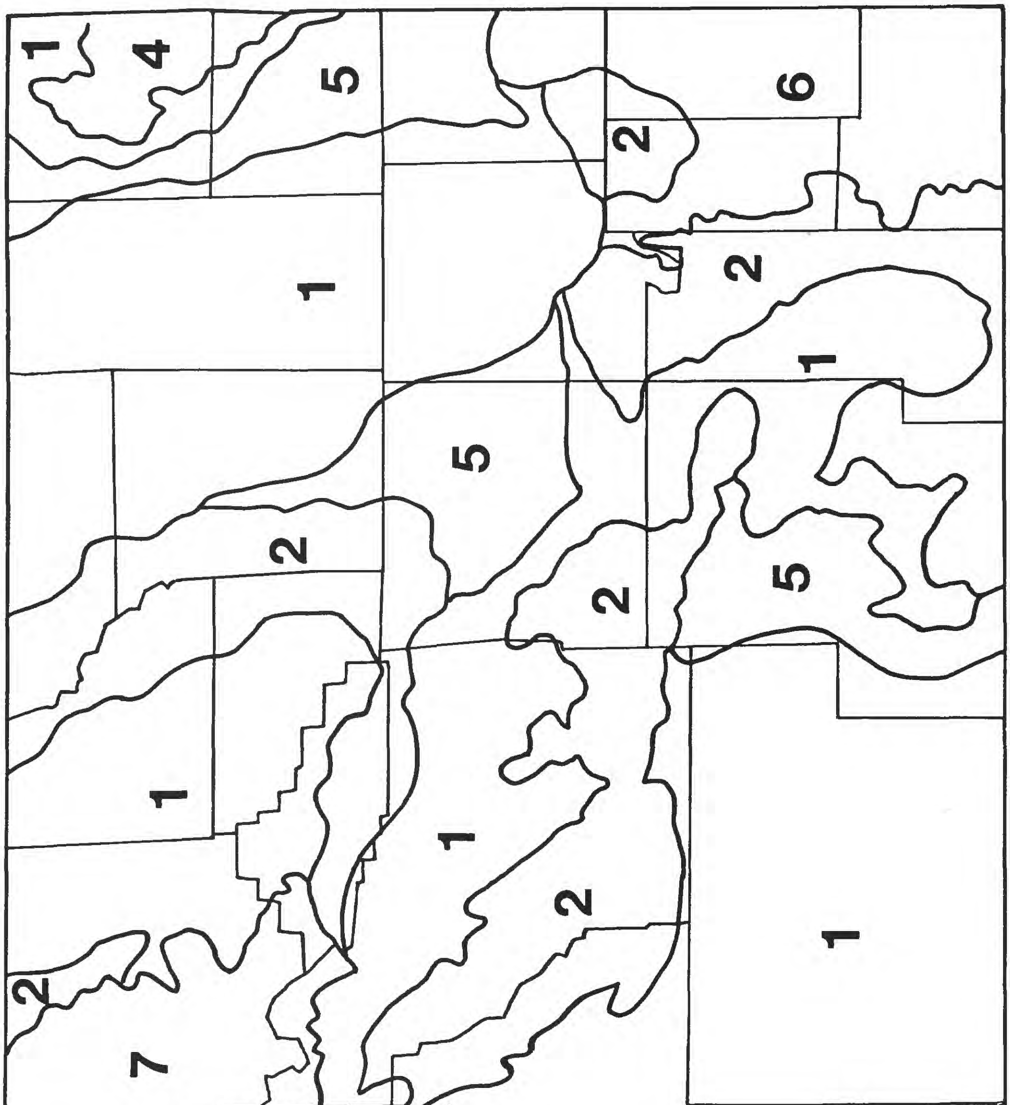


Figure 9. Map showing radon potential areas of Wyoming (see text and Table 1 for discussion of numbered areas).

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