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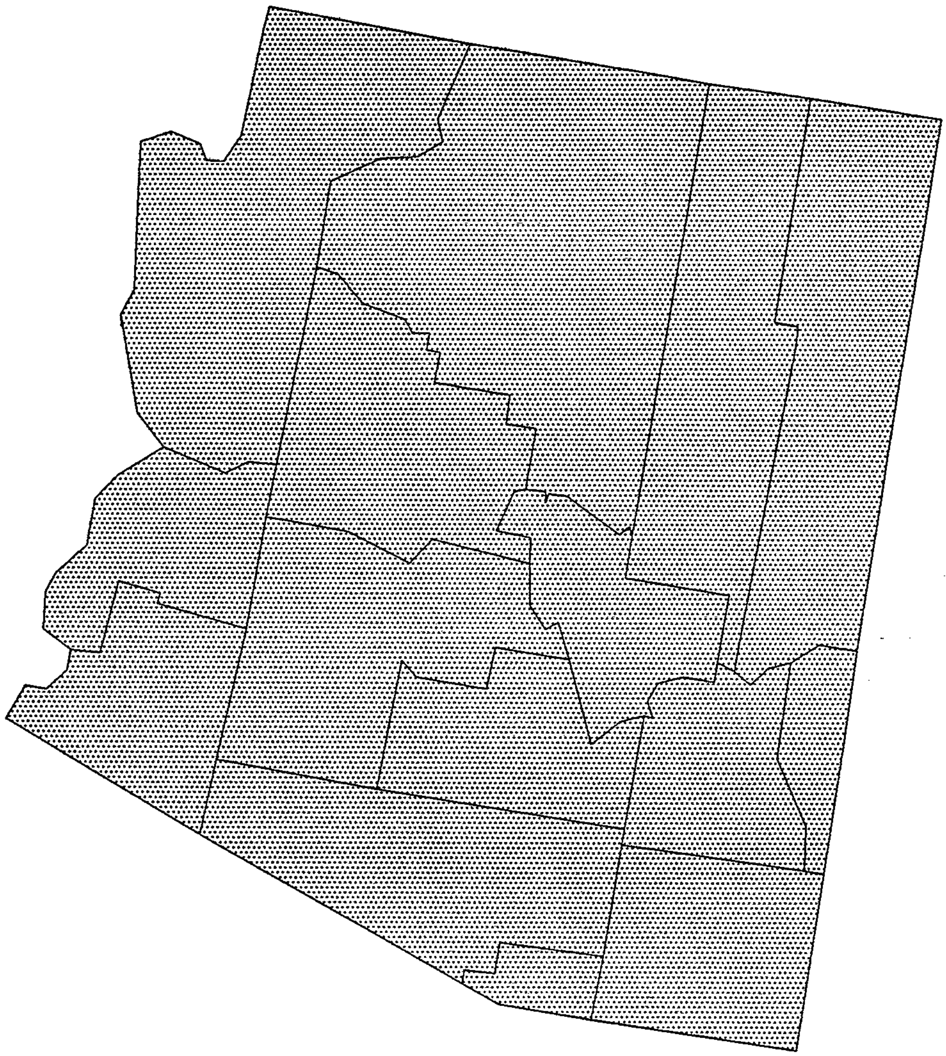
EPA's Map of Radon Zones

ARIZONA



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EPA'S MAP OF RADON ZONES
ARIZONA

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

SEPTEMBER, 1993

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OVERVIEW

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

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

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

BACKGROUND

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

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

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

Purpose of the Map of Radon Zones

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

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

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

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

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

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

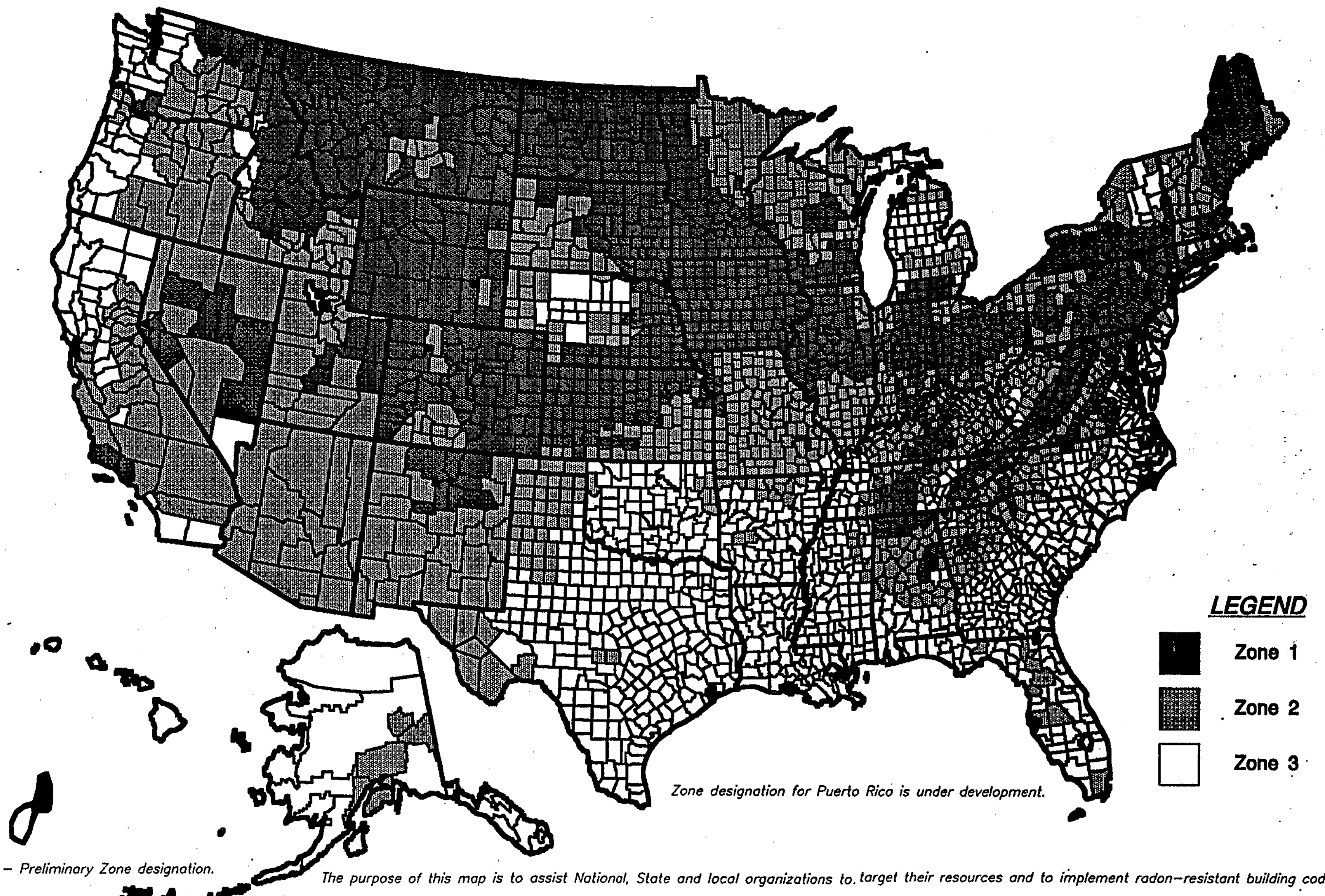
The Map of Radon Zones and its supporting documentation establish no regulatory requirements. Use of this map by State or local radon programs and building code officials is voluntary. The information presented on the Map of Radon Zones and in the supporting documentation is not applicable to radon in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

Development of the Map of Radon Zones

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

Figure 1

EPA Map of Radon Zones



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

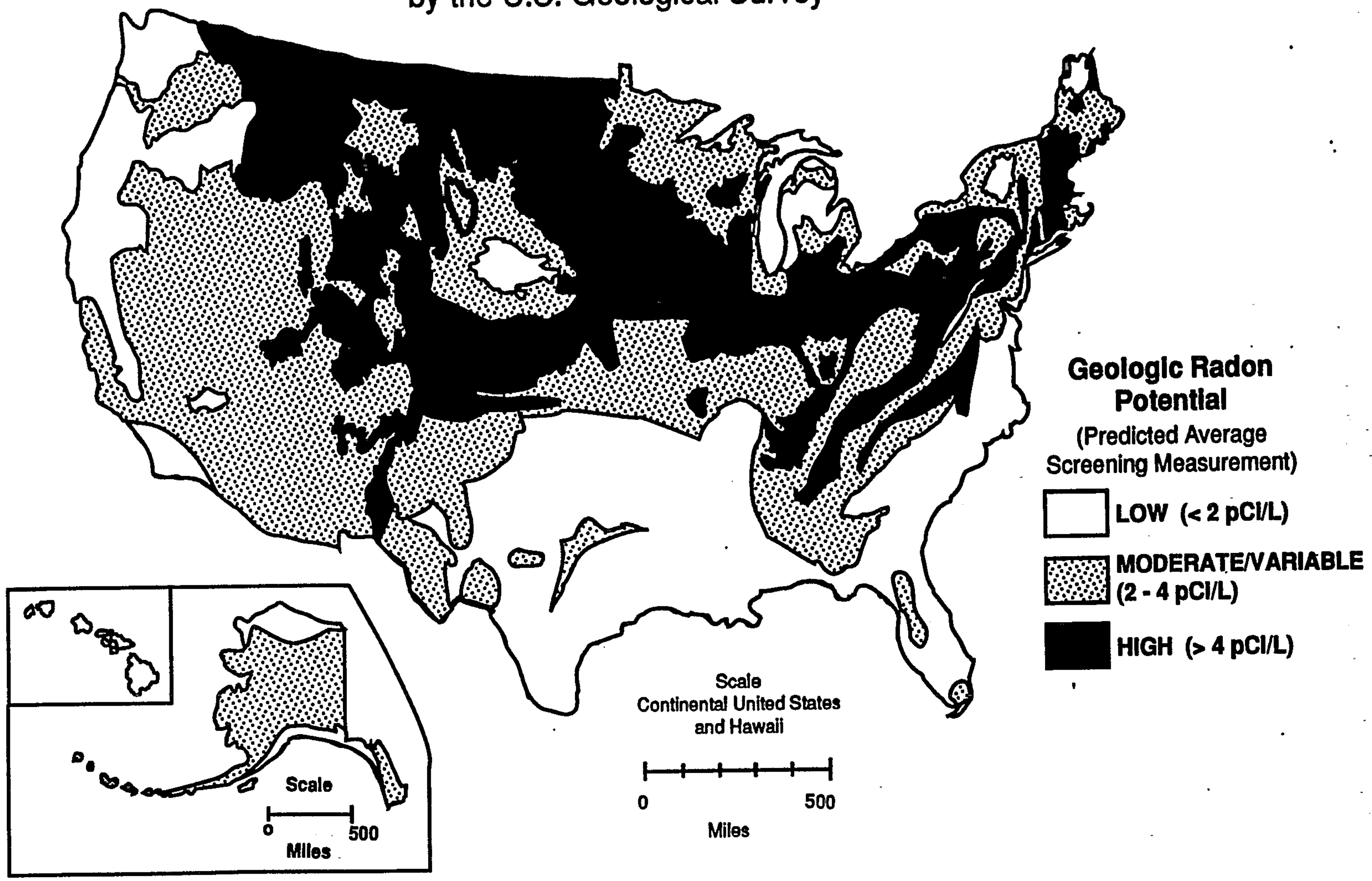
*This map is not intended to be used to determine if a home in a given zone should be tested for radon. Homes with elevated levels of radon have been found in all three zones. **All homes should be tested, regardless of geographic location.***

IMPORTANT: Consult the EPA Map of Radon Zones document (EPA-402-R-93-071) before using this map. This document contains information on radon potential variations within counties. EPA also recommends that this map be supplemented with any available local data in order to further understand and predict the radon potential of a specific area.

Figure 2

GENERALIZED GEOLOGIC RADON POTENTIAL OF THE UNITED STATES

by the U.S. Geological Survey



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potential and some data are available for each of these factors in every geologic province. The province boundaries do not coincide with political borders (county and state) but define areas of general radon potential. The five factors were assigned numerical values based on an assessment of their respective contribution to radon potential, and a confidence level was assigned to each contributing variable. The approach used by USGS to estimate the radon potential for each province is described in Part II of this document.

EPA subsequently developed the Map of Radon Zones by extrapolating from the province level to the county level so that all counties in the U.S. were assigned to one of three radon zones. EPA assigned each county to a given zone based on its provincial radon potential. For example, if a county is located within a geologic province that has a predicted average screening level greater than 4 pCi/L, it was assigned to Zone 1. Likewise, counties located in provinces with predicted average screening levels ≥ 2 pCi/L and ≤ 4 pCi/L, and less than 2 pCi/L, were assigned to Zones 2 and 3, respectively.

If the boundaries of a county fall in more than one geologic province, the county was assigned to a zone based on the predicted radon potential of the province in which most of the area lies. For example, if three different provinces cross through a given county, the county was assigned to the zone representing the radon potential of the province containing most of the county's land area. (In this case, it is not technically correct to say that the predicted average screening level applies to the entire county since the county falls in multiple provinces with differing radon potentials.)

Figures 3 and 4 demonstrate an example of how EPA extrapolated the county zone designations for Nebraska from the USGS geologic province map for the State. As figure 3 shows, USGS has identified 5 geologic provinces for Nebraska. Most of the counties are extrapolated "straight" from their corresponding provinces, but there are counties "partitioned" by several provinces -- for example, Lincoln County. Although Lincoln county falls in multiple provinces, it was assigned to Zone 3 because most of its area falls in the province with the lowest radon potential.

It is important to note that EPA's extrapolation from the province level to the county level may mask significant "highs" and "lows" within specific counties. In other words, within-county variations in radon potential are not shown on the Map of Radon Zones. EPA recommends that users who may need to address specific within-county variations in radon potential (e.g., local government officials considering the implementation of radon-resistant construction codes) consult USGS' Geologic Radon Province Map and the State chapters provided with this map for more detailed information, as well as any locally available data.

Map Validation

The Map of Radon Zones is intended to represent a preliminary assessment of radon potential for the entire United States. The factors that are used in this effort --indoor radon data, geology, aerial radioactivity, soils, and foundation type -- are basic indicators for radon potential. It is important to note, however, that the map's county zone designations are not "statistically valid" predictions due to the nature of the data available for these 5 factors at the county level. In order to validate the map in light of this lack of statistical confidence, EPA conducted a number of analyses. These analyses have helped EPA to identify the best situations in which to apply the map, and its limitations.

Figure 3

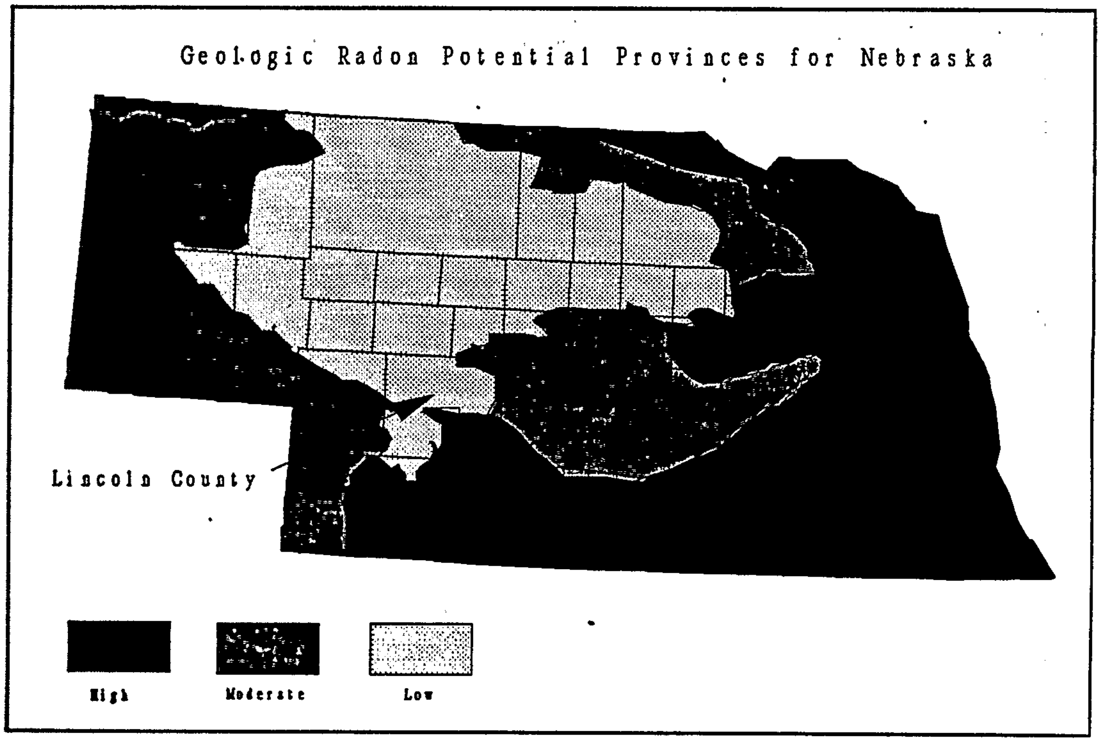
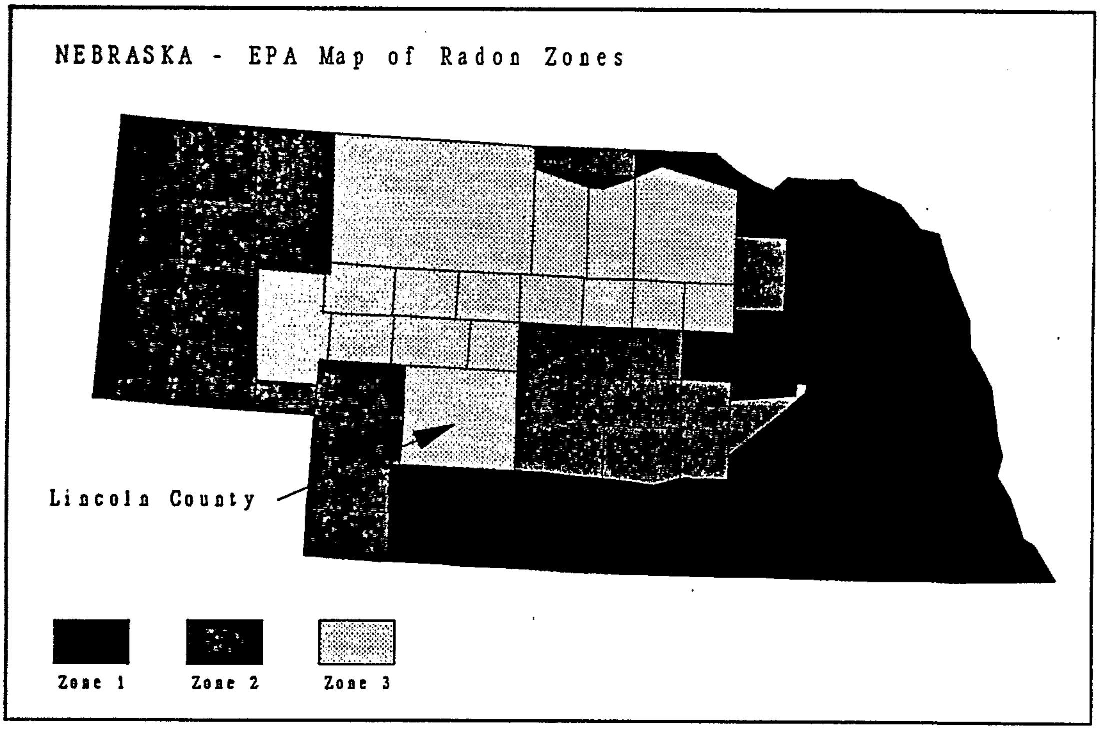


Figure 4



One such analysis involved comparing county zone designations to indoor radon measurements from the State/EPA Residential Radon Surveys (SRRS). Screening averages for counties with at least 100 measurements were compared to the counties' predicted radon potential as indicated by the Map of Radon Zones. EPA found that 72% of the county screening averages were correctly reflected by the appropriate zone designations on the Map. In all other cases, they only differed by 1 zone.

Another accuracy analysis used the annual average data from the National Residential Radon Survey (NRRS). The NRRS indicated that approximately 6 million homes in the United States have annual averages greater than or equal to 4 pCi/L. By cross checking the county location of the approximately 5,700 homes which participated in the survey, their radon measurements, and the zone designations for these counties, EPA found that approximately 3.8 million homes of the 5.4 million homes with radon levels greater than or equal to 4 pCi/L will be found in counties designated as Zone 1. A random sampling of an equal number of counties would have only found approximately 1.8 million homes greater than 4 pCi/L. In other words, this analysis indicated that the map approach is three times more efficient at identifying high radon areas than random selection of zone designations.

Together, these analyses show that the approach EPA used to develop the Map of Radon Zones is a reasonable one. In addition, the Agency's confidence is enhanced by results of the extensive State review process -- the map generally agrees with the States' knowledge of and experience in their own jurisdictions. However, the accuracy analyses highlight two important points: the fact that elevated levels will be found in Zones 2 and 3, and that there will be significant numbers of homes with lower indoor radon levels in all of the Zones. For these reasons, users of the Map of Radon Zones need to supplement the Map with locally available data whenever possible. Although all known "hot spots", i.e., localized areas of consistently elevated levels, are discussed in the State-specific chapters, accurately defining the boundaries of the "hot spots" on this scale of map is not possible at this time. Also, unknown "hot spots" do exist.

The Map of Radon Zones is intended to be a starting point for characterizing radon potential because our knowledge of radon sources and transport is always growing. Although this effort represents the best data available at this time, EPA will continue to study these parameters and others such as house construction, ventilation features and meteorology factors in order to better characterize the presence of radon in U.S homes, especially in high risk areas. These efforts will eventually assist EPA in refining and revising the conclusions of the Map of Radon Zones. And although this map is most appropriately used as a targeting tool by the aforementioned audiences -- **the Agency encourages all residents to test their homes for radon, regardless of geographic location or the zone designation of the county in which they live. Similarly, the Map of Radon Zones should not to be used in lieu of testing during real estate transactions.**

Review Process

The Map of Radon Zones has undergone extensive review within EPA and outside the Agency. The Association of American State Geologists (AASG) played an integral role in this review process. The AASG individual State geologists have reviewed their State-specific information, the USGS Geologic Radon Province Map, and other materials for their geologic content and consistency.

In addition to each State geologist providing technical comments, the State radon offices were asked to comment on their respective States' radon potential evaluations. In particular, the States were asked to evaluate the data used to assign their counties to specific zones. EPA and USGS worked with the States to resolve any issues concerning county zone designations. In a few cases, States have requested changes in county zone designations. The requests were based on additional data from the State on geology, indoor radon measurements, population, etc. Upon reviewing the data submitted by the States, EPA did make some changes in zone designations. These changes, which do not strictly follow the methodology outlined in this document, are discussed in the respective State chapters.

EPA encourages the States and counties to conduct further research and data collection efforts to refine the Map of Radon Zones. EPA would like to be kept informed of any changes the States, counties, or others make to the maps. Updates and revisions will be handled in a similar fashion to the way the map was developed. States should notify EPA of any proposed changes by forwarding the changes through the Regional EPA offices that are listed in Part II. Depending on the amount of new information that is presented, EPA will consider updating this map periodically. The State radon programs should initiate proper notification of the appropriate State officials when the Map of Radon Zones is released and when revisions or updates are made by the State or EPA.

THE USGS/EPA RADON POTENTIAL ASSESSMENTS: AN INTRODUCTION

by
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BACKGROUND

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

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

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

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

RADON GENERATION AND TRANSPORT IN SOILS

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

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

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

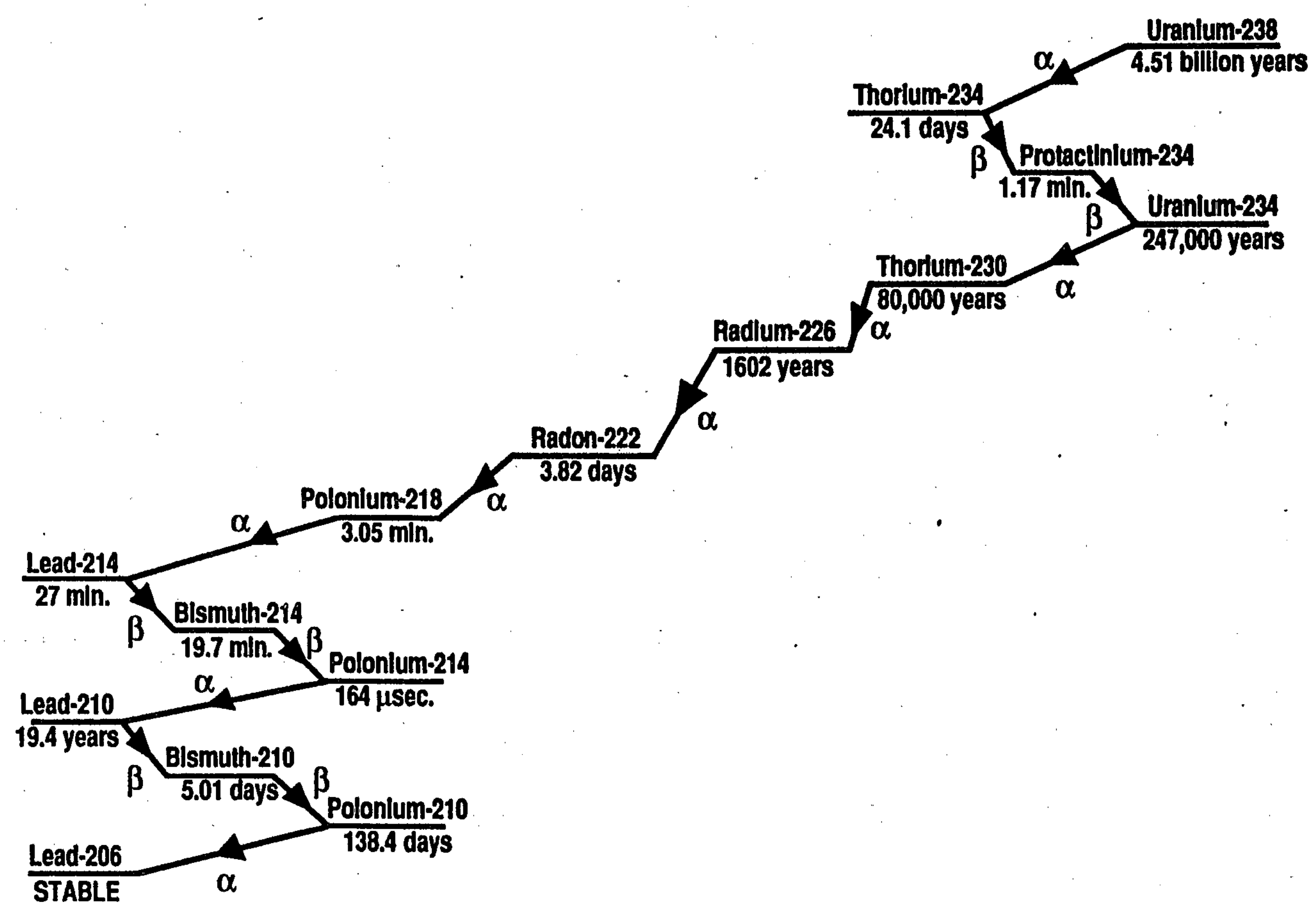

Figure 1. The uranium-238 decay series, showing the half-lives of elements and their modes of decay (after Wanty and Schoen, 1991). α denotes alpha decay, β denotes beta decay.

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

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

Not all radium contained in soil grains and grain coatings will result in mobile radon when the radium decays. Depending on where the radium is distributed in the soil, many of the radon atoms may remain imbedded in the soil grain containing the parent radium atom, or become imbedded in adjacent soil grains. The portion of radium that releases radon into the pores and fractures of rocks and soils is called the emanating fraction. When a radium atom decays to radon, the energy generated is strong enough to send the radon atom a distance of about 40 nanometers (1 nm = 10^{-9} meters), or about $2x10^{-6}$ 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).

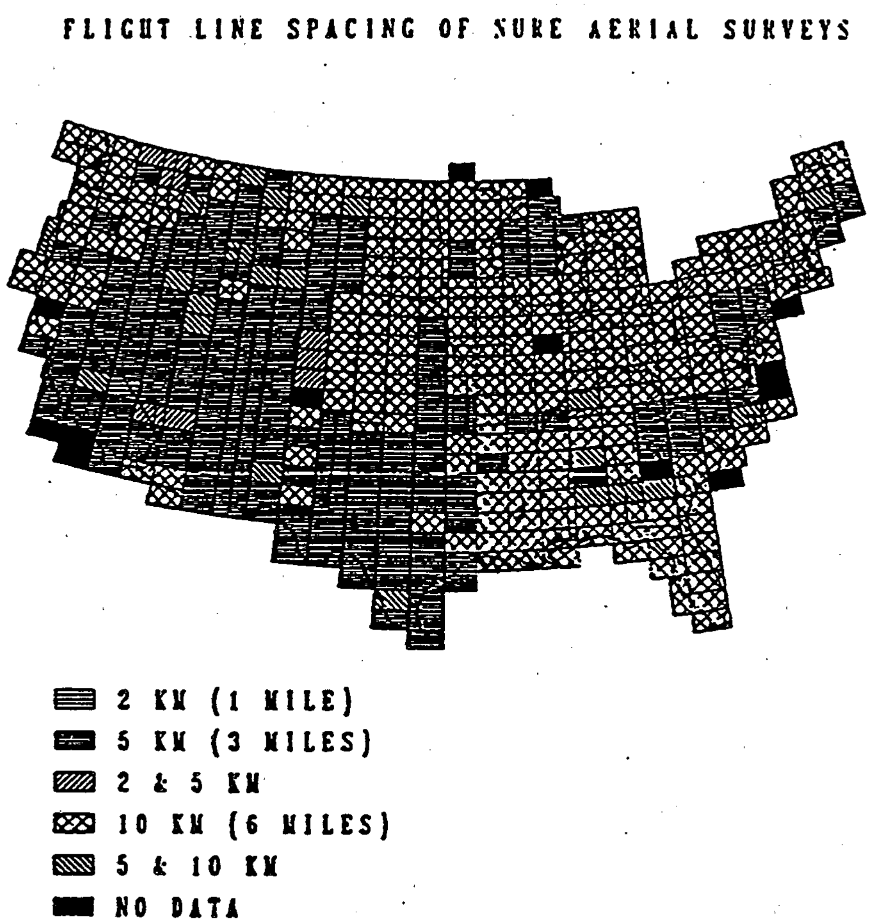

Figure 2. Nominal flightline spacings for NURE aerial gamma-ray surveys covering the contiguous United States (from Duval and others, 1990). Rectangles represent 1°x2° quadrangles.

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

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

SOIL SURVEY DATA

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

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

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

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

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

INDOOR RADON DATA

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

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

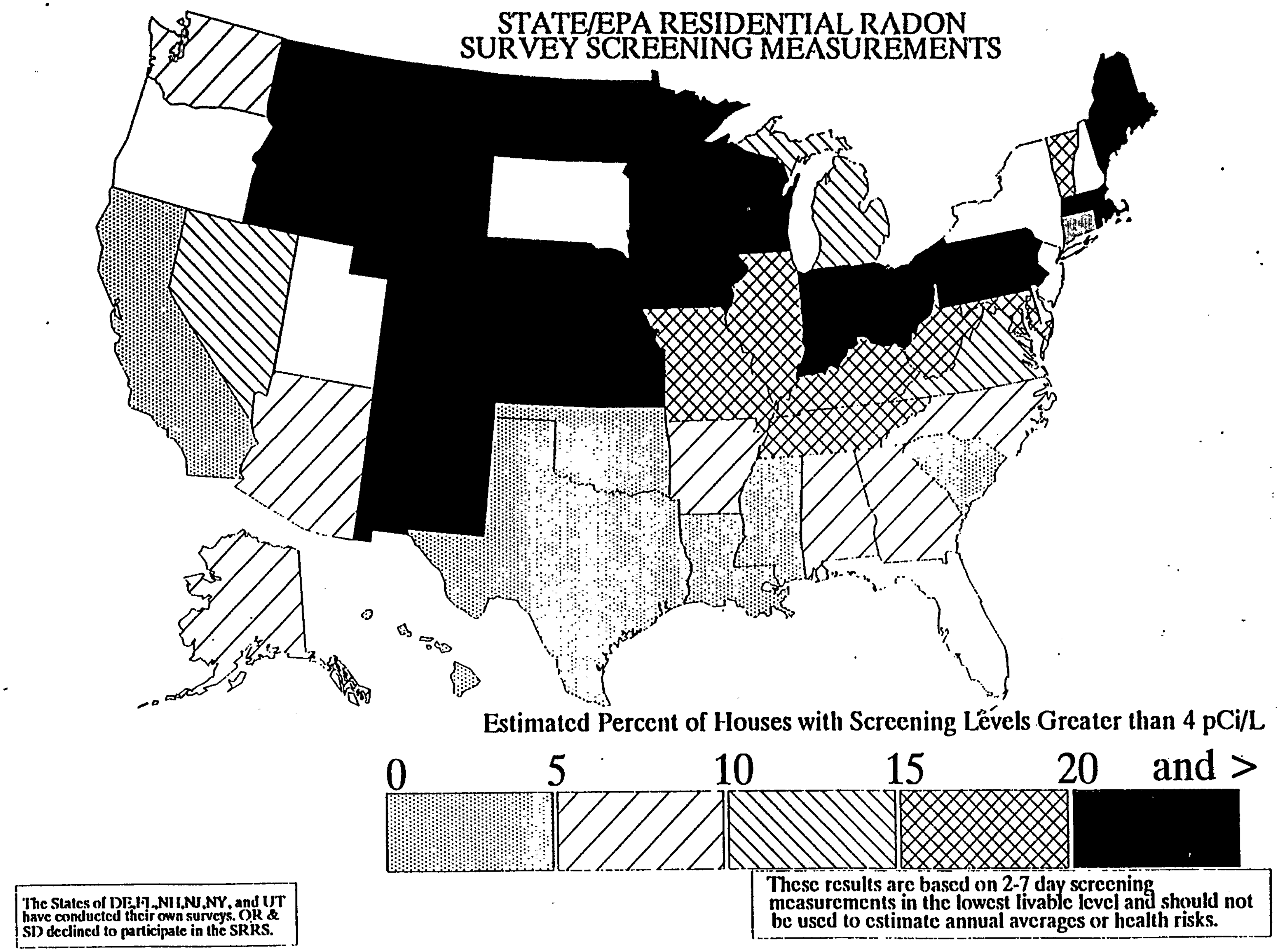

Figure 3. Percent of homes tested in the State/EPA Residential Radon Survey with screening indoor radon levels exceeding 4 pCi/L.

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

RADON INDEX AND CONFIDENCE INDEX

Many of the geologic methods used to evaluate an area for radon potential require subjective opinions based on the professional judgment and experience of the individual geologist. The evaluations are nevertheless based on established scientific principles that are universally applicable to any geographic area or geologic setting. This section describes the methods and conceptual framework used by the U.S. Geological Survey to evaluate areas for radon potential based on the five factors discussed in the previous sections. The scheme is divided into two basic parts, a Radon Index (RI), used to rank the general radon potential of the area, and the Confidence Index (CI), used to express the level of confidence in the prediction based on the quantity and quality of the data used to make the determination. This scheme works best if the areas to be evaluated are delineated by geologically-based boundaries (geologic provinces) rather than political ones (state/county boundaries) in which the geology may vary across the area.

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

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

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

INCREASING RADON POTENTIAL →

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

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

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

SCORING:

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

POSSIBLE RANGE OF POINTS = 3 to 17

TABLE 2. CONFIDENCE INDEX MATRIX

INCREASING CONFIDENCE →

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

SCORING:

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

POSSIBLE RANGE OF POINTS = 4 to 12

included as supplementary information and are discussed in the individual State chapters. If the average screening indoor radon level for an area was less than 2 pCi/L, the indoor radon factor was assigned 1 point, if it was between 2 and 4 pCi/L, it was scored 2 points, and if the average screening indoor radon level for an area was greater than 4 pCi/L, the indoor radon factor was assigned 3 RI points.

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

The geology factor is complex and actually incorporates many geologic characteristics. In the matrix, "positive" and "negative" refer to the presence or absence and distribution of rock types known to have high uranium contents and to generate elevated radon in soils or indoors. Examples of "positive" rock types include granites, black shales, phosphatic rocks, and other rock types described in the preceding "geologic data" section. Examples of "negative" rock types include marine quartz sands and some clays. The term "variable" indicates that the geology within the region is variable or that the rock types in the area are known or suspected to generate elevated radon in some areas but not in others due to compositional differences, climatic effects, localizeddistribution of uranium, or other factors. Geologic information indicates not only how much uranium is present in the rocks and soils but also gives clues for predicting general radon emanation and mobility characteristics through additional factors such as structure (notably the presence of faults or shears) and geochemical characteristics (for example, a phosphate-rich sandstone will likely contain more uranium than a sandstone containing little or no phosphate because the phosphate forms chemical complexes with uranium). "Negative", "variable", and "positive" geology were assigned 1, 2, and 3 points, respectively.

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

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

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

The overall RI for an area is calculated by adding the individual RI scores for the 5 factors, plus or minus GFE points, if any. The total RI for an area falls in one of three categories—low, moderate or variable, or high. The point ranges for the three categories were determined by examining the possible combinations of points for the 5 factors and setting rules such that a majority (3 of 5 factors) would determine the final score for the low and high categories, with allowances for possible deviation from an ideal score by the other two factors. The moderate/variable category lies between these two ranges. A total deviation of 3 points from the "ideal" score was considered reasonable to allow for natural variability of factors—if two of the five factors are allowed to vary from the "ideal" for a category, they can differ by a minimum of 2 (1 point different each) and a maximum of 4 points (2 points different each). With "ideal" scores of 5, 10, and 15 points describing low, moderate, and high geologic radon potential, respectively, an ideal low score of 5 points plus 3 points for possible variability allows a maximum of 8 points in the low category. Similarly, an ideal high score of 15 points minus 3 points gives a minimum of 12 points for the high category. Note, however, that if both other factors differ by two points from the "ideal", indicating considerable variability in the system, the total point score would lie in the adjacent (i.e., moderate/variable) category.

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

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

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

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

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

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

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APPENDIX A
GEOLOGIC TIME SCALE

Subdivisions (and their symbols)						Age estimates of boundaries in mega-annum (Ma)[1]
Eon or Eonothem	Era or Erathem	Period, System, Subperiod, Subsystem		Epoch or Series		
Phanerozoic[2]	Cenozoic[2] (Cz)	Quaternary[2] (Q)		Holocene		0.010
				Pleistocene		1.6 (1.6–1.9)
		Tertiary (T)	Neogene[2] Subperiod or Subsystem (N)	Pliocene		5 (4.9–5.3)
				Miocene		24 (23–26)
			Paleogene[2] Subperiod or Subsystem (Pɛ)	Oligocene		38 (34–38)
				Eocene		55 (54–56)
				Paleocene		66 (63–66)
	Mesozoic[2] (Mz)	Cretaceous (K)		Late	Upper	96 (95–97)
				Early	Lower	138 (135–141)
		Jurassic (J)		Late	Upper	
				Middle	Middle	
				Early	Lower	205 (200–215)
		Triassic (Ŧ)		Late	Upper	
				Middle	Middle	
				Early	Lower	~240
	Paleozoic[2] (Pz)	Permian (P)		Late	Upper	
				Early	Lower	290 (290–305)
		Carboniferous Systems (C)	Pennsylvanian (Ꝑ)	Late	Upper	
				Middle	Middle	
				Early	Lower	~330
			Mississippian (M)	Late	Upper	
				Early	Lower	360 (360–365)
		Devonian (D)		Late	Upper	
				Middle	Middle	
				Early	Lower	410 (405–415)
		Silurian (S)		Late	Upper	
				Middle	Middle	
				Early	Lower	435 (435–440)
		Ordovician (O)		Late	Upper	
				Middle	Middle	
				Early	Lower	500 (495–510)
		Cambrian (Є)		Late	Upper	
				Middle	Middle	
				Early	Lower	~570[3]
Proterozoic (Ᵽ)	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-Є), a time term without specific rank.

[4]Informal time term without specific rank.

APPENDIX B
GLOSSARY OF TERMS

Units of measure

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

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

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

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

Geologic terms and terms related to the study of radon

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

eolian Pertaining to sediments deposited by the wind.

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

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

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

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

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

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

formation A mappable body of rock having similar characteristics.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

placer deposit See heavy minerals

residual Formed by weathering of a material in place.

residuum Deposit of residual material.

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

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

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

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

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

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

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

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

shrink-swell clay See clay mineral.

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

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

slope An inclined part of the earth's surface.

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

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

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

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

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

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

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

uraniferous Containing uranium, usually more than 2 ppm.

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

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

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

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

APPENDIX C
EPA REGIONAL OFFICES

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EPA Region 5 (5AR26)
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State	EPA Region
Alabama	4
Alaska	10
Arizona	9
Arkansas	6
California	9
Colorado	8
Connecticut	1
Delaware	3
District of Columbia	3
Florida	4
Georgia	4
Hawaii	9
Idaho	10
Illinois	5
Indiana	5
Iowa	7
Kansas	7
Kentucky	4
Louisiana	6
Maine	1
Maryland	3
Massachusetts	1
Michigan	5
Minnesota	5
Mississippi	4
Missouri	7
Montana	8
Nebraska	7
Nevada	9
New Hampshire	1
New Jersey	2
New Mexico	6
New York	2
North Carolina	4
North Dakota	8
Ohio	5
Oklahoma	6
Oregon	10
Pennsylvania	3
Rhode Island	1
South Carolina	4
South Dakota	8
Tennessee	4
Texas	6
Utah	8
Vermont	1
Virginia	3
Washington	10
West Virginia	3
Wisconsin	5
Wyoming	8

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EPA REGION 9 GEOLOGIC RADON POTENTIAL SUMMARY

by
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EPA Region 9 includes the states of Arizona, California, Hawaii, and Nevada. 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 9 is given in the individual state chapters. The individual chapters describing the geology and radon potential of the states in EPA Region 9, 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.

The continental part of Region 9 includes thirteen distinct major geologic provinces: the Klamath Mountains, the Cascade Range, the Modoc Plateau, the Sierra Nevada, the Great Valley, the Northern Coast Ranges, the Southern Coast and Transverse Ranges, the Peninsular Ranges, the Colorado Desert, the Basin and Range, the Mojave-Sonoran Desert, the Transition Zone, and the Colorado Plateau (fig. 1). Hawaii forms its own distinctive geologic province. The moderate climate, use of air conditioning, evaporative coolers, or open windows, and the small number of houses with basements throughout much of Region 9 contribute to generally low indoor radon levels in spite of the fact that this area has some of the highest surface radioactivity of any area in the United States.

Maps showing arithmetic means of indoor radon data from State/EPA Residential Radon Surveys of counties in California, Nevada, Arizona, and Hawaii are shown in figure 2. County sacreening indoor radon averages range from less than 1 pCi/L to 4.6 pCi/L. Details of the indoor radon studies are described in the individual state chapters.

Klamath Mountains

The Klamath Mountains (1, fig. 1) are underlain by Paleozoic and Mesozoic metavolcanic and metasedimentary rocks, Jurassic ultramafic rocks, and Mesozoic granitic intrusive rocks. The Klamath Mountains overall exhibit the lowest eU values in the continental part of Region 9. Most areas have less than 0.5 parts per million equivalent uranium (ppm eU). Values range from 0.5 to 1.5 ppm eU in some areas. Only one small area has more than 1.5 ppm eU. The Klamath Mountains are considered to have low radon potential due to the relatively low eU and the high rainfall and soil moisture. Some structures sited on steeply-sloped soils, or excessively well-drained, permeable alluvium may have indoor radon levels exceeding 4 pCi/L.

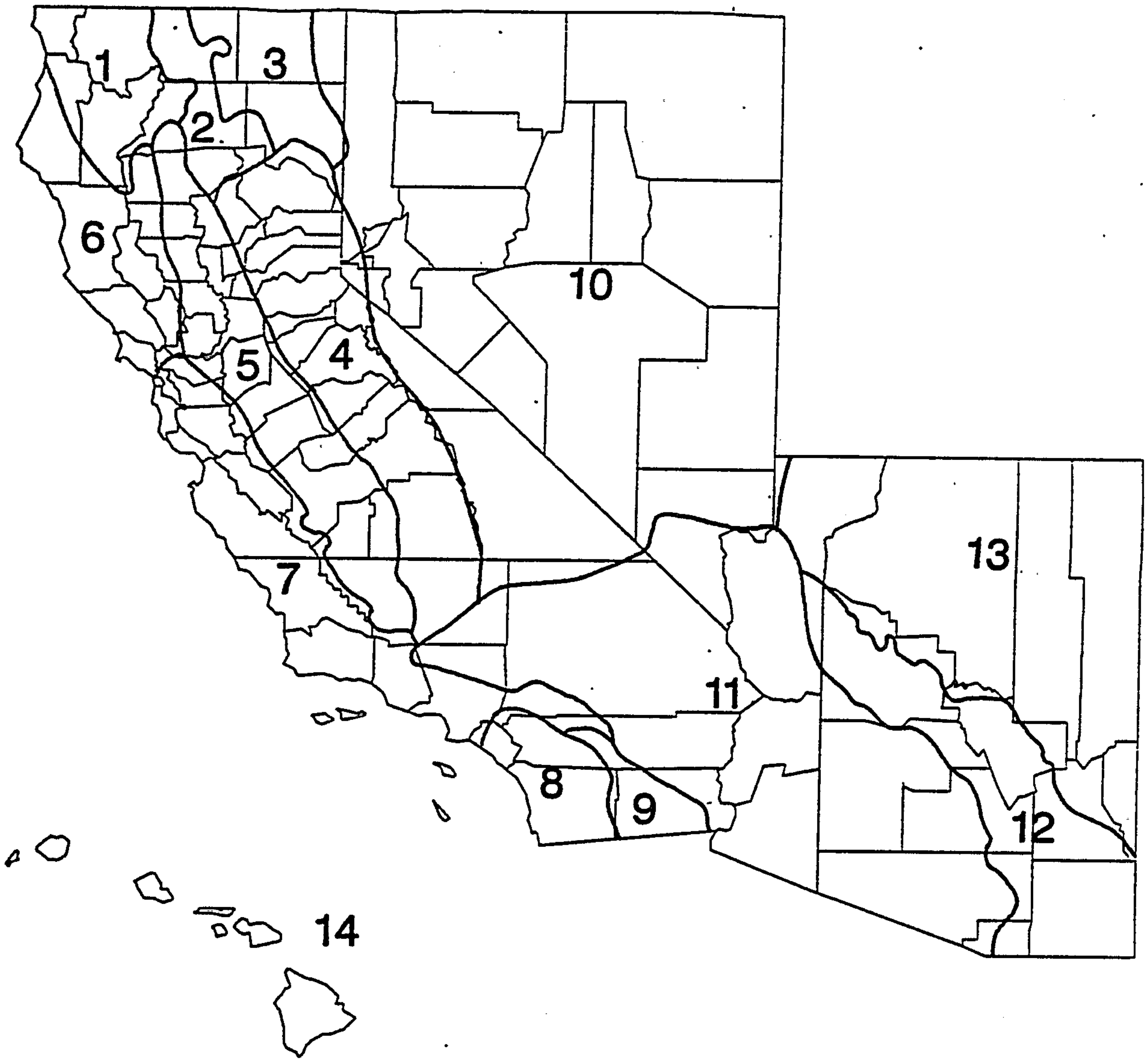

Figure 1- Geologic radon provinces of EPA region 9. 1- Klamath Mountains; 2- Cascade Range; 3- Modoc Plateau; 4- Sierra Nevada; 5- Great Valley; 6- Northern Coast Ranges; 7- Southern Coast and Transverse Ranges; 8- Peninsular Ranges; 9- Colorado Desert; 10- Basin and Range; 11- Mojave-Sonoran Desert; 12- Transition Zone; 13- Colorado Plateau; 14- Hawaii

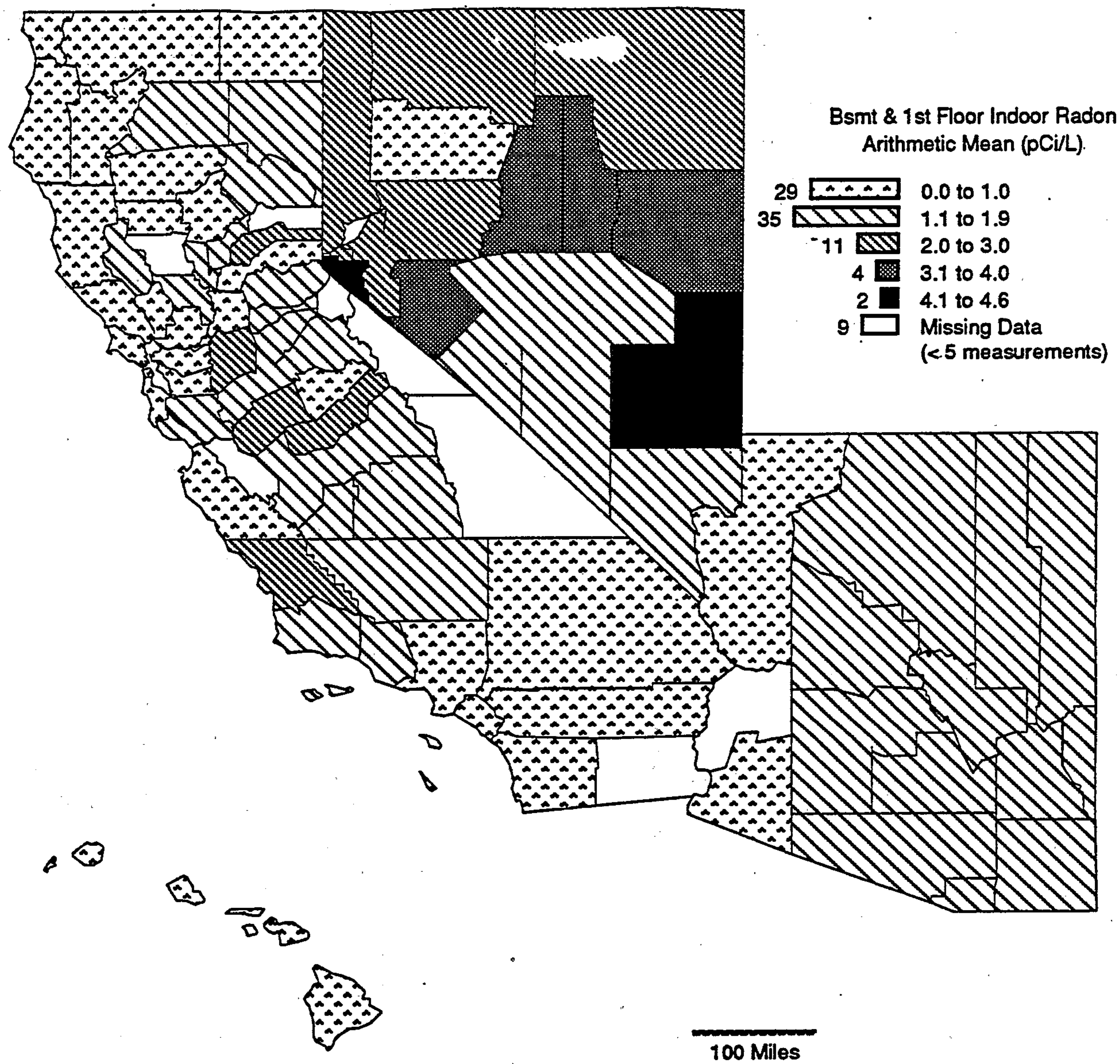

Figure 2. Screening indoor radon data from the State/EPA Residential Radon Survey, for counties with 5 or more measurements in EPA Region 9. Data are from 2-7 day charcoal canister tests. Histograms in map legends show the number of counties in each category. The number of samples in each county may 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.

Cascade Range

The Cascade Range (2, fig. 1) is underlain primarily by Upper Tertiary and Quaternary extrusive rocks, mainly basalt and lesser andesite and rhyolite. In the Cascade Range eU values range generally from less than 0.5 ppm to 1.5 ppm, however local eU values of as much as 4.5 ppm are present where silicic volcanic rocks occur.

The Cascade Range is thought to have low radon potential overall in spite of the scattered areas of moderate eU values. The indoor data are sparse in this lightly populated area. Soils are drier here than in areas closer to the coast and this could contribute to some locally elevated indoor radon levels in spite of relatively low eU. Steep topography and excessively well-drained soils may also contribute to some locally elevated indoor radon levels (for the purposes of this discussion, "elevated", when used in the context of indoor radon, refers to levels greater than 4 pCi/L).

Modoc Plateau

The Modoc Plateau (3, fig. 1) is underlain by Tertiary basalt flows, Upper Tertiary to Quaternary basalt flows, and lesser amounts of andesite and rhyolite. Like the Cascade Range, eU values in the Modoc Plateau generally range from less than 0.5 ppm to 1.5 ppm eU; however, locally higher eU values occur near outcrops of silicic volcanic rocks.

The Modoc Plateau has low radon potential overall in spite of the locally moderate eU signatures. Like the Cascade Range, the indoor data are sparse in this lightly populated area, and soils are drier here than in areas closer to the coast. Steep topography and excessively well-drained dry soils may contribute locally to some elevated radon values indoors.

Sierra Nevada

The northern part of the Sierra Nevada (4, fig. 1) is underlain by Paleozoic and Mesozoic metamorphic rocks with lesser Mesozoic granitic rocks, whereas in the southern part, Mesozoic granitic rocks predominate with lesser outcrop areas of Mesozoic metamorphic rocks. In the northern part, Tertiary volcanic rocks, including basalt, rhyolite, and the sedimentary rocks derived from them, crop out along the crests of many ranges.

The metamorphic rocks and early Mesozoic granites of the northern Sierra Nevada typically have low eU values ranging from less than 0.5 to 1.5 ppm. However, from Lake Tahoe southward the rocks show persistently high eU values, with large areas ranging from 3.0 to greater than 5.5 ppm. Low values occur only where areas of basaltic volcanic rocks, metamorphosed sedimentary rocks, or ultramafic rocks crop out. In the central and southern Sierra Nevada, these lower eU values are restricted to rocks of the western foothills.

The Sierra Nevada has moderate radon potential overall owing to high eU throughout much of the province and the predominance of steeply sloped, well-drained soils that are likely to favor radon transport. Small areas with high potential are most likely in areas of elevated eU south of the latitude of Lake Tahoe.

Great Valley

The Great Valley (5, fig. 1) is underlain by surficial materials composed of Quaternary alluvium derived largely from the Sierra Nevada to the east and the Coast Ranges to the west. Equivalent uranium values for rocks and soils in the Great Valley are influenced greatly by the uranium content of material supplied by the nearby mountains. The northernmost part of the Great Valley has eU values that generally range from 0.5 to 2.5 ppm, except for the Sutter Buttes area which has values of as much as 5.5 ppm eU. From Sacramento southward, the eU signature of the alluvium on the east flank of the valley increases, and eU values locally exceed 5.5 ppm. Alluvial fans derived from less uraniferous rocks in the Sierra foothills locally have lower eU signatures, some as low as 0.5 ppm. Alluvial fans from the Southern Coast Ranges also vary in eU values, but overall they are lower than those derived from the Sierra Nevada. An exception to this occurs in the southernmost Great Valley, where uranium-bearing marine sedimentary rocks of the Southern Coast Ranges contribute alluvium to the valley floor.

The Great Valley has low radon potential overall. The area along the east side of the valley from Sacramento southward, however, appears more likely to have elevated average indoor radon levels and a greater percentage of homes over 4 pCi/L than the rest of the Great Valley.

Northern Coast Ranges

The Northern Coast Ranges (6, fig. 1) are underlain principally by the Franciscan Complex, an assemblage of metamorphosed marine sedimentary rocks and ultramafic rocks. Cretaceous sedimentary rocks lie along the eastern edge of the Northern Coast Ranges and some volcanic rocks occur in the southern part of the Coast Ranges. Numerous major strike-slip faults tend to align the mountain ranges parallel to the Pacific Coast.

Equivalent uranium values of 0.5 to 1.5 ppm characterize the Franciscan rocks of most of the Northern Coast Ranges. Higher eU values are associated with Quaternary and Tertiary extrusive rocks, especially those found north of the San Francisco Bay area, where eU signatures of as much as 4.5 ppm were measured.

The Northern Coast Range province has low radon potential overall. Some indoor radon levels greater than 4 pCi/L are likely to occur in areas of elevated eU along the east side of the southern half of this province, especially where steep, excessively well-drained, or highly permeable soils coincide with the elevated eU in soils.

Southern Coast and Transverse Ranges

The Southern Coast Ranges (7, fig. 1) include the Franciscan and Cretaceous rocks mentioned above, Triassic metamorphic rocks and Mesozoic granitic rocks, and a series of fault-bounded linear basins in which Tertiary marine and continental sedimentary rocks were deposited. The San Andreas fault and other parallel faults pass through the Southern Coast Ranges. Mountain ranges tend to be aligned parallel to these faults.

Equivalent uranium values vary significantly for the Southern Coast Ranges. Values for Franciscan metamorphic rocks, Triassic metamorphic rocks, and Tertiary sedimentary rocks derived from them generally range 0.5-2.0 ppm eU. Mesozoic granitic rocks, Tertiary sedimentary rocks derived from them, and Tertiary marine sedimentary rocks deposited in restricted environments locally exceed 5.5 ppm eU.

The Transverse Ranges are an east-west trending mountain block bordered and transected by several faults, including the San Andreas fault. The eastern part of the Transverse Ranges are underlain by Precambrian metamorphic rocks and Mesozoic granitic rocks, whereas the western part of the Province is underlain principally by Cretaceous to Pliocene marine sedimentary rocks. The Los Angeles Basin, considered part of this physiographic province, is underlain by surficial materials composed primarily of Quaternary alluvium. The Transverse Ranges generally exhibit low eU (1.0-2.0 ppm) in the eastern part, which is underlain by Precambrian metamorphic rocks and Mesozoic intrusive rocks, but in the western Transverse Ranges many of the sedimentary units contain more uranium (as much as 5.5 ppm eU). The western area includes marine sedimentary rock deposited in restricted marine environments favorable for uranium accumulation and continental sedimentary rocks containing uranium occurrences.

The Southern Coast Range and Transverse Ranges have moderate radon potential overall; however, much of the radon potential is associated with areas of elevated radioactivity from Monterey Bay southward in the Coast Range and in the western two-thirds of the Transverse Ranges. Houses sited directly on uranium-enriched marine sedimentary rocks in these two areas, such as the Monterey Formation and the Rincon Shale, are very likely to exceed 4 pCi/L, especially where parts of the home are below grade.

Peninsular Ranges

The Peninsular Ranges (8, fig. 1) are dominated by Mesozoic granitic rocks with lesser Mesozoic metamorphic rocks. Tertiary sedimentary rocks lie along the coast. Mesozoic intrusive rocks of the Peninsular Ranges are generally low in uranium, with eU values ranging 1.0-2.5 ppm. Some areas of Tertiary sedimentary rocks and Mesozoic granitic rocks are more uraniferous. The Peninsular Ranges have low radon potential as indicated by the low to moderate eU across the area. Areas of elevated eU and excessively drained soils in the foothills east of the San Diego metropolitan area may locally yield some elevated radon levels indoors.

Colorado Desert

The Colorado Desert (9, fig.1) is underlain by Quaternary alluvium derived from the adjacent mountains. Equivalent uranium signatures over the Colorado Desert vary significantly. Some Quaternary alluvium derived from rocks in the adjacent Mojave Desert are elevated in eU (>2.5 ppm), but other areas range from 1.0-2.5 ppm eU.

The Colorado Desert province has a low potential for radon indoors.

Basin and Range

The Basin and Range (10, fig. 1) is composed of Precambrian metamorphic rocks, late Precambrian and Paleozoic metamorphosed and unmetamorphosed sedimentary and less abundant igneous rocks, Mesozoic metamorphosed and unmetamorphosed volcanic and sedimentary rocks, Mesozoic and Tertiary intrusive rocks, and Tertiary sedimentary and volcanic rocks. The region is structurally complex, with the aforementioned rocks forming the mountain ranges and alluvium derived from the ranges filling the basins. Sedimentary rocks of the mountain ranges include marine carbonates, shales, cherts, quartzites, and sandstones, as well as fluvial and continental sandstones, siltstones, and shales. Locally, uranium deposits occur in the sedimentary rocks.

The Basin and Range also shows variation in eU related to mapped rock units. Precambrian metamorphic rocks, most Mesozoic granitic rocks, and Tertiary silicic volcanic rocks have elevated eU values. Tertiary sedimentary rocks and Quaternary alluvium derived from the uraniferous rocks of the ranges and from uraniferous rocks of the Sierra Nevada to the west are generally also uranium-enriched. All these rocks generally range from 2.5 to greater then 5.5 ppm eU. Late Precambrian and Paleozoic sedimentary and metamorphosed sedimentary rocks, Mesozoic diorite, early Mesozoic granites, and alluvium derived from them contain less uranium, typically ranging from 0.5 to 2.5 ppm eU. These latter rocks are widely exposed in the area around Las Vegas and contribute to the low eU signature observed in the mountains and valleys in that area.

Overall, the Basin and Range has moderate radon potential. Areas with moderate and locally high radon potential include the Tertiary volcanic rocks, particularly the Miocene and

Pliocene age rocks that are found throughout the Basin and Range Province, Precambrian gneiss in southern Nevada, and the Carson Valley alluvium, which is derived from uraniferous granites in the Sierra Nevada.

Mojave-Sonoran Desert

The Mojave-Sonoran Desert (11, fig. 1) consists of faulted mountain ranges that are partially or completely surrounded by late Cenozoic basins. Uplifted rocks in the ranges consist primarily of Precambrian metamorphic, igneous, and sedimentary rocks, variably altered and metamorphosed Paleozoic to Cenozoic sandstone and limestone, and Tertiary plutonic and volcanic rocks. Mesozoic sedimentary rocks occur in some mountain blocks. The intervening basins are filled by fluvial, lacustrine, colluvial, and alluvial-fan deposits.

From the central Mojave Desert to Tucson in the eastern Sonoran Desert, most of the rocks of the mountains and the intervening basins contain more than 2.5 ppm eU, with a broad area of mountains and adjacent valley alluvium in southeasternmost California and westernmost Arizona above 5.5 ppm eU. In the western Mojave, much of the area has eU in the 1.0-2.5 ppm range, except for the area underlain by the Tertiary sedimentary rocks of the Barstow Basin, where values of as much as 4.5 ppm eU occur. Highly uraniferous Tertiary lacustrine sedimentary rocks are exposed in many of the basins. Uranium occurrences and deposits are numerous.

The Mojave-Sonoran Desert Province has moderate radon potential overall due to its high eU signature. Highest indoor radon levels are to be expected where homes are sited on uranium-bearing rocks, such as Tertiary lacustrine sedimentary rocks or fractured granites.

Transition Zone

The Transition Zone (12, fig. 1), running generally southeast to northwest across the central part of Arizona, contains mountainous areas of uplifted plutonic and metamorphic rocks, with many intervening valleys filled with upper Cenozoic alluvium and lacustrine deposits. Many of the granitic rocks of the mountainous areas are enriched in uranium and have elevated eU values (3 ppm eU or more). Some of the lacustrine rocks in the intervening valleys are also uraniferous and host uranium deposits.

The Transition Zone has moderate radon potential. Elevated to extreme indoor radon levels may occur if a home is sited on a uranium occurrence, fractured uraniferous granite, or uraniferous lacustrine rocks.

Colorado Plateau

The Colorado Plateau (13, fig. 1) covers the northeastern third of Arizona. Subhorizontal to gently folded Paleozoic to Cenozoic sedimentary strata composed mostly of sandstone, limestone, shale, and coal cover the entire area. In the deepest parts of the Grand Canyon, Precambrian sedimentary, igneous, and metamorphic rocks are exposed. Locally, Tertiary and Quaternary volcanic rocks cover the sedimentary strata. Many of the sedimentary rocks are anomalously uraniferous, notably the Cretaceous and Triassic sandstones and shales. Locally, these units host substantial sandstone uranium deposits. Breccia pipe uranium deposits occur in the Grand Canyon area. The areas where these deposits occur is generally sparsely populated.

The Colorado Plateau has moderate radon potential overall. Elevated to extreme indoor radon levels may occur if a structure is sited on one of the uraniferous shales or sandstones or on a uranium occurrence.

Hawaii

The volcanic island chain of Hawaii (14, fig. 1) consists of Tertiary to Recent volcanic rock, predominantly basaltic lavas, ashes, and tuffs, with minor carbonate and clastic marine sediments, alluvium, colluvium, dune sands, and mudflow deposits. Although some soil gas contains greater than 500 pCi/L radon, the low uranium content of the rocks throughout the islands, the local architecture, and the lifestyle of the inhabitants contributes to the overall very low potential for indoor radon in the islands. About 0.4 percent of the homes measured in the State/EPA Residential Radon Survey in Hawaii exceed 4 pCi/L.

PRELIMINARY GEOLOGIC RADON POTENTIAL ASSESSMENT OF ARIZONA

by
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INTRODUCTION

Because uranium-bearing bedrock and the soils and alluvium derived from those rocks are present in many areas of Arizona, and because radon is a daughter product of uranium decay, several areas of Arizona have the potential to locally generate and transport radon in sufficient concentrations to be of concern in indoor air. However, some construction practices common to houses in the semiarid to arid environment of Arizona, such as concrete slab floors, may serve to exclude soil gas from indoor air. In addition, both the lack of heating in houses through much of the year and the use of evaporative coolers or air conditioning, which create positive indoor air pressure, may serve to reduce or exclude soil gas from indoor air (Spencer, 1986).

Arizona has produced significant quantities of uranium ore from many geologic settings. Arizona's uranium deposits occur both in the Basin and Range and in the Colorado Plateau provinces, although those deposits within the Basin and Range are much smaller and account for significantly less production compared to those of the Colorado Plateau (Wenrich and others, 1989). In addition to localized economically important uranium deposits, several areas of the State have rocks that contain uranium concentrations that are not economically important but that may contribute to the generation of radon.

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

Arizona is located in the arid southwest and is bordered by New Mexico on the east, Utah on the north, Nevada and California on the west and the Mexican State of Sonora on the south. The state is divided into 15 large counties (fig. 1). Elevations in Arizona (fig. 2) range from near sea level along the Colorado River in the southwest corner of the State to over 10,000 feet in the mountains.

Arizona's population is concentrated in the southern half of the State (fig. 3). Phoenix and Tucson contain over 50 percent of Arizona's population, and their respective counties, Maricopa and Pima, represent over 75 percent of the State's population. The southern part of Arizona also has the smallest amount of annual rainfall in the State (fig. 4). Southern Arizona's climate (fig. 5)

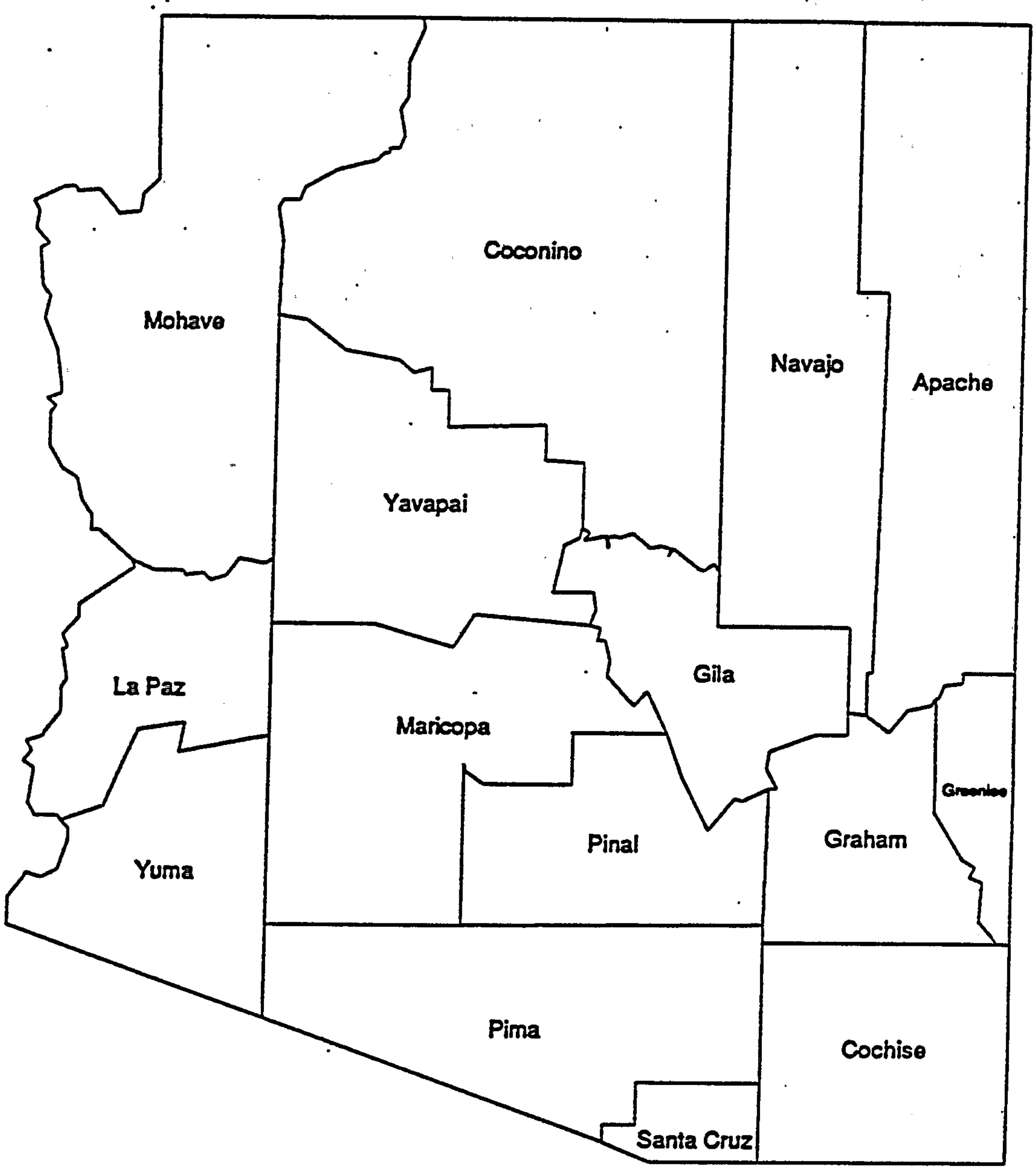


Figure 1. Map showing counties in Arizona.

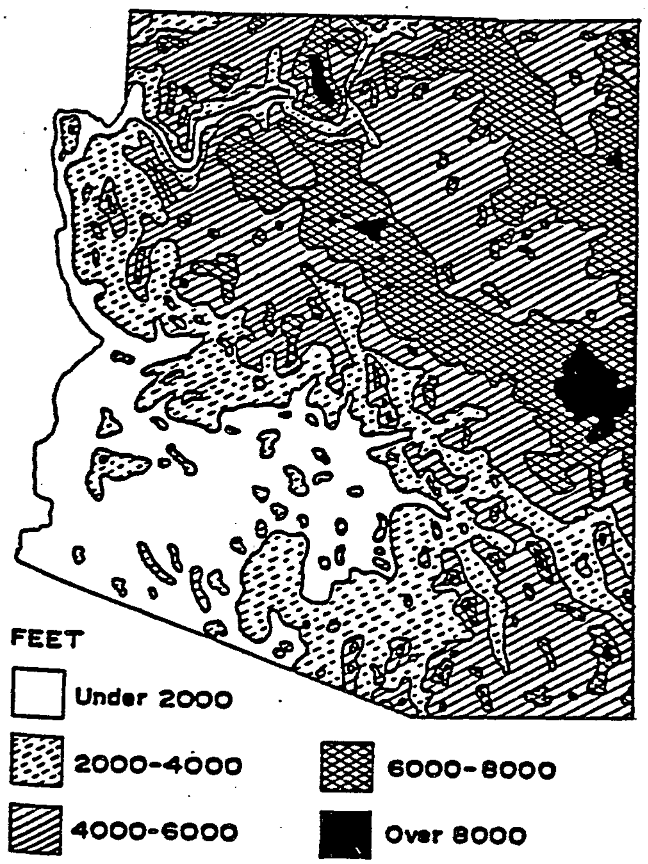


Figure 2. Map showing generalized topography in Arizona (modified from Bahre, 1976).

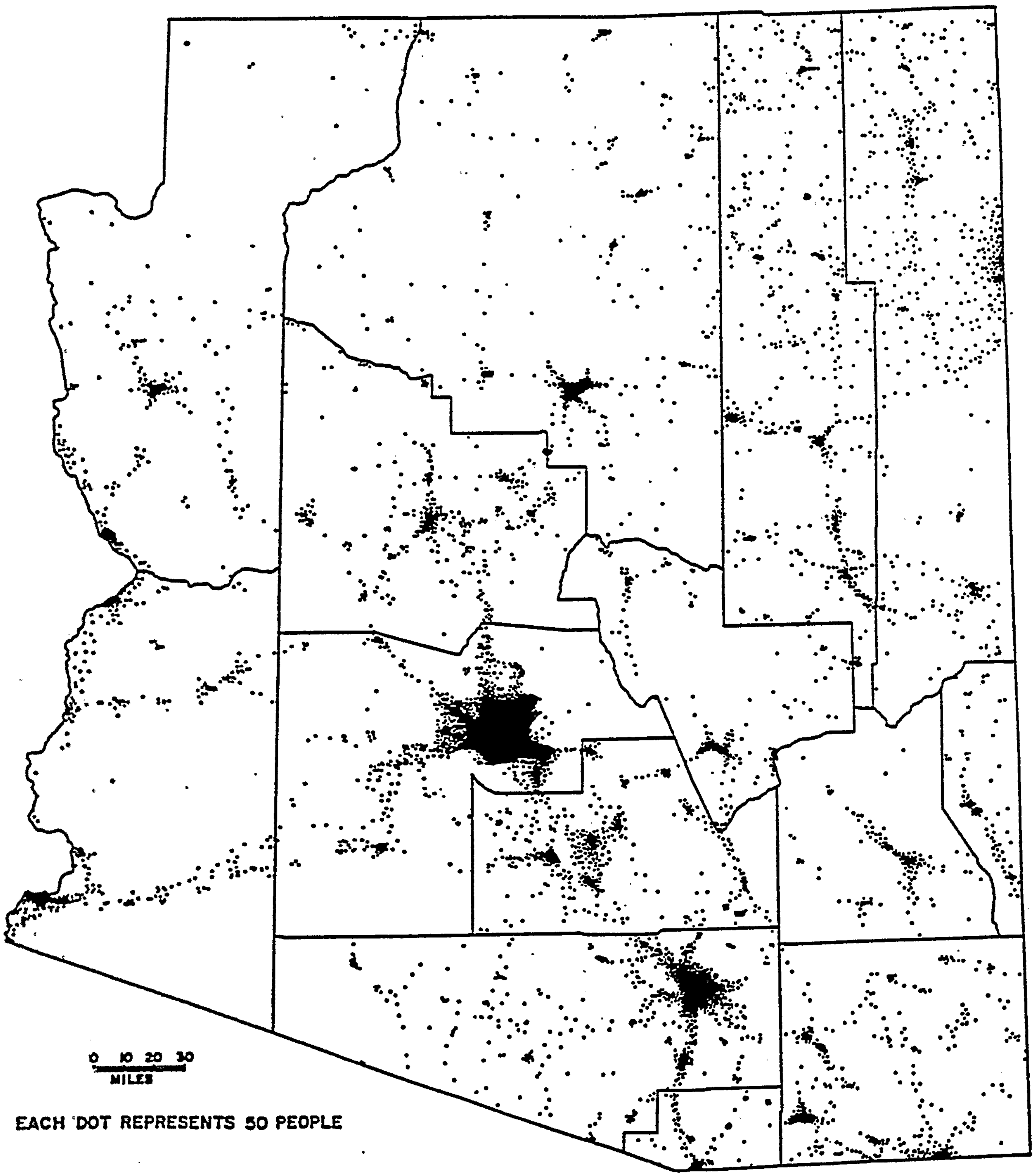


Figure 3A. Map showing population distribution in Arizona (modified from Bahre, 1976).

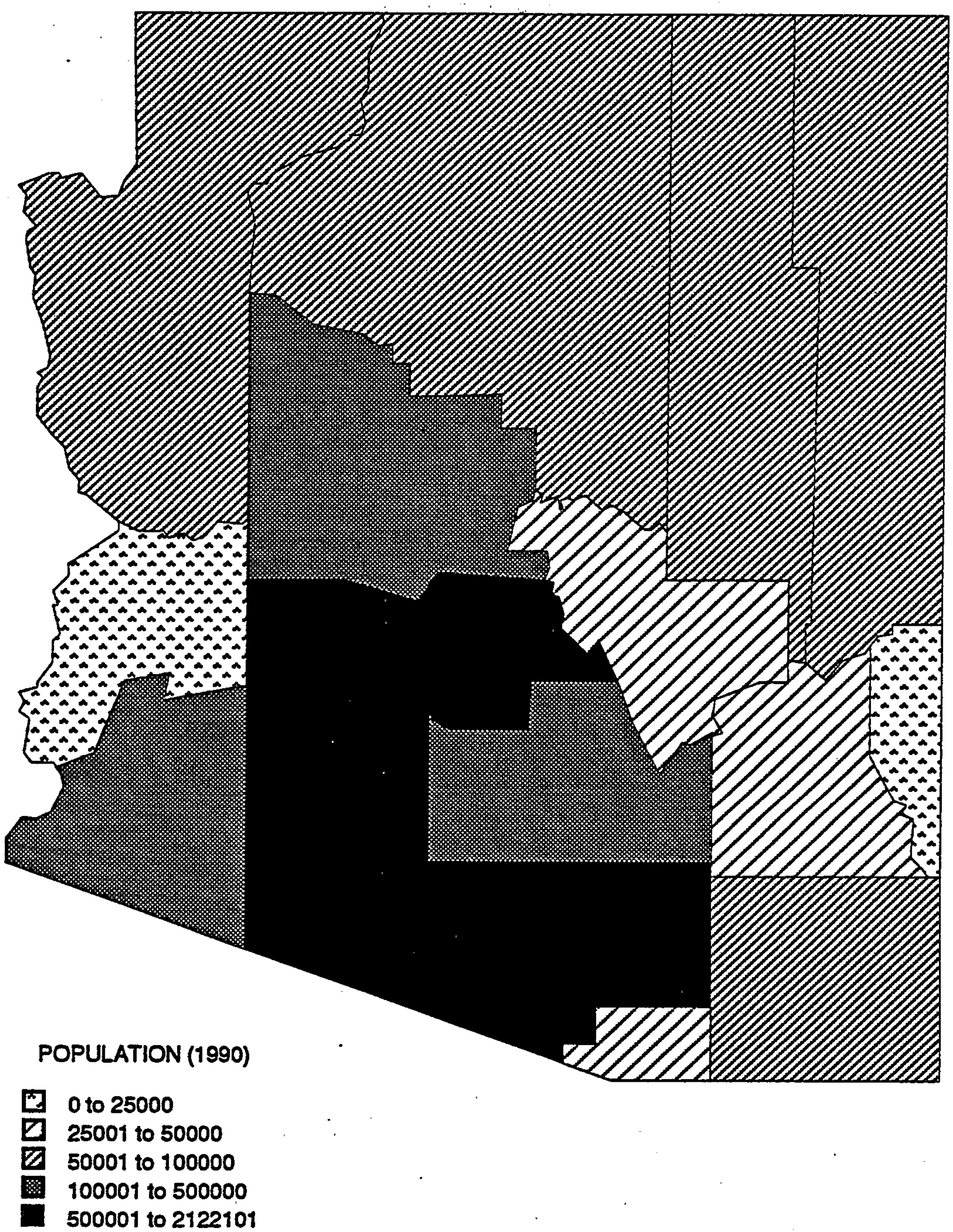


Figure 3B. Population of counties in Arizona (1990 U.S. Census data).

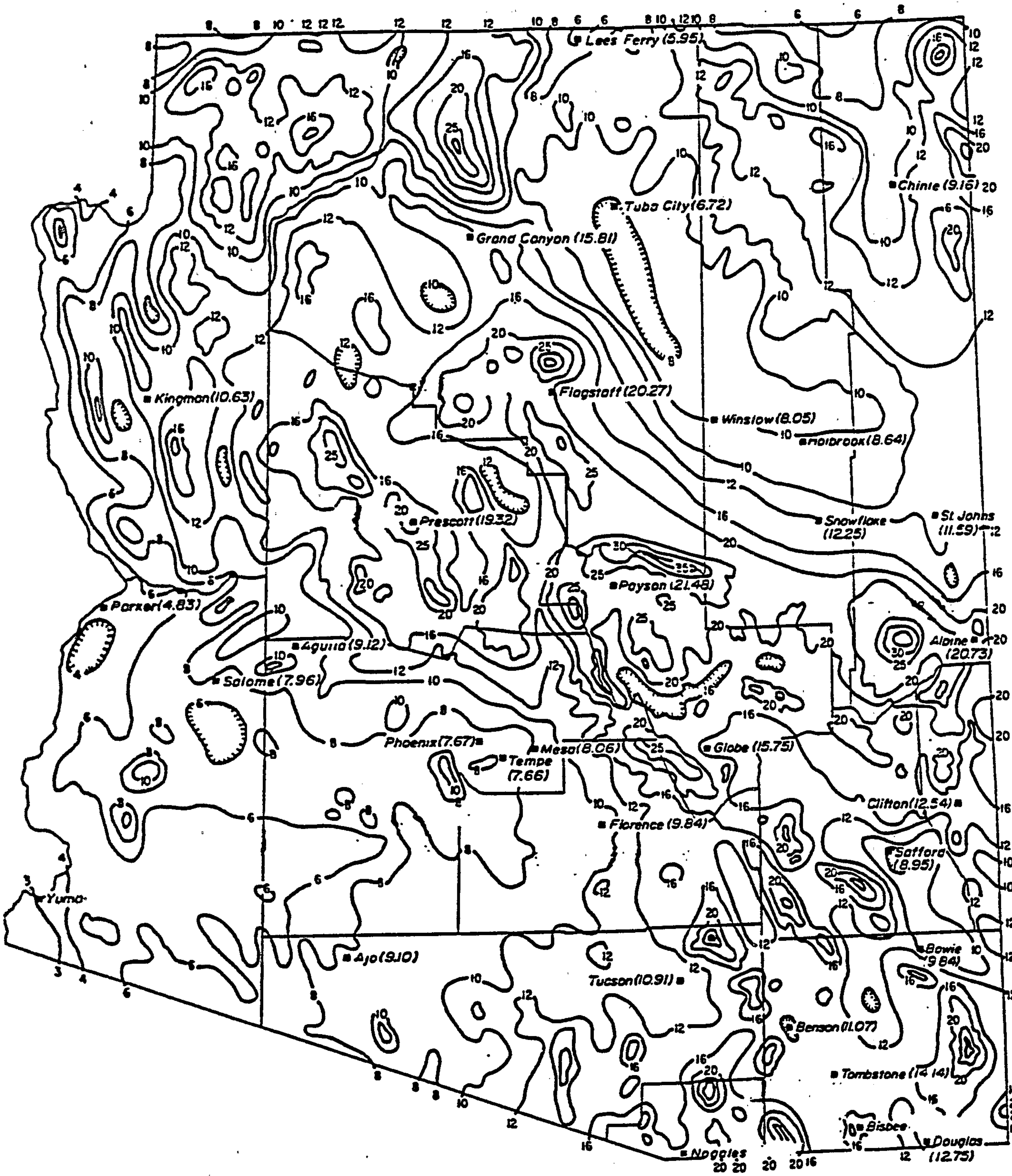
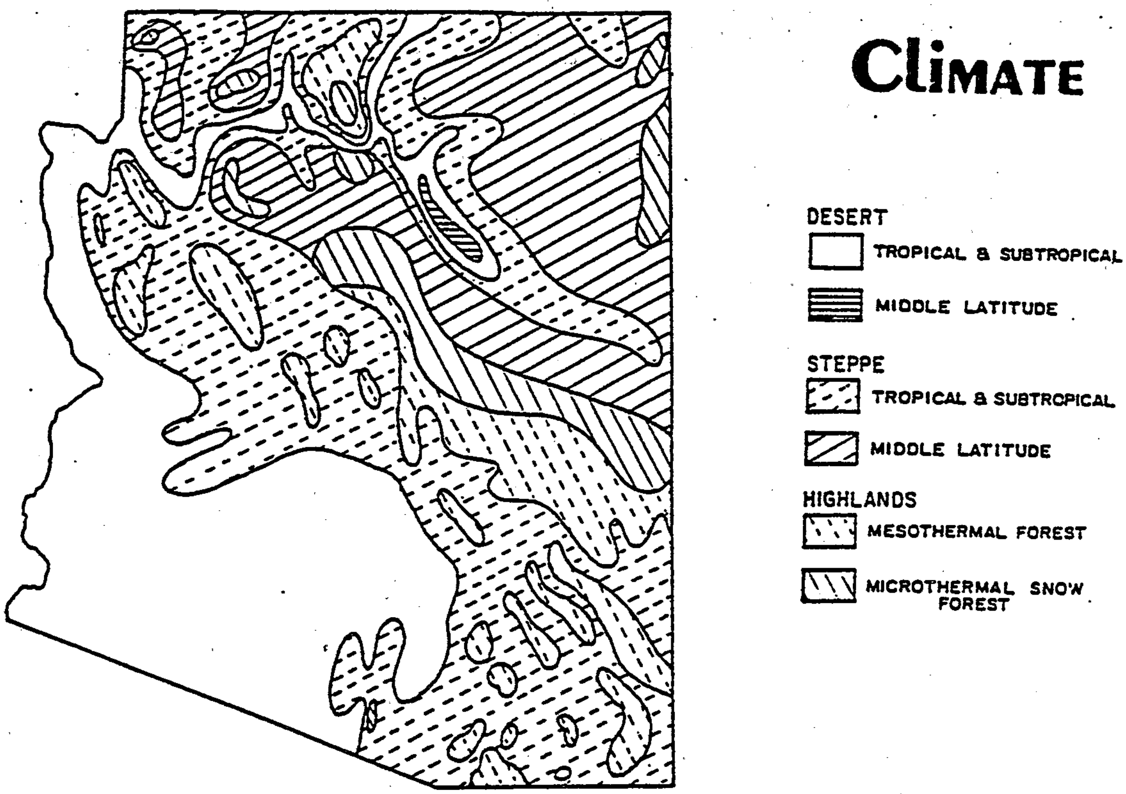


Figure 4. Map showing rainfall distribution for Arizona in inches (modified from Bahre, 1976).

CLIMATE



TEMPERATURES

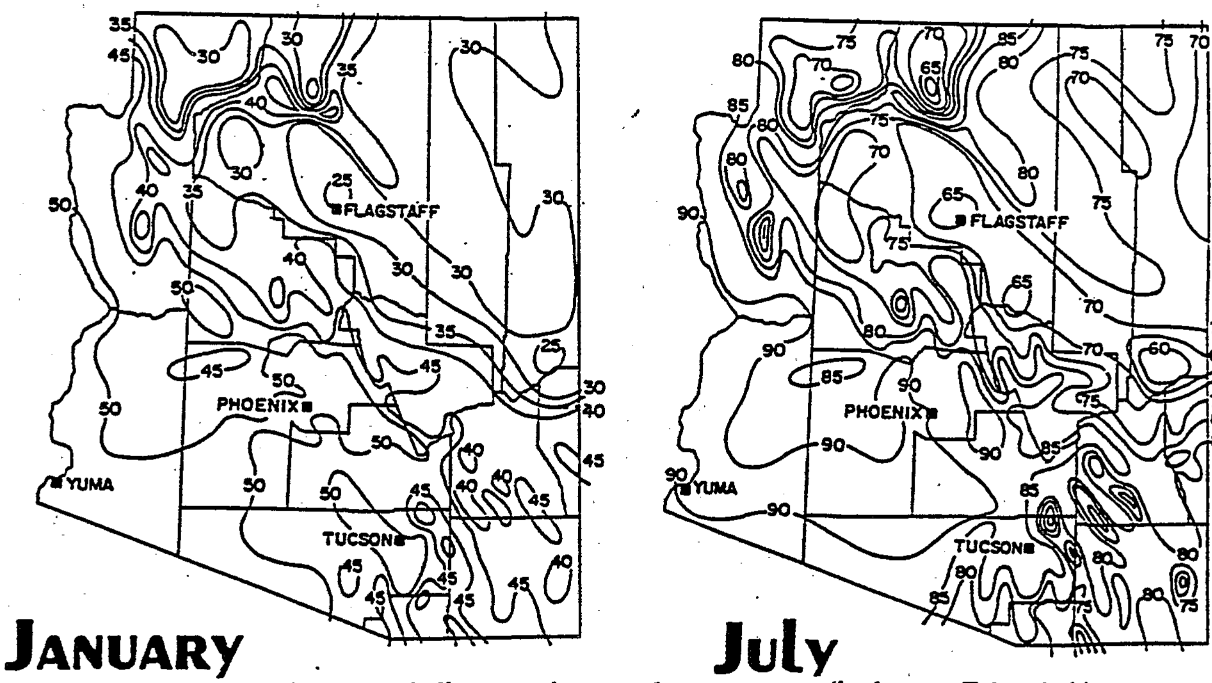


Figure 5. Maps showing general climate and seasonal temperatures (in degrees Fahrenheit) (modified from Bahre, 1976).

is primarily desert and steppe (steppe=an extensive semi-arid, treeless grassland). Northeastern Arizona's climate is primarily steppe.

The federal government owns or administers approximately 70 percent of the land in Arizona, of which more than 25 percent is Indian Reservations and National Parks (Bahre, 1976). Private land amounts to about 17 percent, and State land represents about 12 percent. Retail trade, government installations, manufacturing, mining, tourism, and agriculture are the mainstays of Arizona's economy. Agriculture is generally restricted to irrigated areas in the southern half of the State.

Arizona has two distinct physiographic provinces, the Basin and Range Province in the south and west and the Colorado Plateau Province in the north and northeast (fig. 6); a Transition Zone, or Central Highlands, between the two has characteristics of both areas. The Basin and Range consists of faulted mountain ranges that are partially or completely surrounded by late Cenozoic basins. The styles or models of faulting are described as combinations of horst and graben, tilted blocks, and listric faults (fig. 7A; Hendricks and others, 1985). Most of the basins have through-flowing drainages, except for the Wilcox Lake/Playa in Cochise County and Red Lake in Mohave County (Hendricks and others, 1985). 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, variably altered and metamorphosed 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. The basin fills are generally quite thick and consist of gravel, sand, silt, clay, marl, limestone, gypsum, and salt.

The Colorado Plateau covers approximately the northeast third of Arizona and bedrock geology consists primarily of Paleozoic, Mesozoic, and Cenozoic, flat-lying to gently folded sedimentary strata. The conglomerate, sandstone, siltstone, mudstone, and limestone are locally interrupted by Cenozoic intrusive plutonic and extrusive volcanic rocks. Perhaps the most spectacular geologic feature on the Colorado Plateau is the Grand Canyon in northern Arizona. Erosion by the Colorado River and its tributaries in the Grand Canyon exposes rocks from Precambrian granites and gneisses at river level, upward through Paleozoic sandstones and limestones, into Mesozoic sandstones and shales, and finally to Tertiary and Quaternary basalts.

The Transition Zone, running generally southeast to northwest across the central part of Arizona, contains mountainous areas of uplifted plutonic and metamorphic rocks, with many intervening valleys filled by upper Cenozoic alluvium and lacustrine deposits.

GEOLOGY

Arizona's geologic history is complex, and rocks of various ages and lithologies are exposed (fig. 8A). The following discussion of the geology and soils of Arizona is summarized from Wilson and others (1969), AES and SCS (1964), Soil Conservation Service (1975), Hendricks and others (1985), Reynolds (1988), and AAPG (1990). The discussion on uranium geology of Arizona is condensed from Wenrich and others (1989).

In the Basin and Range, Tertiary tectonism uplifted or faulted Precambrian through Cenozoic rocks to the surface. In the late Oligocene, extensional faulting associated with volcanism began, and it continued into the Miocene, a period characterized by intense normal faulting and crustal extension. In the late Miocene, renewed tectonism produced block-fault mountain ranges that typically trend NW-SE or N-S. The tectonism was followed by basin filling

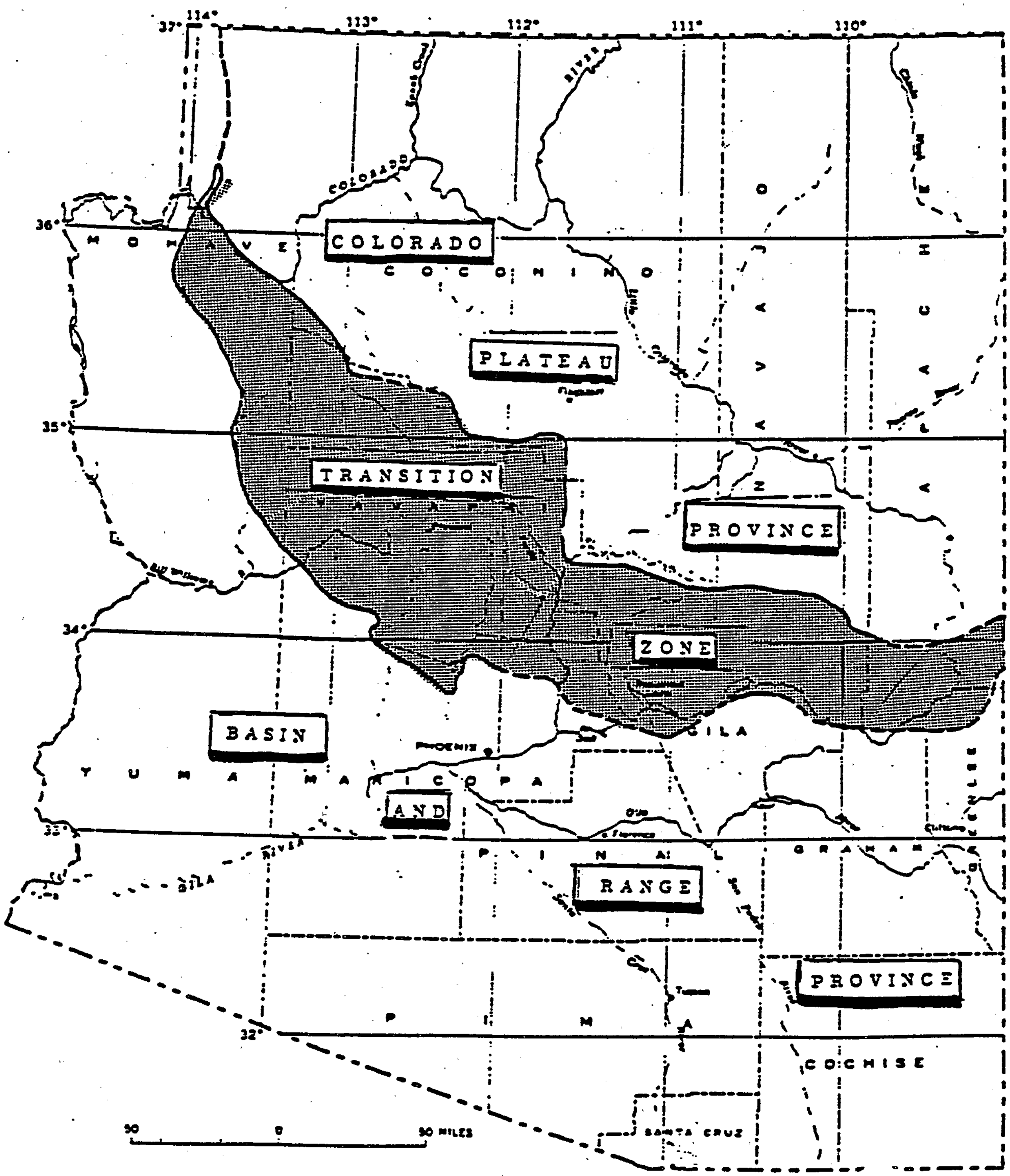


Figure 6. Map showing physiographic provinces in Arizona (modified from Scarborough and Wilt, 1979).

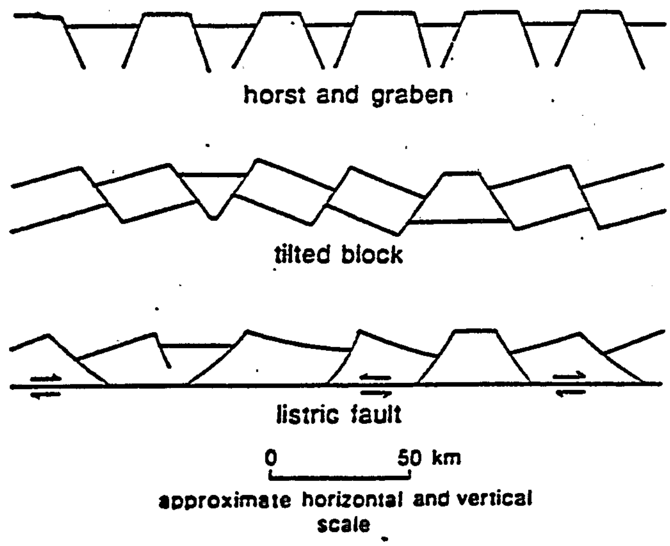


Figure 7A. Model showing types of faulting (modified from Hendricks and others, 1985).

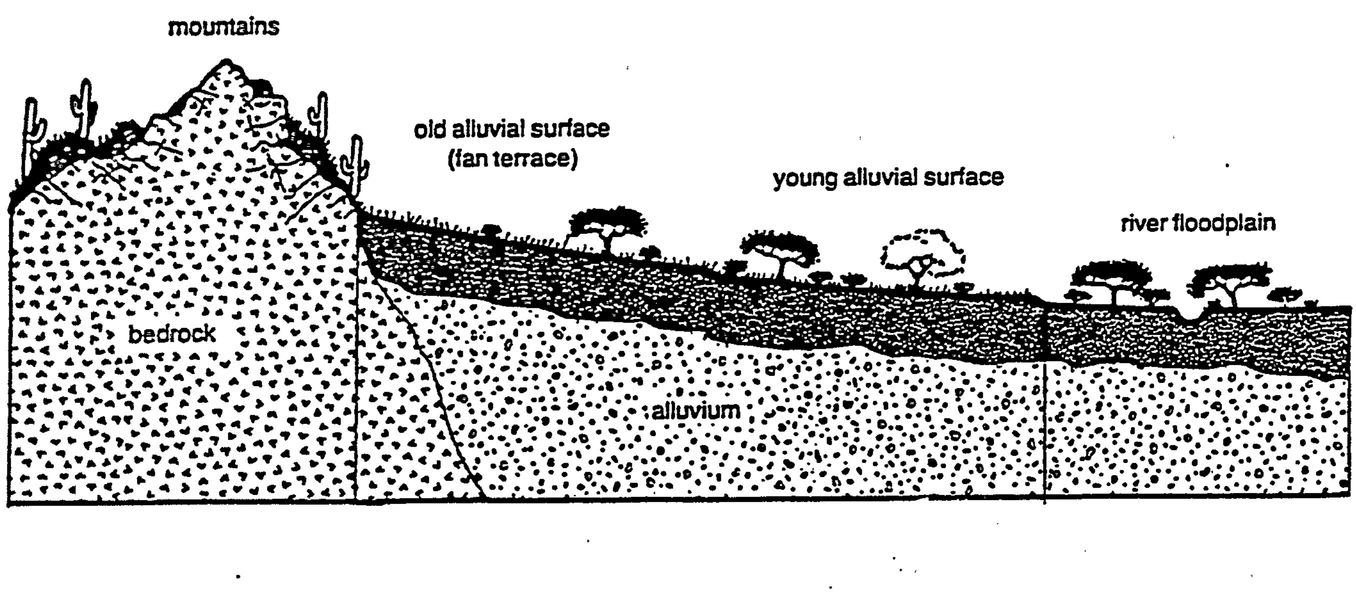
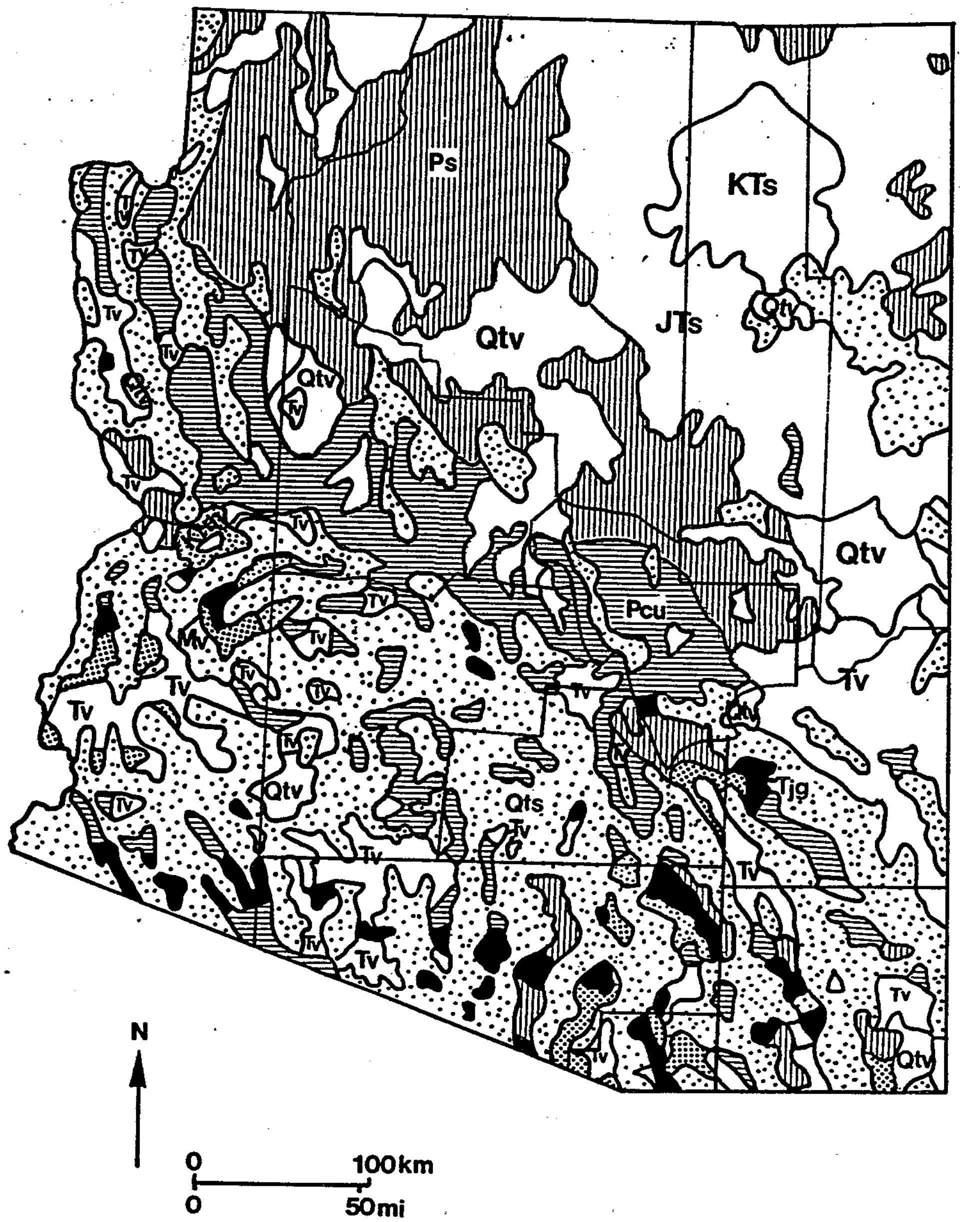


Figure 7B. Typical cross section of Arizona's Basin and Range features (modifed from Hendricks and others, 1985).



EXPLANATION

- Qts — Quaternary and upper Tertiary sedimentary deposits
- Qtv — Quaternary and upper Tertiary volcanic rocks
- Ktm — middle Tertiary to Cretaceous metamorphic rocks
- Tv — middle Tertiary volcanic and sedimentary rocks
- (solid black) — middle Tertiary to Jurassic granitic rocks
- Mv — Mesozoic volcanic and sedimentary rocks: locally metamorphosed
- Kts — Cretaceous and/or lower Tertiary sedimentary rocks
- Jts — Jurassic and Triassic sedimentary rocks
- Qtv — Paleozoic sedimentary rocks: locally includes Precambrian sedimentary rocks
- Tv — Precambrian igneous, metamorphic and sedimentary rocks

Figure 8A. Map showing generalized geology of Arizona (modified from Hendricks and others, 1985).

that continued into the Pliocene. Filling of many basins continued into the Pleistocene. Stream downcutting, development of alluvial terraces, and erosion by the major rivers in the region has occurred fron Pleistocene to recent times (fig. 7B).

The Basin and Range and adjacent Transition Zone expose a wide variety of rocks of different ages and lithologies (fig. 8A). Precambrian igneous plutonic rocks and metasedimentary, metavolcanic, and metamorphic rocks are scattered throughout the region and include granite, diorite, gabbro, gneiss, basalt, diabase, and quartzite. Paleozoic rocks exposed in minor outcrops adjacent to uplifts and faults include limestone, sandstone, and shale. Mesozoic and Cenozoic rocks include a complex array of sedimentary strata, granitic intrusions, and extrusive volcanic rocks.

Compared to the Basin and Range and the Transition Zone, the geology on the Colorado Plateau in northern and northeastern Arizona is relatively uncomplicated. Flat-lying to gently folded sedimentary strata cover the entire area. In the deepest parts of the Grand Canyon in northern Arizona, Precambrian igneous and metamorphic rocks underlie the oldest sedimentary strata exposed on the Colorado Plateau, including Precambrian sandstone, limestone, shale, and quartzite. These rocks are overlain by Paleozoic sandstone, shale, and limestone that crop out in the gorge of the Grand Canyon, along the northern rim of the Central Highlands, and locally in uplifted areas of the State such as the Defiance Plateau in northeastern Arizona and the Kaibab and Coconino Plateaus in northern Arizona. The remainder of the Colorado Plateau exposes Mesozoic to Cenozoic sedimentary strata consisting of sandstone, shale, limestone, and coal. Locally, Tertiary and Quaternary volcanic rocks cover the sedimentary strata.

The tectonic stability of the Colorado Plateau has contributed to the widespread preservation of large uranium ore bodies (fig. 8B; Wenrich and others, 1989). Basin and Range tectonics, which affect approximately 60 percent of Arizona, would have permitted oxidation and local removal by solution, or more simply by erosion, of possible uranium ore bodies that may have been present in southern Arizona. In addition, uranium ore bodies on the Colorado Plateau occur primarily in upper Paleozoic and Mesozoic sedimentary rocks, most of which have been eroded from or are not exposed in the Basin and Range. The anomalously uranium-rich Precambrian basement that apparently underlies much of the Colorado Plateau, along with the tectonic stability and subsequent preservation of upper Paleozoic and Mesozoic strata, resulted in significant large uranium deposits on the Colorado Plateau. Nevertheless, abundant small uranium deposits and locally large non-economic concentrations of uranium are known from a variety of rocks in both the Basin and Range and the Transition Zone (fig. 8B).

In the Transition Zone and the Basin and Range, ore-grade uranium was discovered near Bagdad and near Nogales, and numerous ore deposits and uranium occurrences are found in the Dripping Spring Quartzite of the Middle Proterozoic Apache Group in the Sierra Ancha in Gila County (fig. 8B; Wenrich and others, 1989). The 1,400 million-year-old granite suite found across much of southern Arizona is anomalously enriched in uranium and hosts uranium occurrences where it is cut by shear zones or faults (Scarborough, 1981). The suite includes Proterozoic granites in the northern Rincon Mountains of Pima County and at the north end of the Whetstone Mountains in Cochise County, and the Lawler Peak Granite near Bagdad in Yavapai County. Flat-lying Pennsylvanian and Permian sedimentary strata on the northern flank of the Central Highlands contain anomalous radioactivity and several uranium-mineralized areas, including Promontory Butte, Fossil Creek, Cibecue, and Carrizo Creek (Pierce and others, 1977). Small uranium occurrences are in silicic volcanic rocks that are numerous in south-central Arizona, and a few isolated occurrences are located in rhyolitic rocks in extreme southeastern Arizona near

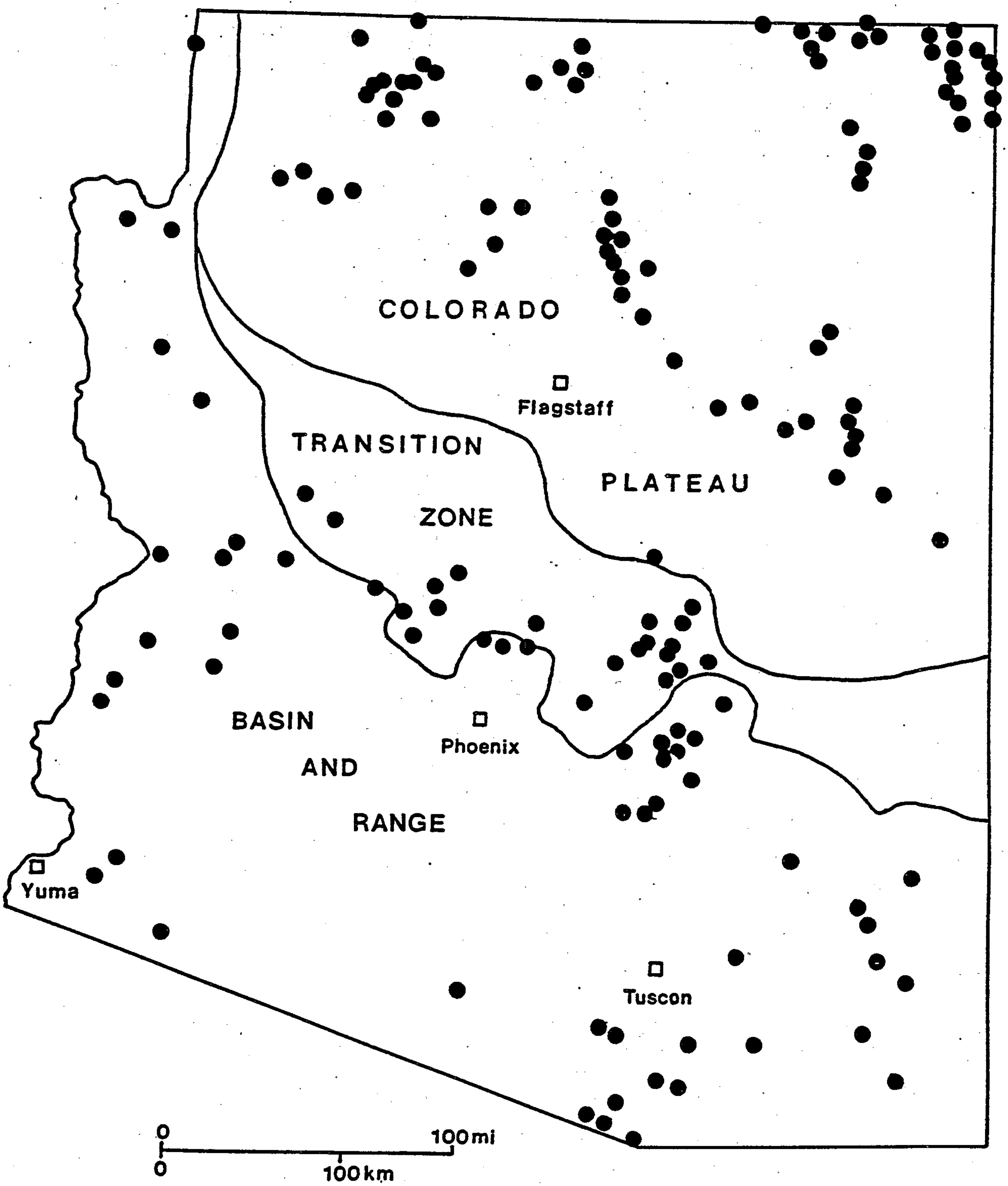


Figure 8B. Map showing distribution of uranium deposits in Arizona (modified from Wenrich and others, 1989).

Ruby in Santa Cruz County and near Arivaca in southeastern Pima County. Many of the Lower Jurassic to mid-Tertiary silicic volcanic rocks in southern Arizona are poorly mapped in detail and are little studied to date; preliminary work (Scarborough, 1981; Wenrich and others, 1989) indicates that many of these rocks may contain small, isolated occurrences of uranium and areas of localized uranium enrichment. Uranium was also produced as a by-product of copper porphyry mining in the Pima, Bisbee, and Morenci mining districts, and uranium was produced on the western flank of the Santa Rita Mountains in Santa Cruz County. Lower to mid-Miocene tuffaceous lakebeds along the north edge of the Date Creek Basin in Yavapai, La Paz, and Mohave Counties and near Tucson in Pima County host large, low-grade uranium deposits, and similar lacustrine sedimentary rocks of uncertain age host uranium in the Big Sandy Basin of Mohave County and in basins near Cave Creek and New River, in the northern suburbs of Phoenix. Low-grade uranium-bearing zones are present around the edge of Wilcox Playa in Cochise County.

The Colorado Plateau has produced more than 99 percent of Arizona's total uranium production, principally from two settings: 1) sandstone-hosted ore bodies in the Upper Triassic Chinle Formation and the Upper Jurassic Morrison Formation, and 2) solution-collapse, breccia-pipe ore bodies hosted by Permian rocks. The Shinarump Member of the Chinle Formation hosts significant uranium ore bodies in several areas of Arizona including southern Monument Valley in Navajo and Coconino Counties. The Petrified Forest Member of the Chinle Formation hosts uranium near Cameron in Coconino County, near St. Johns in Arapahoe County, and near Winslow in Navajo County. A minor occurrence of uranium is in the Lower Jurassic Navajo Sandstone along Comb Ridge in Apache County. The Salt Wash Member of the Upper Jurassic Morrison Formation hosts major uranium ore in the Carrizo Mountains, Lukachukai Mountains, and Chuska Mountains, and on the north and east sides of Black Mesa, all in Apache County. Minor sedimentary rock-hosted uranium deposits occur in the Upper Cretaceous Toreva Formation in the northeast corner of Black Mesa in Apache County. The diatremes and associated maar-lacustrine deposits of the Hopi Buttes in Navajo County contain scattered, low-grade uranium occurrences.

Although they are individually small in area exposed at the surface, solution-collapse breccia pipes have produced the highest-grade uranium ore in Arizona. Thousands of breccia pipes are host to high-grade uranium ore at scattered localities across the Marble, Kaibab, and Coconino Plateaus in northern Arizona. The deposits contain high-grade uranium ore, but they are restricted to vertical pipes from only several hundred to at most several thousand feet in diameter that cut upward from Mississippian limestones to Triassic sandstones and shales (Wenrich and others, 1989).

SOILS

A generalized soils map of Arizona (fig. 8C) compiled from Soil Conservation Service (1975) and Hendricks and others (1985) indicates that, in general, soils in Arizona consist of Aridisols and Subhumid Soils. Soils in different areas have a range in permeability from slow to rapid. 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 (1975), Hendricks and others (1985), and soil surveys of individual counties for more detailed descriptions of the soils and their characteristics in specific areas.

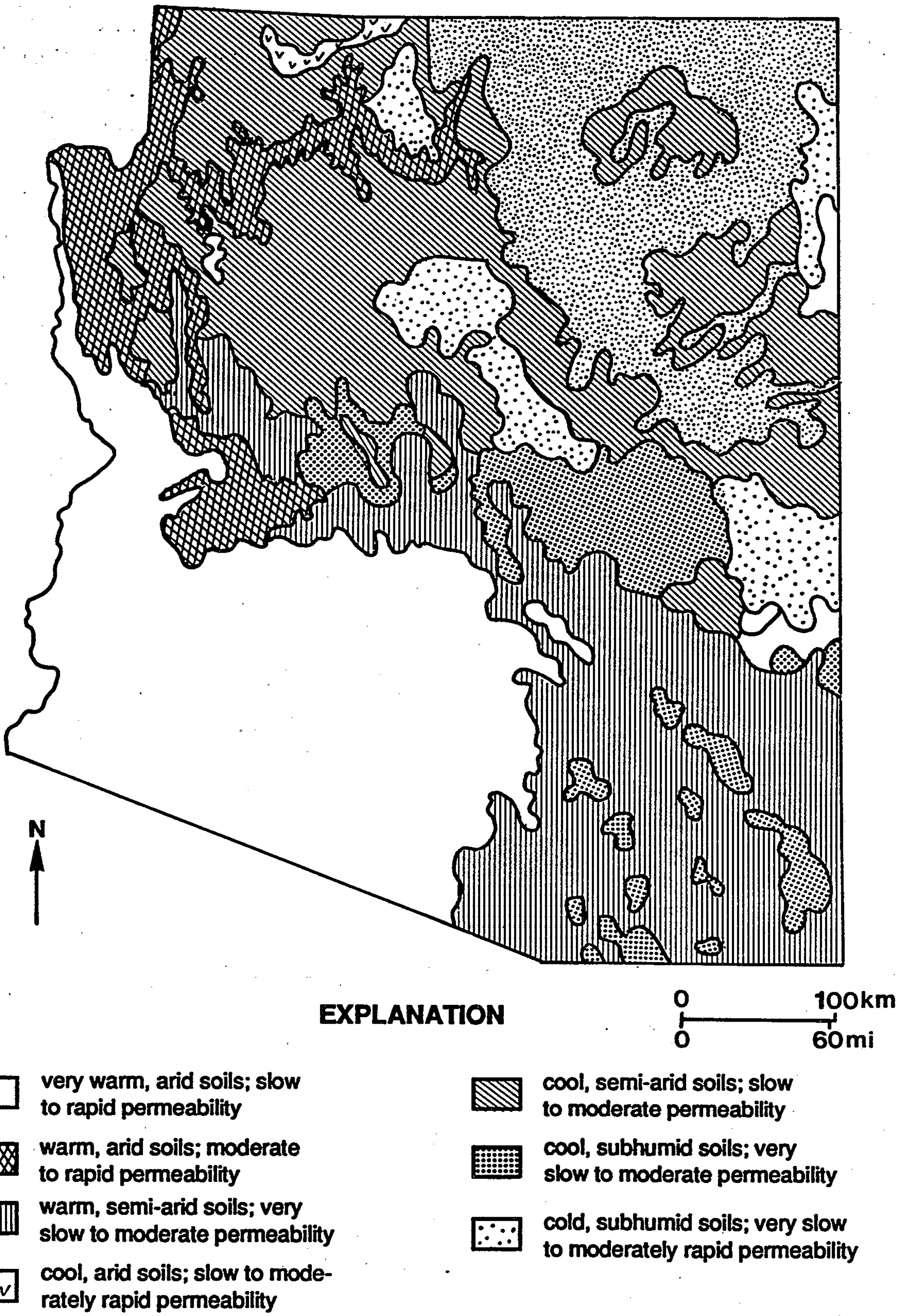


Figure 8C. Map showing generalized soils in Arizona (modified from SCS, 1975).

INDOOR RADON DATA

Indoor radon data for Arizona (fig. 9, Table 1) from the State/EPA Residential Radon Survey conducted in the winter of 1987 to 1988 are summarized in the following section. Discussions on radon in Arizona are published in Spencer (1986), Spencer and Shenk (1986), Fellows (1987), Spencer and others (1987), Emer and others (1988), Spencer and others (1988), Pewe (1989), and Spencer and others (1990). Many counties in Arizona are as large as some eastern states; because the State/EPA sampling was population weighted, large portions of some of the counties have few data points. A map showing the counties in Arizona (fig. 1) is provided to facilitate discussion of the indoor radon data.

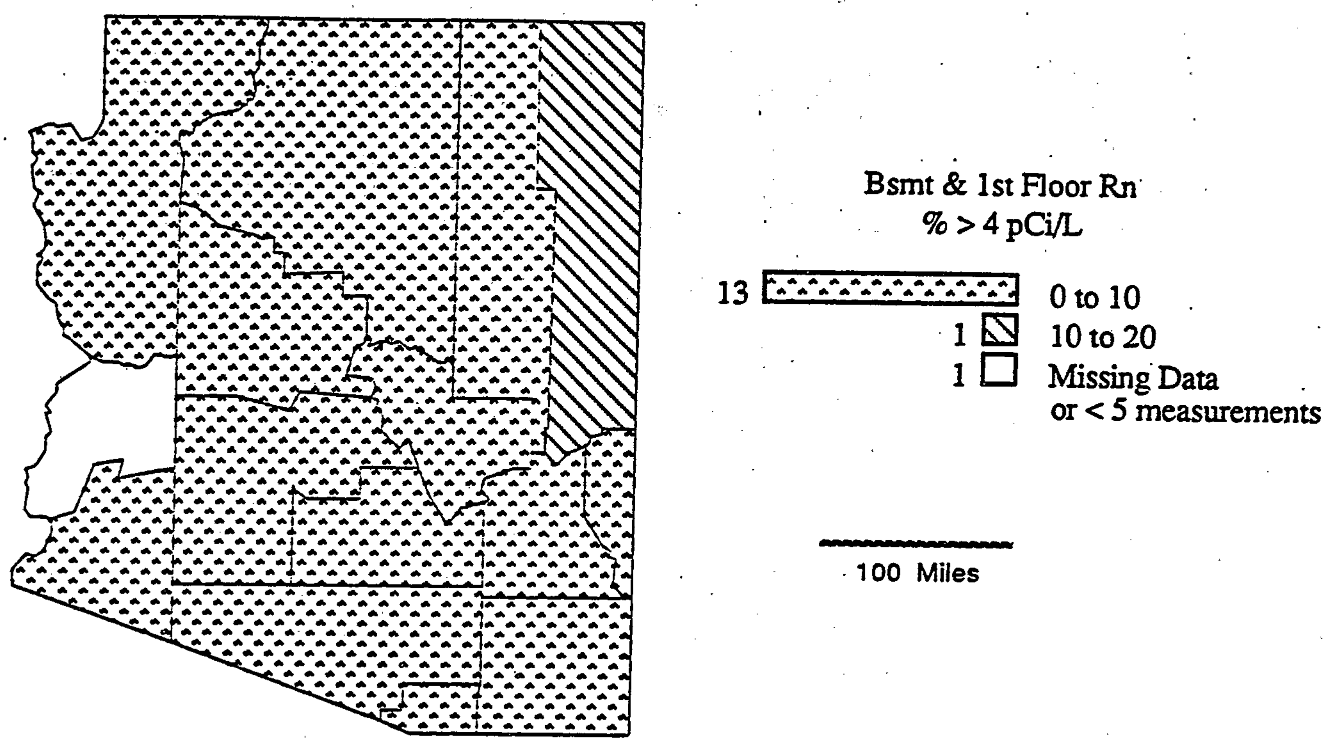
Many homes in Arizona are built on concrete slabs (Spencer, 1986), and only 3 counties (Maricopa, Navajo, and Yavapai) had more than 5 basement measurements in the State/EPA survey. County average screening indoor radon concentrations were between 0.3 and 1.9 pCi/L in the State/EPA Residential Radon Survey. The maximum screening indoor radon level reported in the survey was 50.8 pCi/L in Maricopa County (Table 1). Although not shown in the table, the next highest reading of the 1507 homes tested in the State/EPA survey in Arizona was 16.4 pCi/L, also in Maricopa County. Apache County was the only county in which more than 10 percent of the homes tested (13 percent) had screening indoor radon levels exceeding 4 pCi/L in the State/EPA survey.

Fellows (1987) and Spencer and others (1987) reported on a neighborhood in southwestern Tucson that was built above a limestone containing small quantities of uranium-bearing minerals; about half of the homes in this area contained indoor radon concentrations greater than 4 pCi/L.

GEOLOGIC RADON POTENTIAL

A comparison of the geology (fig. 8A) with aerial radiometric data (fig. 10) and indoor radon data (fig. 9) provides preliminary indications of rock types and geologic features suspected of having the potential to generate elevated indoor radon levels. It should be noted that there is a N-S oriented rectangle in the aerial radiometric data in the southeastern corner of the State that, because of its regular geometric shape, may reflect a data processing problem; data from within this area are internally consistent, but they have not been properly leveled with adjacent data. An overriding factor in the geologic evaluation is the location and distribution of known uranium-producing outcrops in Arizona (fig. 8B) and of areas with elevated concentrations of uranium (Spencer and Shenk, 1986; Spencer and others, 1990). 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 indoor radon levels.

The aerial radiometric data (fig. 10) can be compared to the indoor radon data and to known geologic features in order to identify geologic units that have the potential to contribute to elevated radon levels. Aerial radiometric data and indoor radon data suggest that several rock formations on the Colorado Plateau have the potential to contribute to elevated indoor radon levels. Cretaceous rocks on Black Mesa, Tertiary sedimentary rocks south of Black Mesa, the Upper Jurassic Morrison Formation, and the Upper Triassic Chinle Formation, all of which are known uranium producing units in Arizona, have the potential to produce locally elevated radon levels in indoor air. Scattered localities in the Transition Zone that probably reflect outcrops of uraniferous Paleozoic



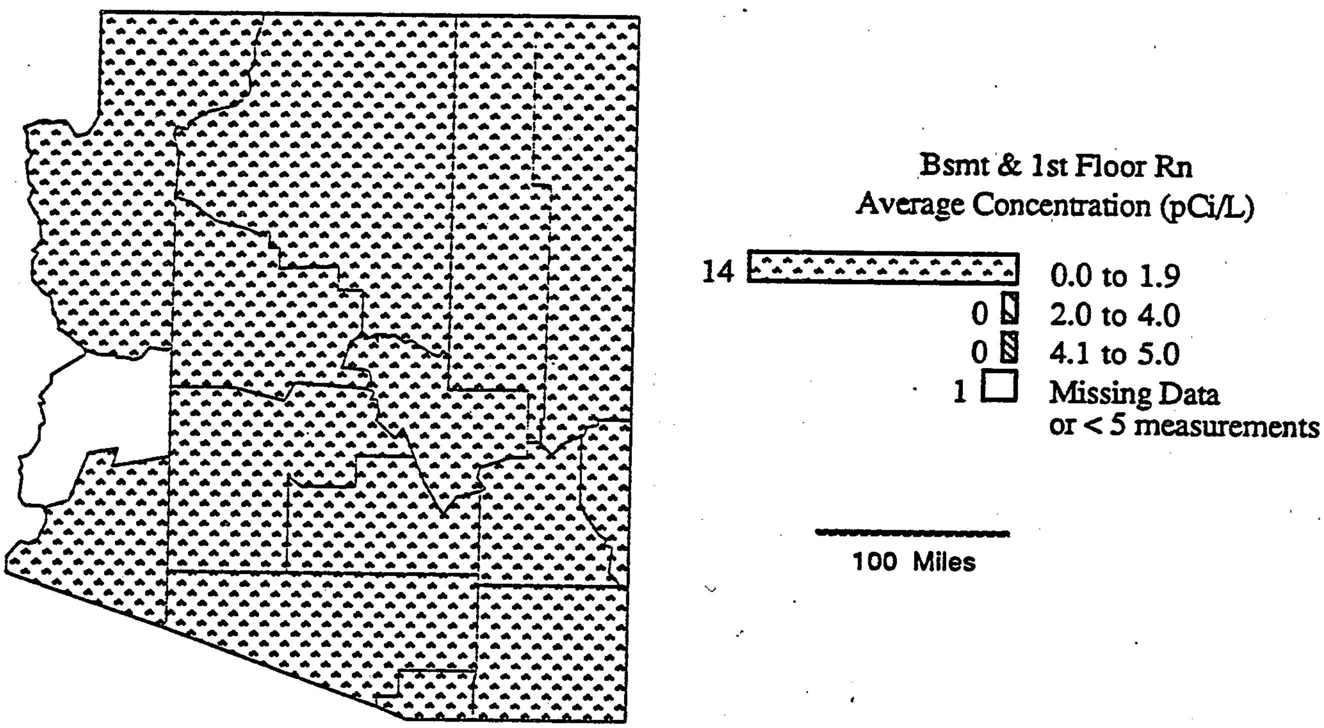


Figure 9. Screening indoor radon data from the EPA/State Residential Radon Survey of Arizona, 1987-88, for counties with 5 or more measurements. Data are from 2-7 day charcoal canister tests. Histograms in map legends show the number of counties in each category. The number of samples in each county (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 Arizona 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
APACHE	15	1.4	0.9	0.6	1.6	5.0	13	0
COCHISE	39	1.6	0.9	0.8	2.0	11.1	5	0
COCONINO	89	1.9	0.9	0.9	2.5	13.5	9	0
GILA	13	1.1	0.8	0.9	0.7	2.4	0	0
GRAHAM	29	1.1	0.7	0.7	0.9	2.8	0	0
GREENLEE	8	1.1	0.9	0.9	0.8	2.4	0	0
LA PAZ	2	0.3	0.2	0.3	0.4	0.5	0	0
MARICOPA	765	1.7	1.1	1.2	2.4	50.8	8	0
MOHAVE	99	1.0	0.6	0.8	0.9	6.1	1	0
NAVAJO	57	1.6	1.1	1.2	1.3	5.9	5	0
PIMA	260	1.4	0.9	1.0	1.3	10.0	6	0
PINAL	33	1.5	0.9	1.2	1.2	4.4	6	0
SANTA CRUZ	13	1.7	1.4	1.5	1.2	4.2	8	0
YAVAPAI	51	1.2	0.8	0.9	1.1	4.6	2	0
YUMA	34	0.7	0.5	0.6	0.5	2.4	0	0

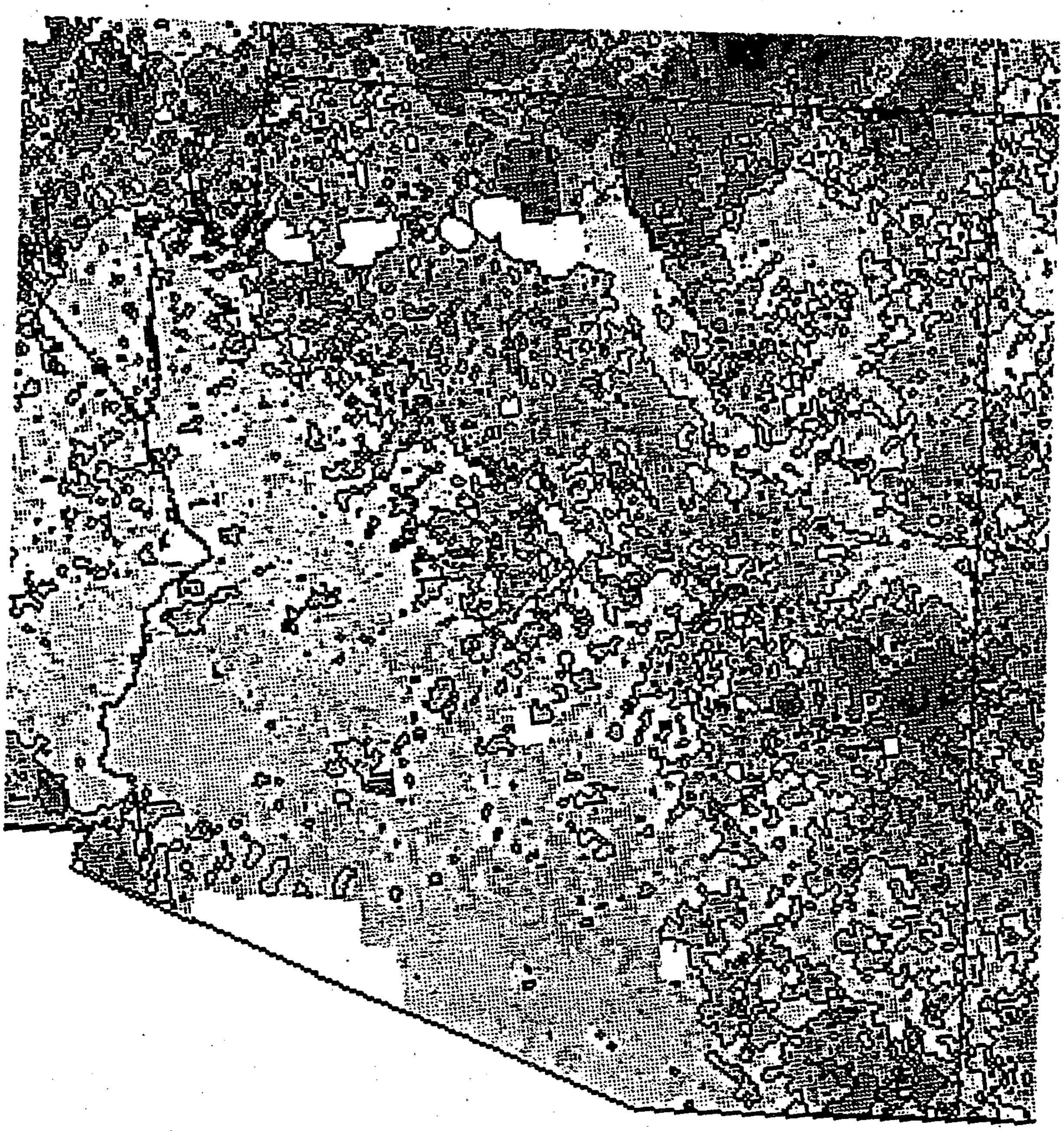


Figure 10. Aerial radiometric map of Arizona (after Duval and others, 1989). Contour lines at 1.5 and 2.5 ppm equivalent uranium (eU). Pixels shaded from 0 to 6.0 ppm eU at 0.5 ppm eU increments; darker pixels have lower eU values; white indicates no data.

sedimentary rocks and Tertiary volcanic rocks also have the potential to generate indoor radon, but the scale of the maps precludes a discussion of individual rock units.

In the Basin and Range, virtually the entire area has an anomalously high signature on the aerial radiometric map (fig. 10), and small areas associated with Precambrian granites and Tertiary volcanics and granites have very high anomalous signatures. Spencer (1986) reported that the Dells Granite near Prescott and the Lawler Peak Granite near Bagdad are both uranium rich. Spencer (1986) also reported that several areas north of Phoenix contain scattered outcrops of tilted Miocene sedimentary and volcanic rocks that are uranium rich. Locally, individual rock units may contribute to elevated indoor radon, but the scale of the maps and available detailed geologic data are not sufficient to characterize other individual rock units.

Evaluating the United States as a whole, Peake and Schumann (1992) concluded that equivalent uranium (eU, which is depicted on the aerial radiometric map in fig. 10) concentrations of 2 parts per million or greater generally indicate areas that have the potential to produce elevated indoor radon levels in a substantial number of homes (note: in this evaluation, the level of eU used to determine "high" in the aerial radioactivity factor of the Radon Index, discussed below, is 2.5 ppm). Despite the fact that almost all areas within the Basin and Range and many areas within the Colorado Plateau and the Transition Zone appear to have eU concentrations greater than 2 parts per million (fig. 10), the indoor-radon data for Arizona (fig. 9) do not support an association among the entire Basin and Range, nor many areas within the Colorado Plateau and the Transition Zone, with elevated indoor radon measurements. Local construction practices in concert with the hot, arid climate in this region of the State may account for the discrepancy between the elevated eU signature on the aerial radiometric map and the apparent lack of substantial numbers of homes with elevated indoor radon levels for counties in Arizona. The prevalent method of concrete slab-on-grade construction and the extensive use of evaporative coolers may contribute to an apparent lack of elevated indoor radon levels for counties in the State. The lack of basements and the use of concrete slab foundations in many homes may prevent the influx of soil gas into homes (Spencer, 1986). Additionally, evaporative coolers are commonly employed for cooling in response to the aridity and heat in Arizona (figs. 4, 5). Spencer (1986) points out that the use of these coolers increases the positive air pressure in a home and forces indoor air downward through cracks and openings, which reduces or may prevent the influx of soil gas. Thus during much of the year, many homes in Arizona may enjoy radon mitigation as a fringe benefit from cooling.

SUMMARY

For purposes of assessing the radon potential of the State, Arizona can be divided into six (6) general areas (termed Area 1 through Area 6; see fig. 11 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 regional booklet (chapter 1). Note that in any specified 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.

Areas 1and 2 each have moderate radon potential (RI=11) associated with a high confidence index (CI=10) on the basis of moderate indoor radon measurements, high surface radioactivity as evidenced by the aerial radiometric data, and the presence of rock formations such as Cretaceous marine sandstones and shales around Black Mesa that contain low but consistent

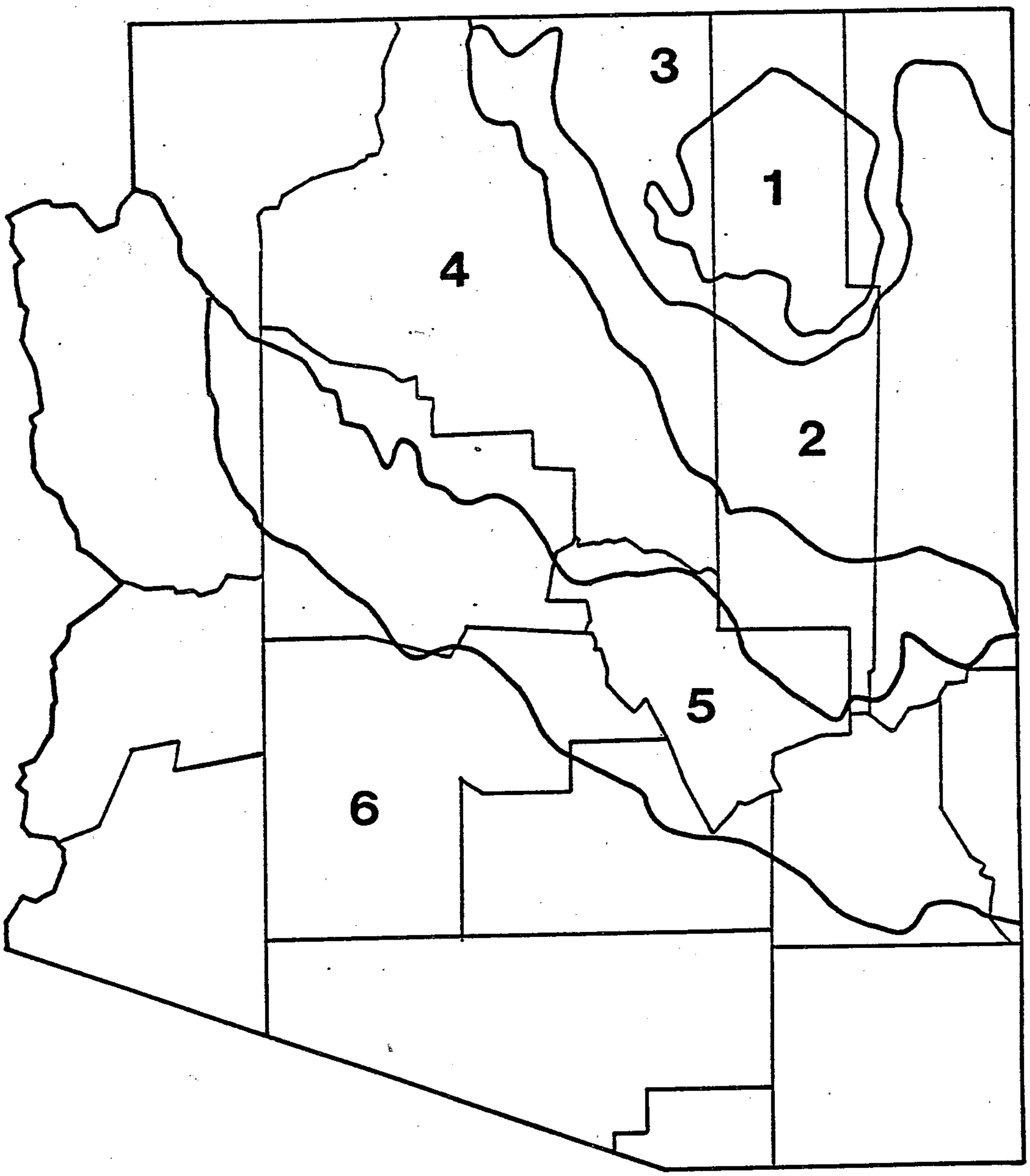


Figure 11. Map showing radon potential areas in Arizona (see Table 1 and text for discussion of areas).

radon cencentrations in Area 1 and Triassic nonmarine sandstones and shales on the Colorado Plateau that are known to contain significant uranium deposits in Area 2. Area 3 is within the Colorado Plateau and has moderate radon potential (RI=9) with a moderate confidence index (CI=9) on the basis of low indoor radon measurements, low aerial radiometric signature, and variable geology, including primarily Triassic and Jurassic eolian sandstones. Areas 4 and 5 each have moderate radon potential (RI=9 and 10, respectively) associated with a moderate confidence index (CI=9 and 10, respectively). These areas exhibit low indoor radon measurements, have moderate to high surface radioactivity, and contain rocks that are known to contain minor amounts of uranium or scattered uranium anomalies, such as Paleozoic limestones of the Colorado Plateau in Area 4 and Precambrian igneous and Tertiary volcanic rocks in Area 5, which encompasses the Transition Zone between the Colorado Plateau and the Basin and Range Provinces. Area 6, which includes part of the Basin and Range Province, has a moderate radon potential (RI=10) with a high confidence index (CI=10) on the basis of moderate indoor radon measurements, high aerial radiometric signature, and variable geology that includes uranium-bearing Teriary volcanic rocks. It should be noted that in Areas 5 and 6, which include the Transition Zone and the Basin and Range respectively, rocks in the mountain ranges generally have a higher potential for indoor radon than do the Quaternary valley fills adjacent to the ranges.

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 Arizona.

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	3	3	2	3
GEOLOGY	3	3	3	3	2	2
SOIL PERM.	2	1	2	1	2	1
ARCHITECTURE	1	--	1	--	1	--
GFE POINTS	0	--	0	--	0	--
TOTAL	11	10	11	10	9	9
RANKING	MOD	HIGH	MOD	HIGH	MOD	MOD

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

RADON INDEX SCORING:

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

Possible range of points = 3 to 17

CONFIDENCE INDEX SCORING:

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

Possible range of points = 4 to 12

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EPA's Map of Radon Zones

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

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

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

ARIZONA MAP OF RADON ZONES

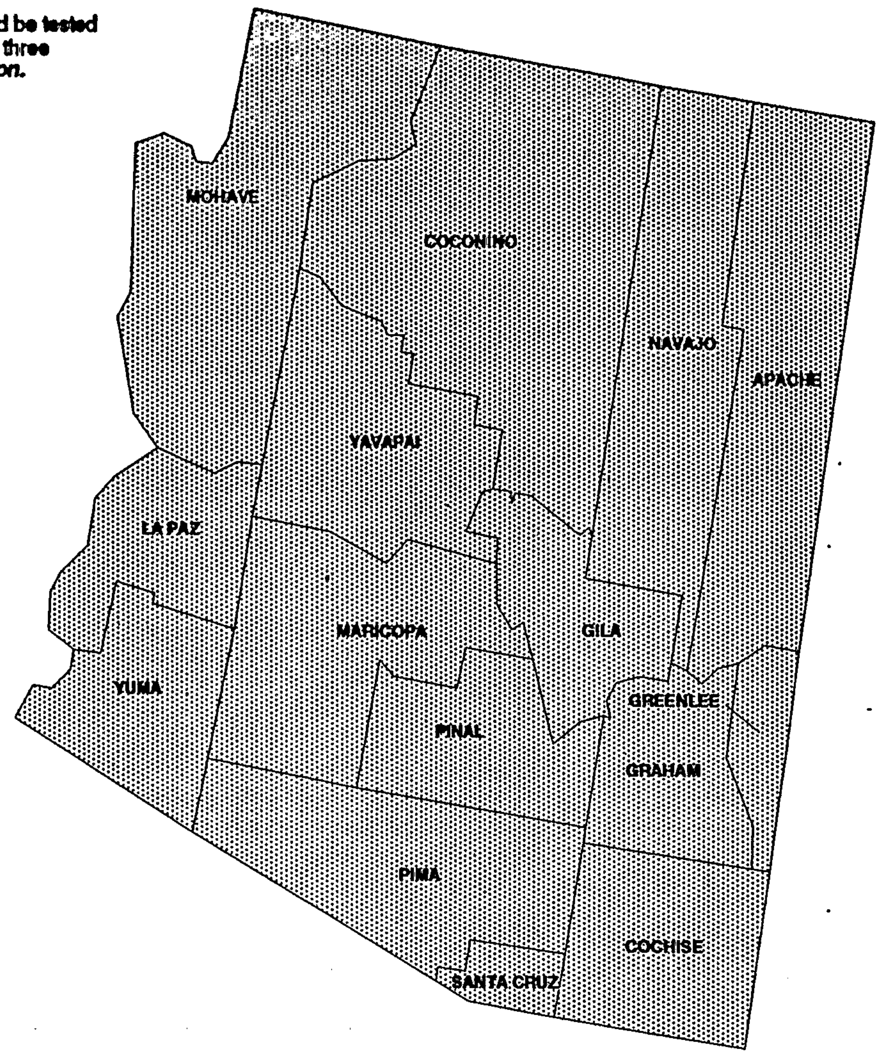
The Arizona Map of Radon Zones and its supporting documentation (Part IV of this report) have received extensive review by Arizona geologists and radon program experts. The map for Arizona generally reflects current State knowledge about radon for its counties. Some States have been able to conduct radon investigations in areas smaller than geologic provinces and counties, so it is important to consult locally available data.

Although the information provided in Part IV of this report -- the State chapter entitled "Preliminary Geologic Radon Potential Assessment of Arizona" -- may appear to be quite specific, it cannot be applied to determine the radon levels of a neighborhood, housing tract, individual house, etc. **THE ONLY WAY TO DETERMINE IF A HOUSE HAS ELEVATED INDOOR RADON IS TO TEST.** Contact the Region 9 EPA office or the Arizona radon program for information on testing and fixing homes. Telephone numbers and addresses can be found in Part II of this report.

ARIZONA - EPA Map of Radon Zones

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

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



Zone 1 | Zone 2 | Zone 3

IMPORTANT: Consult the publication entitled "Preliminary Geologic Radon Potential Assessment of Arizona" before using this map. This document contains information on radon potential variations within counties. EPA also recommends that this map be supplemented with any available local data in order to further understand and predict the radon potential of a specific area.