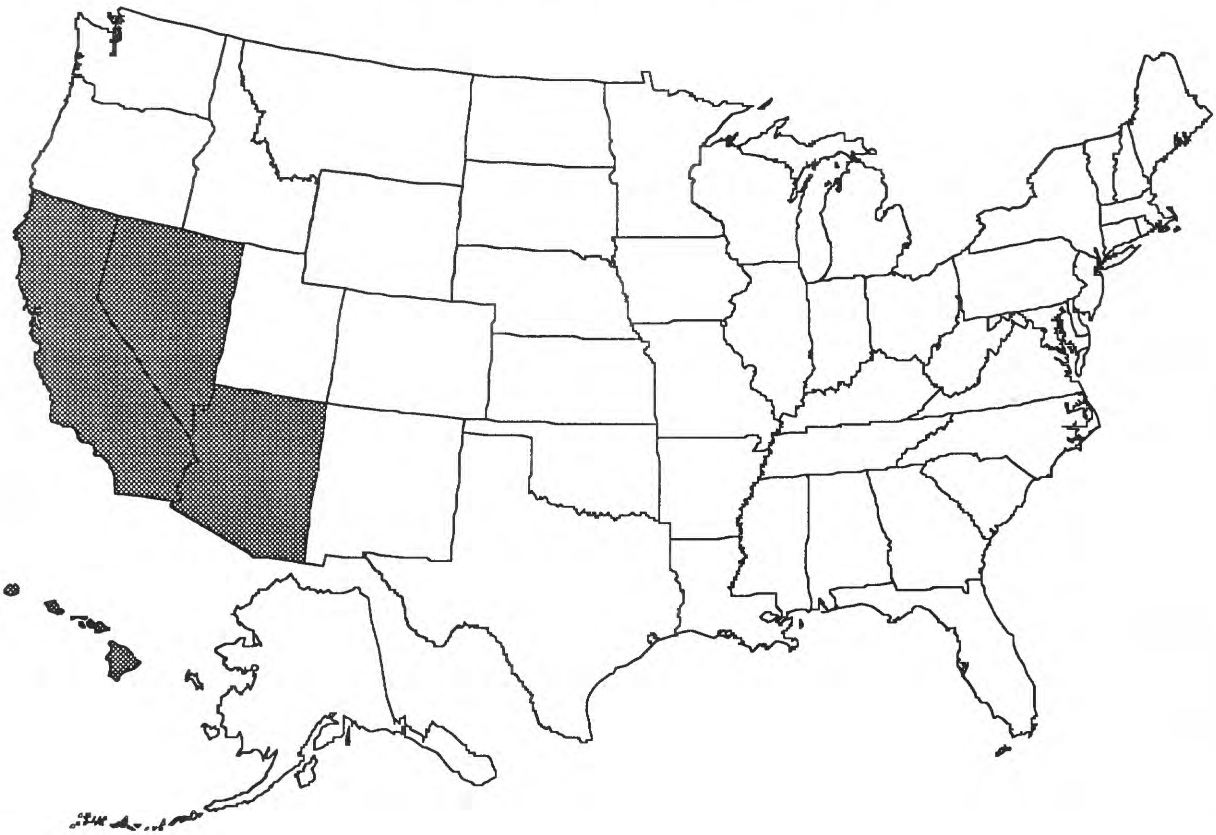
U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

GEOLOGIC RADON POTENTIAL OF EPA REGION 9

Arizona California Hawaii Nevada



OPEN-FILE REPORT 93-292-I

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

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Arizona, California, Hawaii, and Nevada

R. Randall Schumann
EDITOR

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

CONTENTS

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THE USGS/EPA RADON POTENTIAL ASSESSMENTS: AN INTRODUCTION

by
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BACKGROUND

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

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

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

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

RADON GENERATION AND TRANSPORT IN SOILS

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

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

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

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

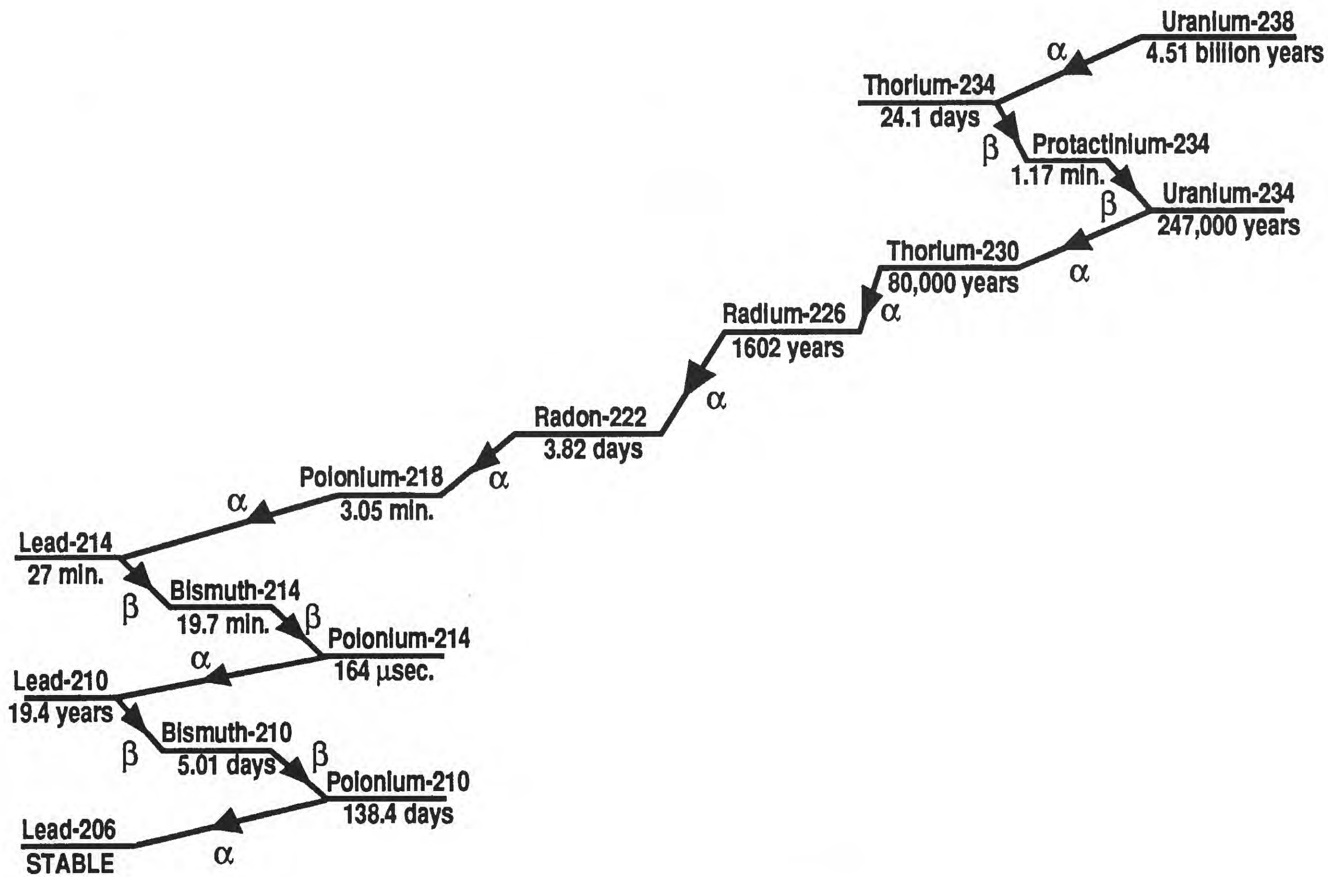


Figure 1. The uranium-238 decay series, showing the half-lives of elements and their modes of decay (after Wanty and Schoen, 1991). α denotes alpha decay, β denotes beta decay.

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

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

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

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

RADON ENTRY INTO BUILDINGS

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

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

METHODS AND SOURCES OF DATA

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

GEOLOGIC DATA

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

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

NURE Aerial Radiometric Data

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

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

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

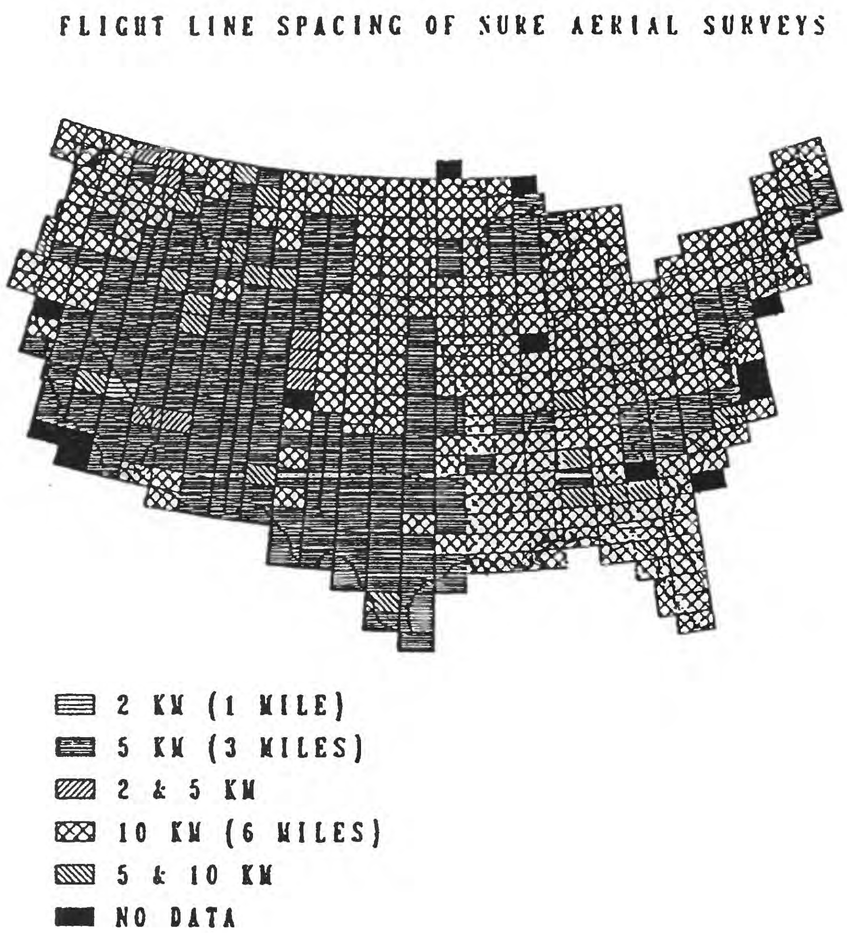


Figure 2. Nominal flightline spacings for NURE aerial gamma-ray surveys covering the contiguous United States (from Duval and others, 1990). Rectangles represent 1°x2° quadrangles.

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

SOIL SURVEY DATA

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

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

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

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

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

INDOOR RADON DATA

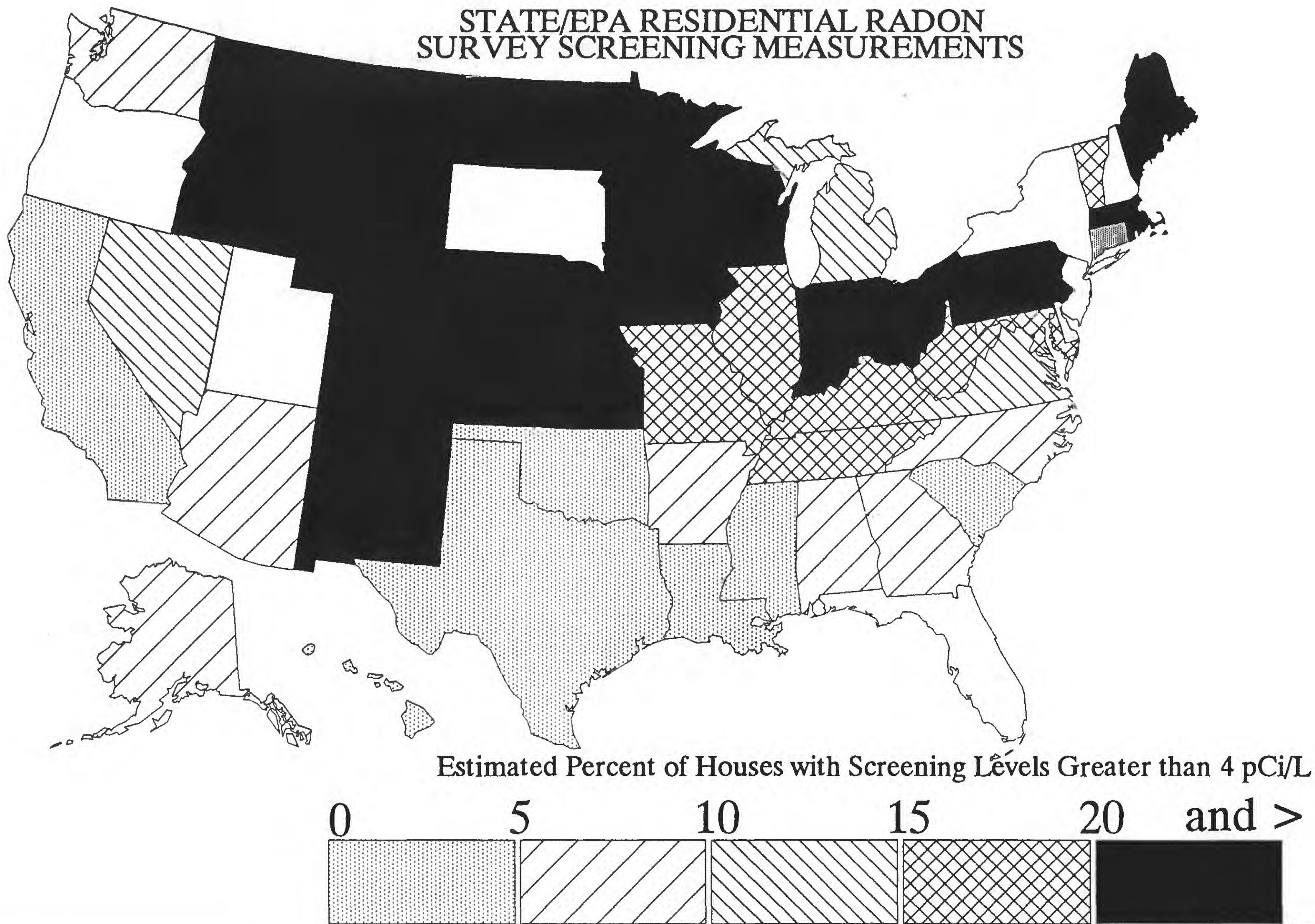
Two major sources of indoor radon data were used. The first and largest source of data is from the State/EPA Residential Radon Survey (Ronca-Battista and others, 1988; Dziuban and others, 1990). Forty-two states completed EPA-sponsored indoor radon surveys between 1986 and 1992 (fig. 3). The State/EPA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

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

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

RADON INDEX AND CONFIDENCE INDEX

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



The States of DE,FL,NH,NJ,NY, and UT have conducted their own surveys. OR & SD declined to participate in the SRRS.

These results are based on 2-7 day screening measurements in the lowest livable level and should not be used to estimate annual averages or health risks.

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

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

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

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

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

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

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

INCREASING RADON POTENTIAL →

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

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

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

SCORING:

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

POSSIBLE RANGE OF POINTS = 3 to 17

TABLE 2. CONFIDENCE INDEX MATRIX

INCREASING CONFIDENCE →

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

SCORING:

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

POSSIBLE RANGE OF POINTS = 4 to 12

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

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

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

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

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

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

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

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

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

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

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

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

EPA COUNTY RADON POTENTIAL MAPS

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

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APPENDIX A
GEOLOGIC TIME SCALE

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

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

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

[3] Rocks older than 570 Ma also called Precambrian (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/m³ (Becquerels per cubic meter)- a metric unit of radioactivity used to describe radon concentrations in a volume of air. One becquerel is equal to one radioactive disintegration per second. One pCi/L is equal to 37 Bq/m^3.

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

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

Geologic terms and terms related to the study of radon

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

eolian Pertaining to sediments deposited by the wind.

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

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

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

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

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

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

formation A mappable body of rock having similar characteristics.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

placer deposit See heavy minerals

residual Formed by weathering of a material in place.

residuum Deposit of residual material.

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

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

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

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

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

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

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

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

shrink-swell clay See clay mineral.

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

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

slope An inclined part of the earth's surface.

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

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

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

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

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

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

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

uraniferous Containing uranium, usually more than 2 ppm.

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

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

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

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

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Alaska	10
Arizona	9
Arkansas	6
California	9
Colorado	8
Connecticut	1
Delaware	3
District of Columbia	3
Florida	4
Georgia	4
Hawaii	9
Idaho	10
Illinois	5
Indiana	5
Iowa	7
Kansas	7
Kentucky	4
Louisiana	6
Maine	1
Maryland	3
Massachusetts	1
Michigan	5
Minnesota	5
Mississippi	4
Missouri	7
Montana	8
Nebraska	7
Nevada	9
New Hampshire	1
New Jersey	2
New Mexico	6
New York	2
North Carolina	4
North Dakota	8
Ohio	5
Oklahoma	6
Oregon	10
Pennsylvania	3
Rhode Island	1
South Carolina	4
South Dakota	8
Tennessee	4
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Utah	8
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EPA REGION 9 GEOLOGIC RADON POTENTIAL SUMMARY

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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.

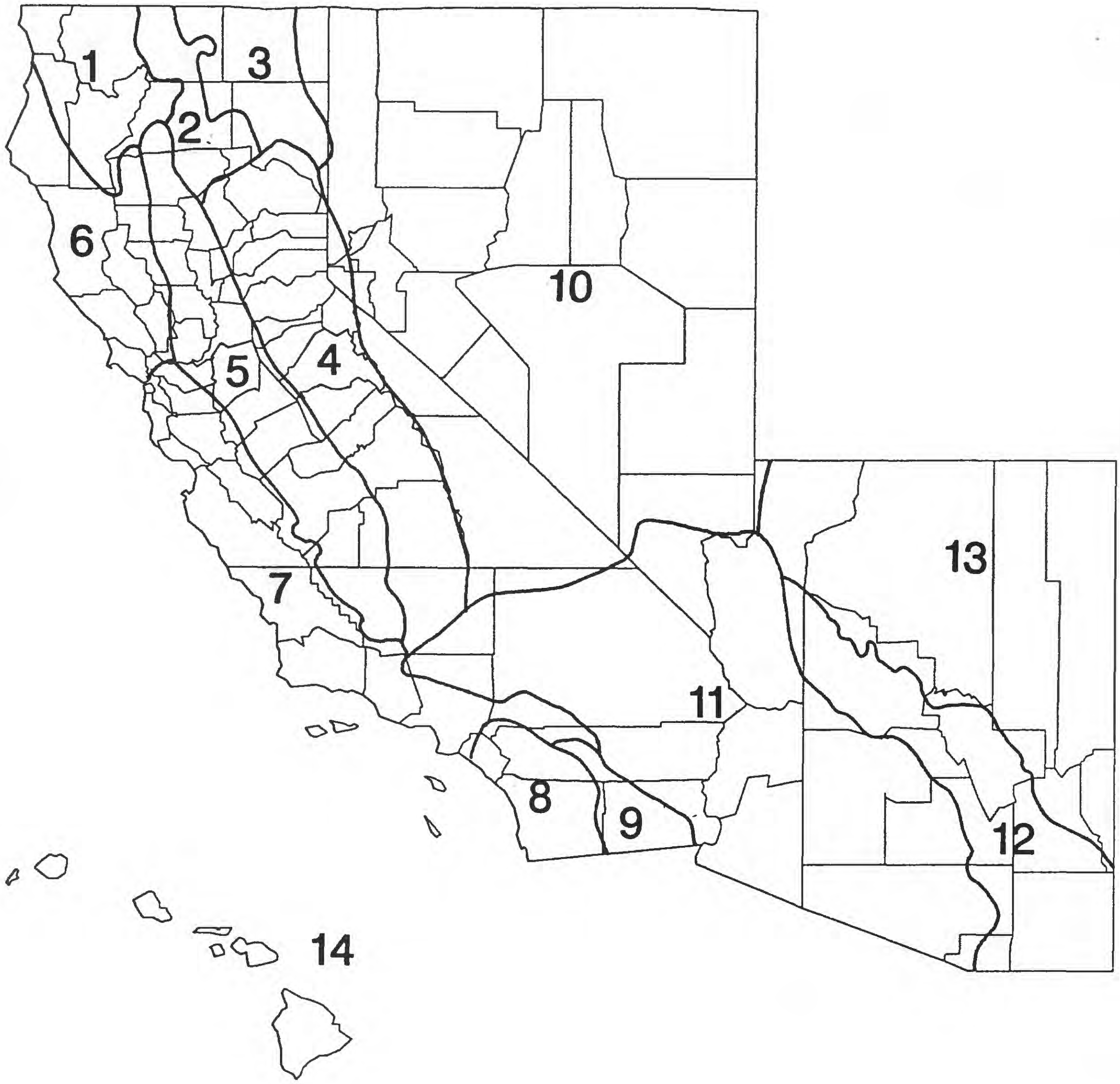

Figure 1- Geologic radon provinces of EPA region 9. 1- Klamath Mountains; 2- Cascade Range; 3- Modoc Plateau; 4- Sierra Nevada; 5- Great Valley; 6- Northern Coast Ranges; 7- Southern Coast and Transverse Ranges; 8- Peninsular Ranges; 9- Colorado Desert; 10- Basin and Range; 11- Mojave-Sonoran Desert;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

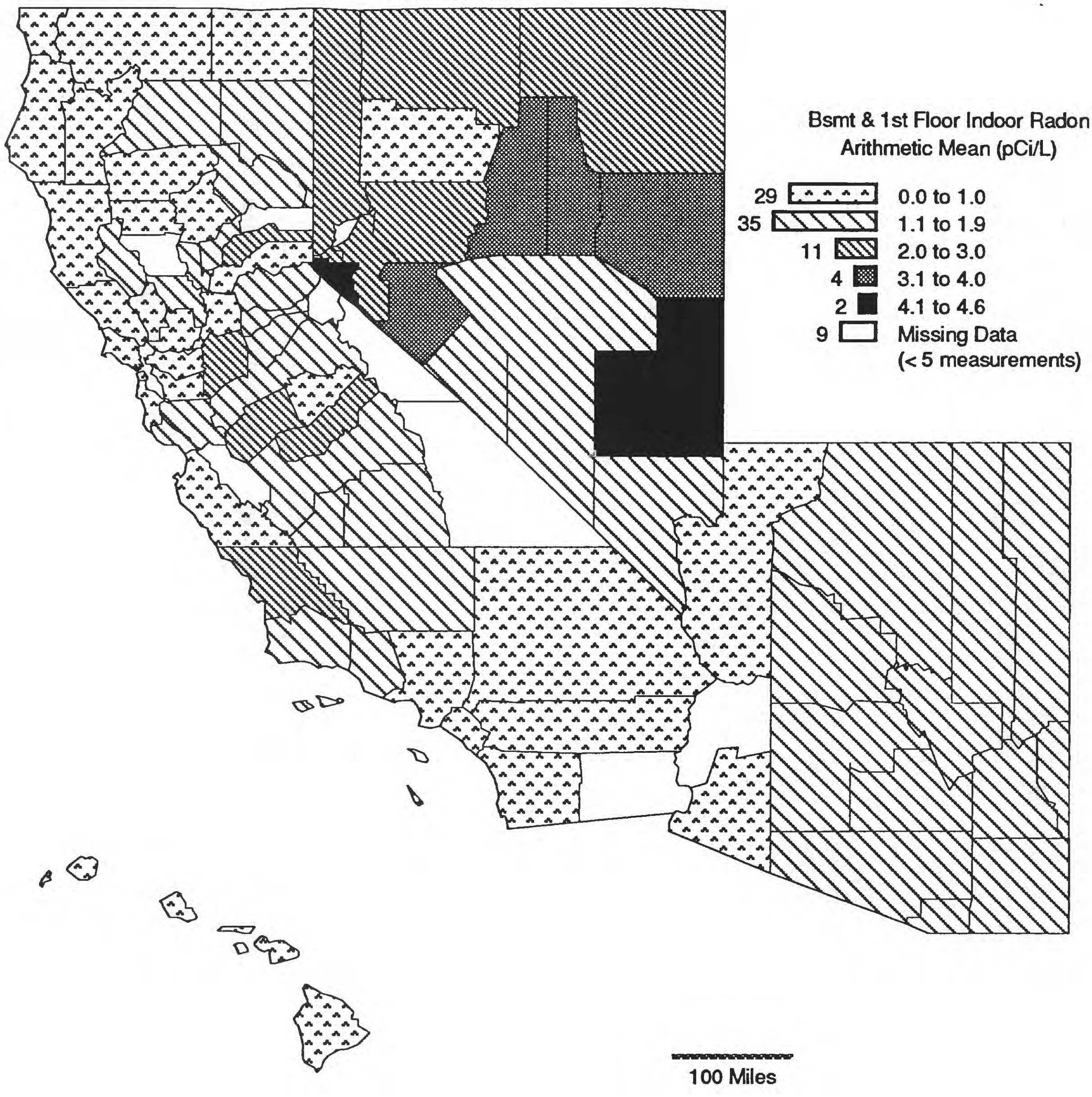

Figure 2. Screening indoor radon data from the State/EPA Residential Radon Survey, for counties with 5 or more measurements in EPA Region 9. Data are from 2-7 day charcoal canister tests. Histograms in map legends show the number of counties in each category. The number of samples in each county may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

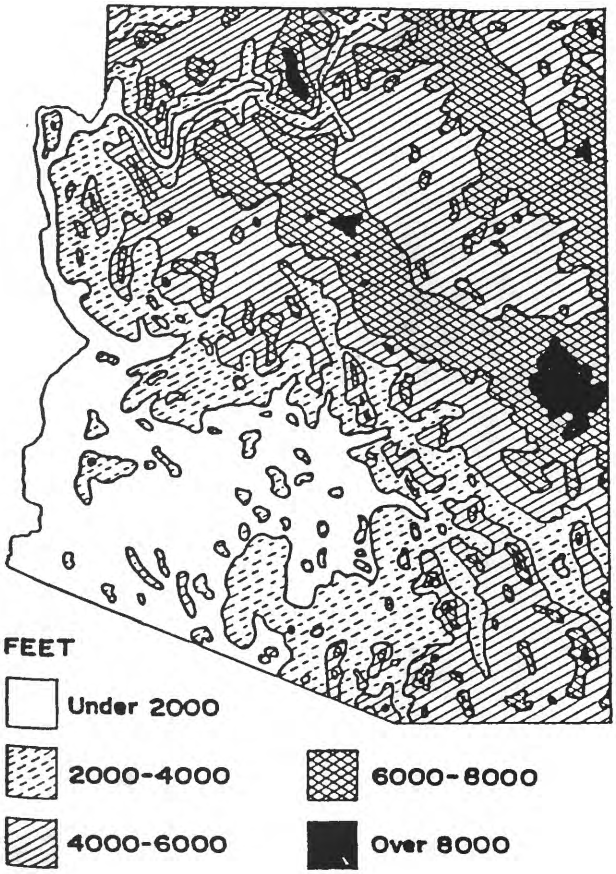


Figure 2. Map showing generalized topography in Arizona (modified from Bahre, 1976).

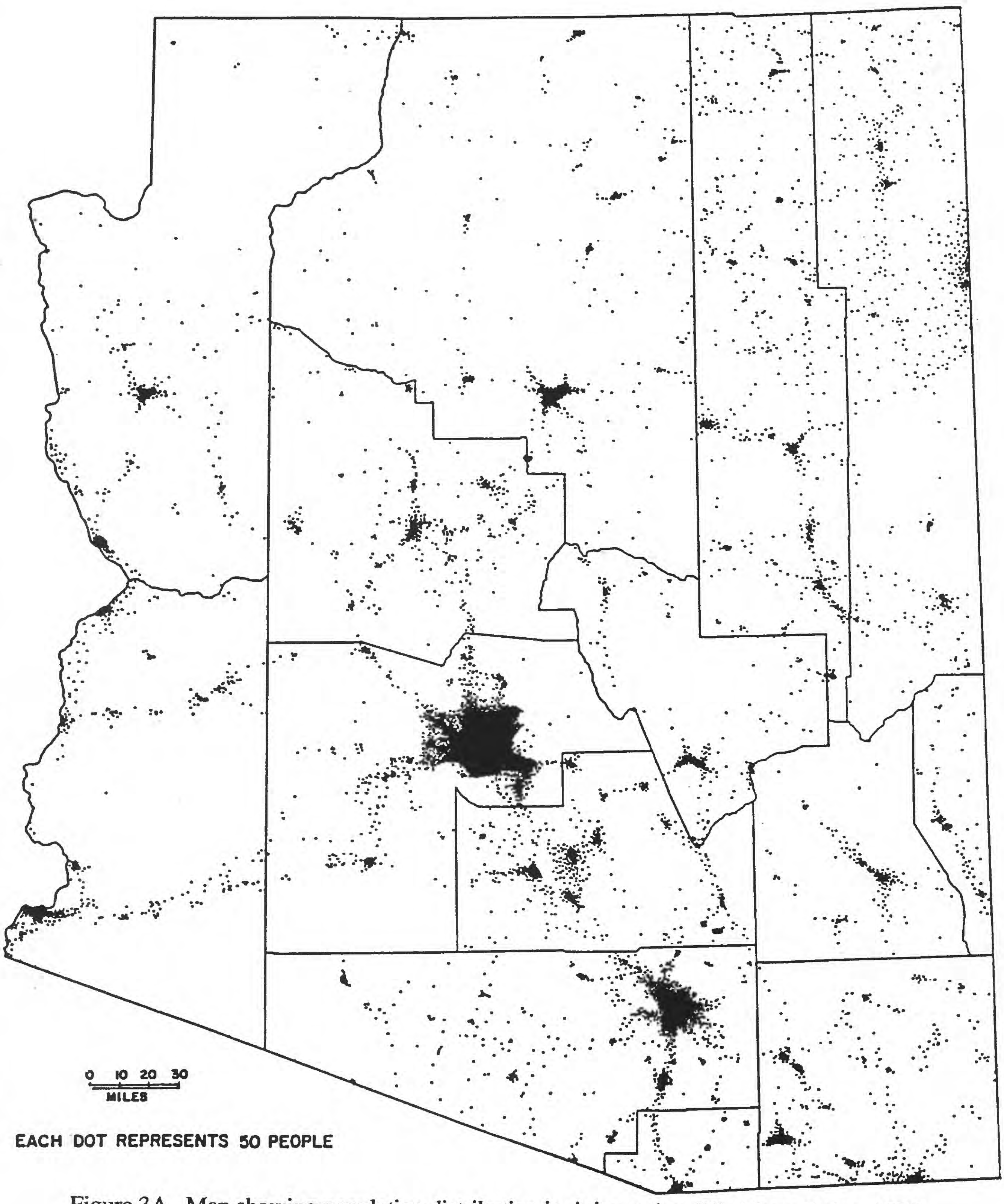


Figure 3A. Map showing population distribution in Arizona (modified from Bahre, 1976).

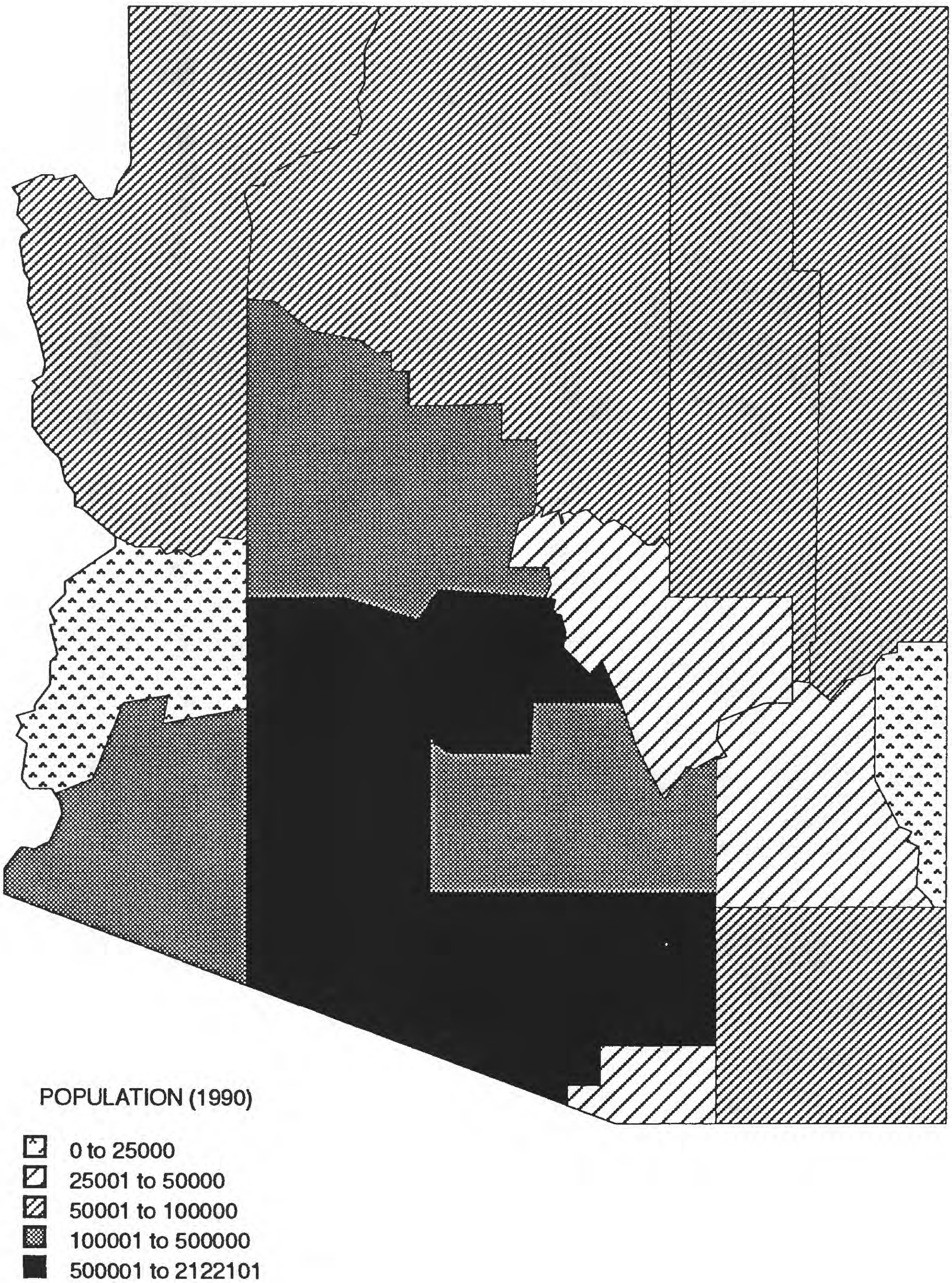


Figure 3B. Population of counties in Arizona (1990 U.S. Census data).

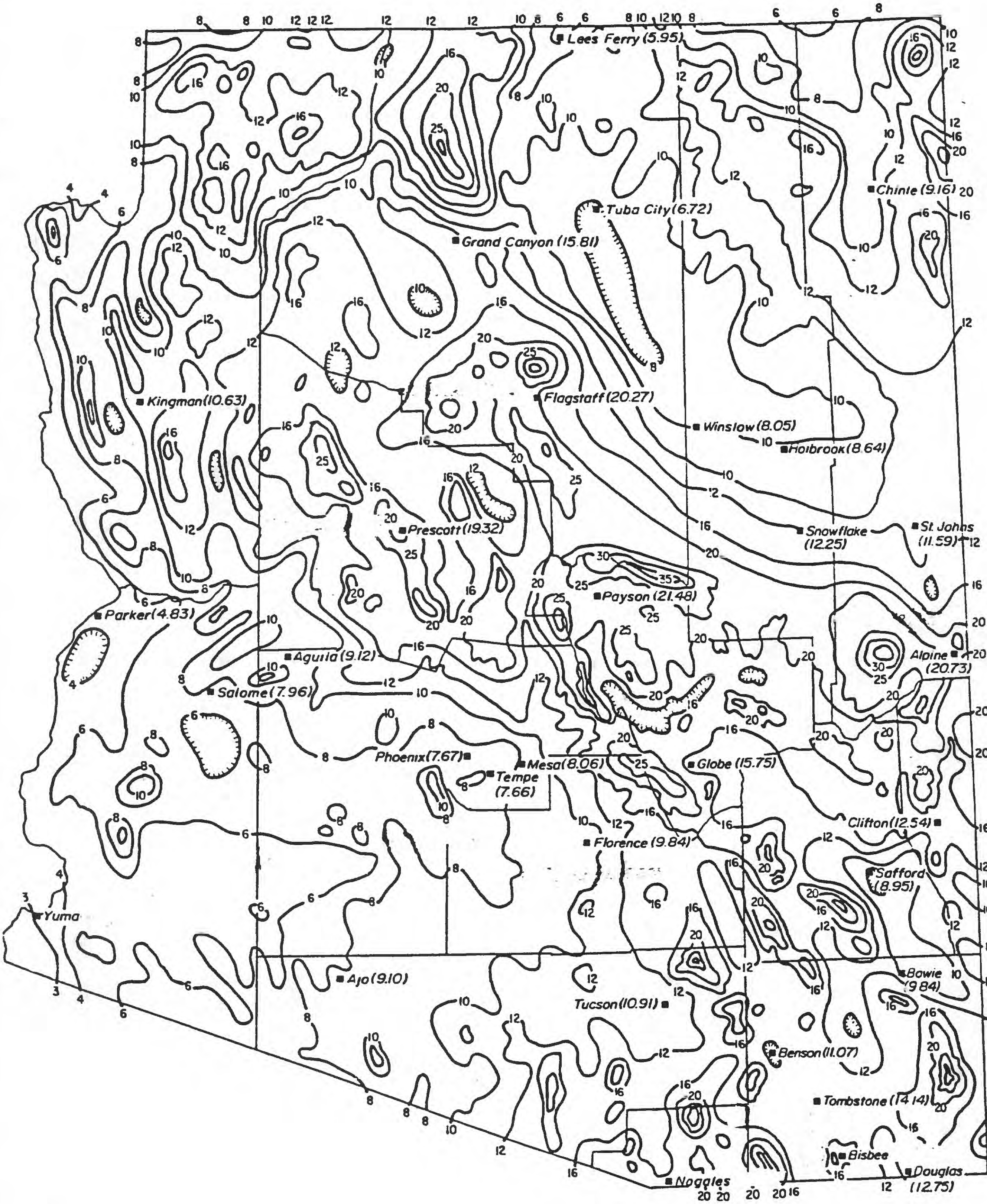


Figure 4. Map showing rainfall distribution for Arizona in inches (modified from Bahre, 1976).

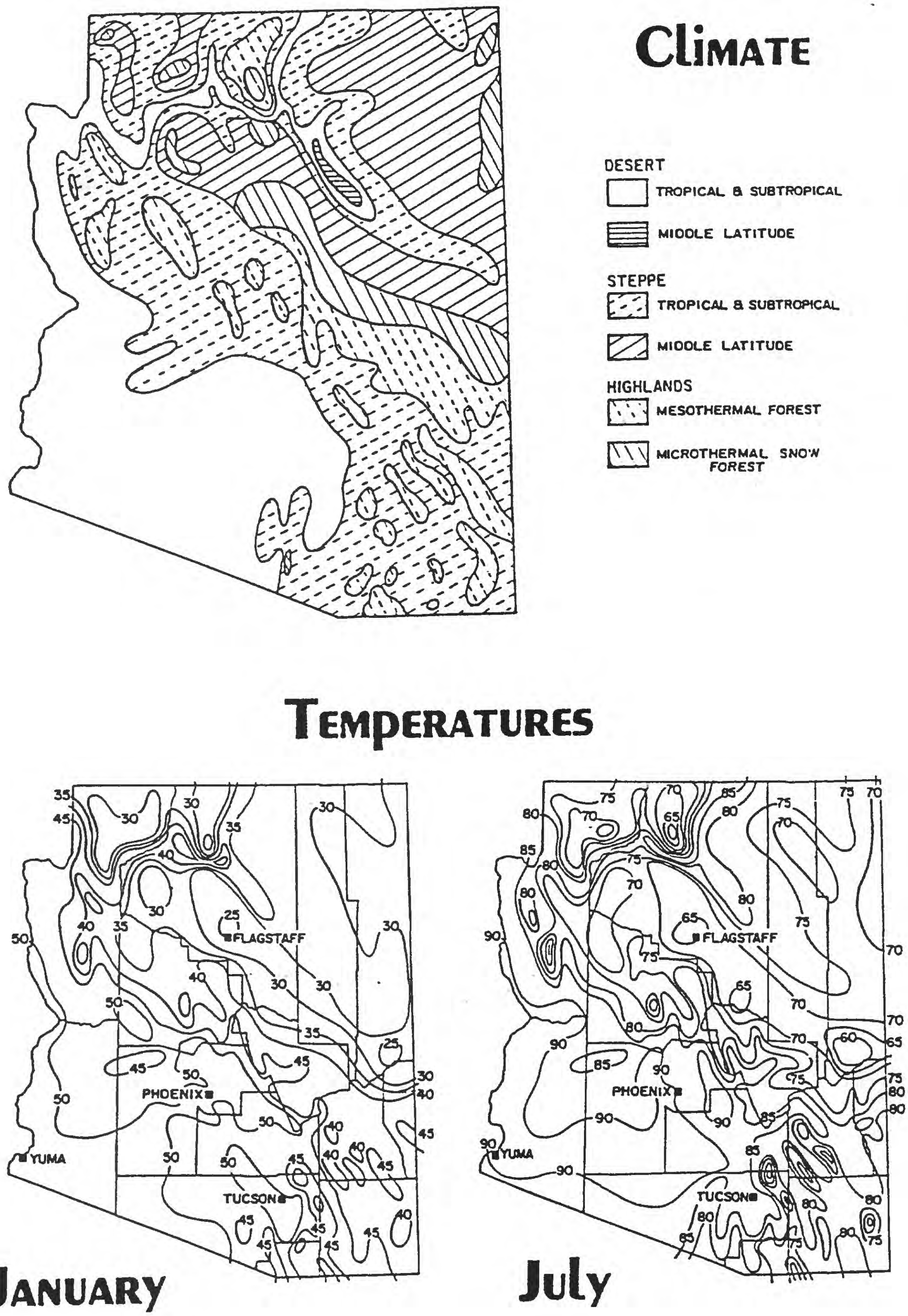


Figure 5. Maps showing general climate and seasonal temperatures (in degrees Fahrenheit) (modified from Bahre, 1976).

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

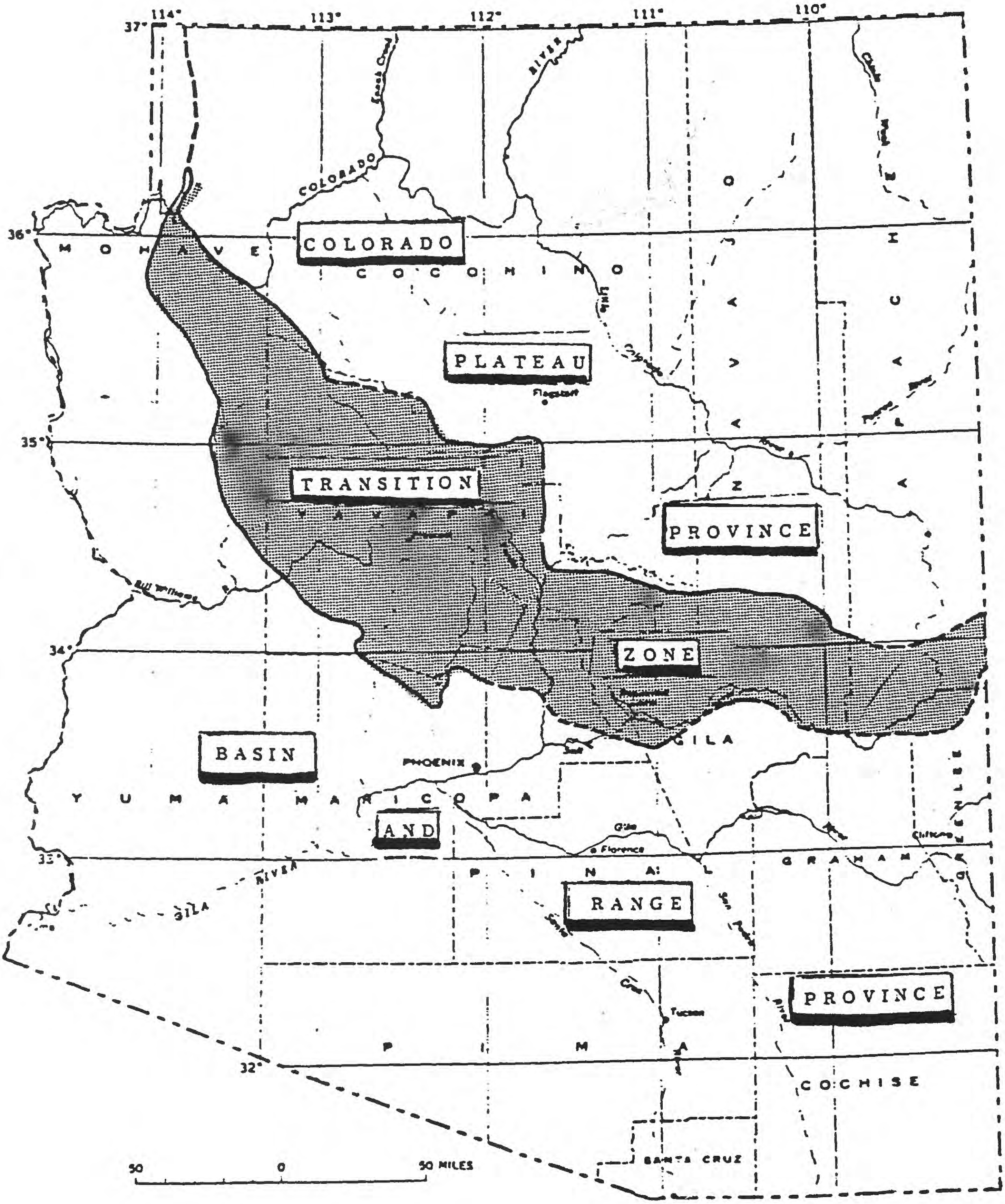


Figure 6. Map showing physiographic provinces in Arizona (modified from Scarborough and Wilt, 1979).

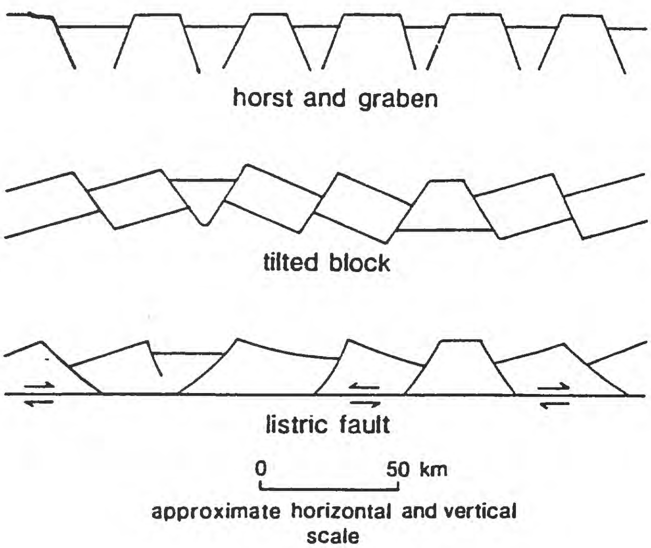


Figure 7A. Model showing types of faulting (modified from Hendricks and others, 1985).

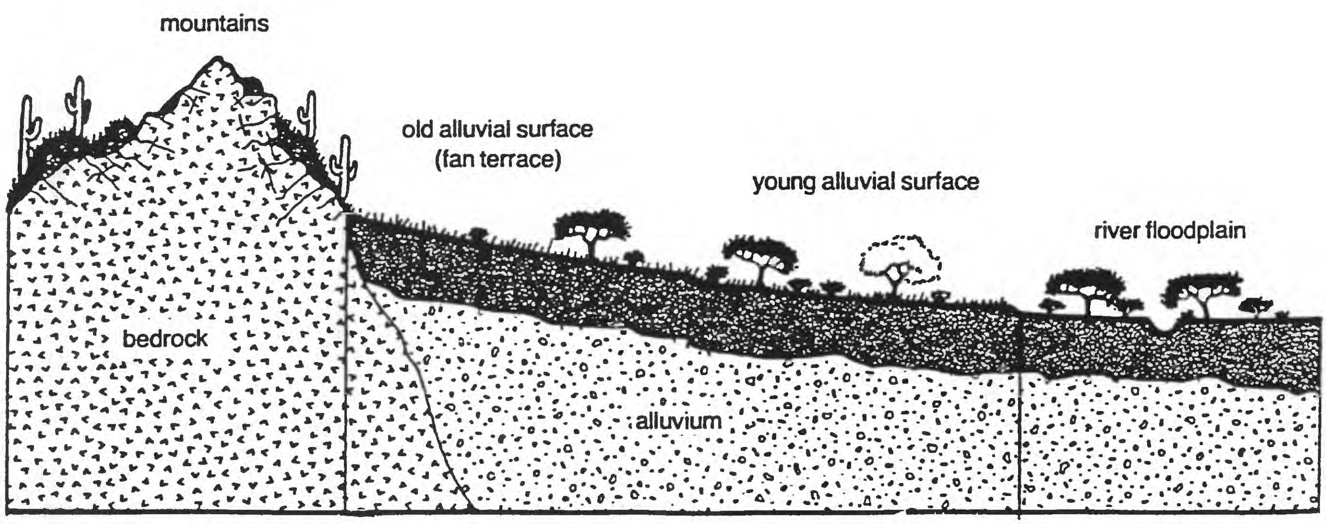


Figure 7B. Typical cross section of Arizona's Basin and Range features (modifed from Hendricks and others, 1985).

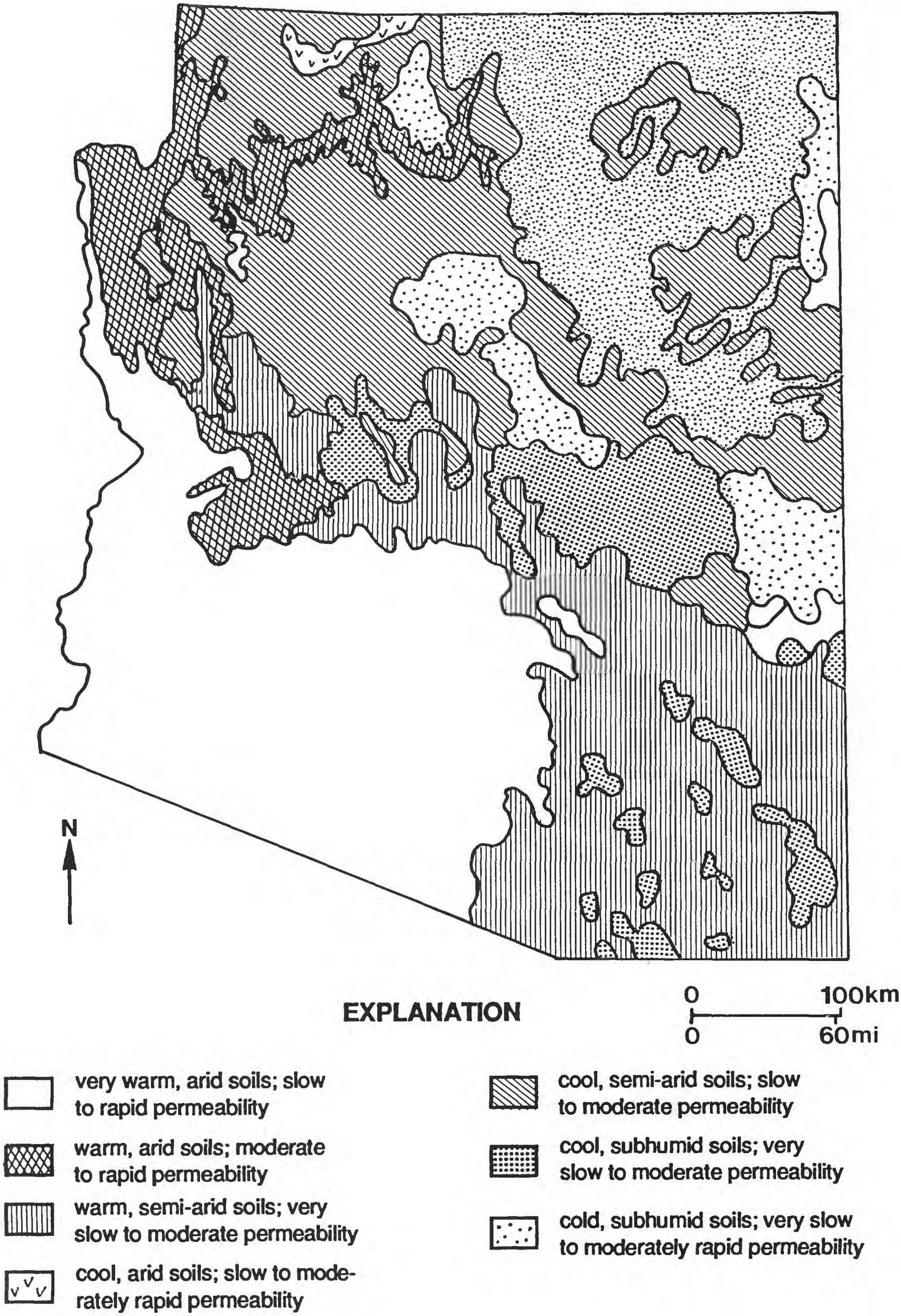


Figure 8A. Map showing generalized geology of Arizona (modified from Hendricks and others, 1985).

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

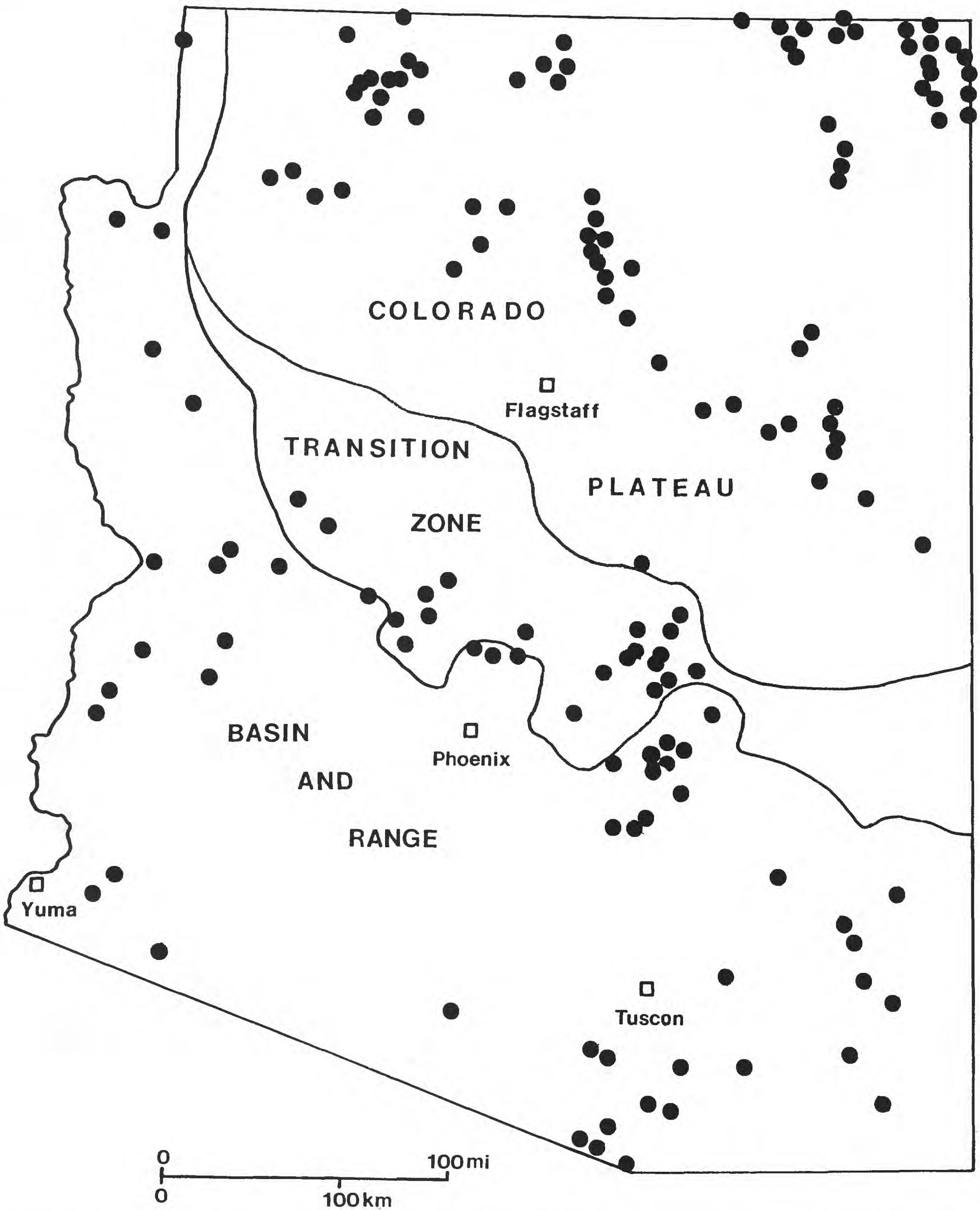


Figure 8B. Map showing distribution of uranium deposits in Arizona (modified from Wenrich and others, 1989).

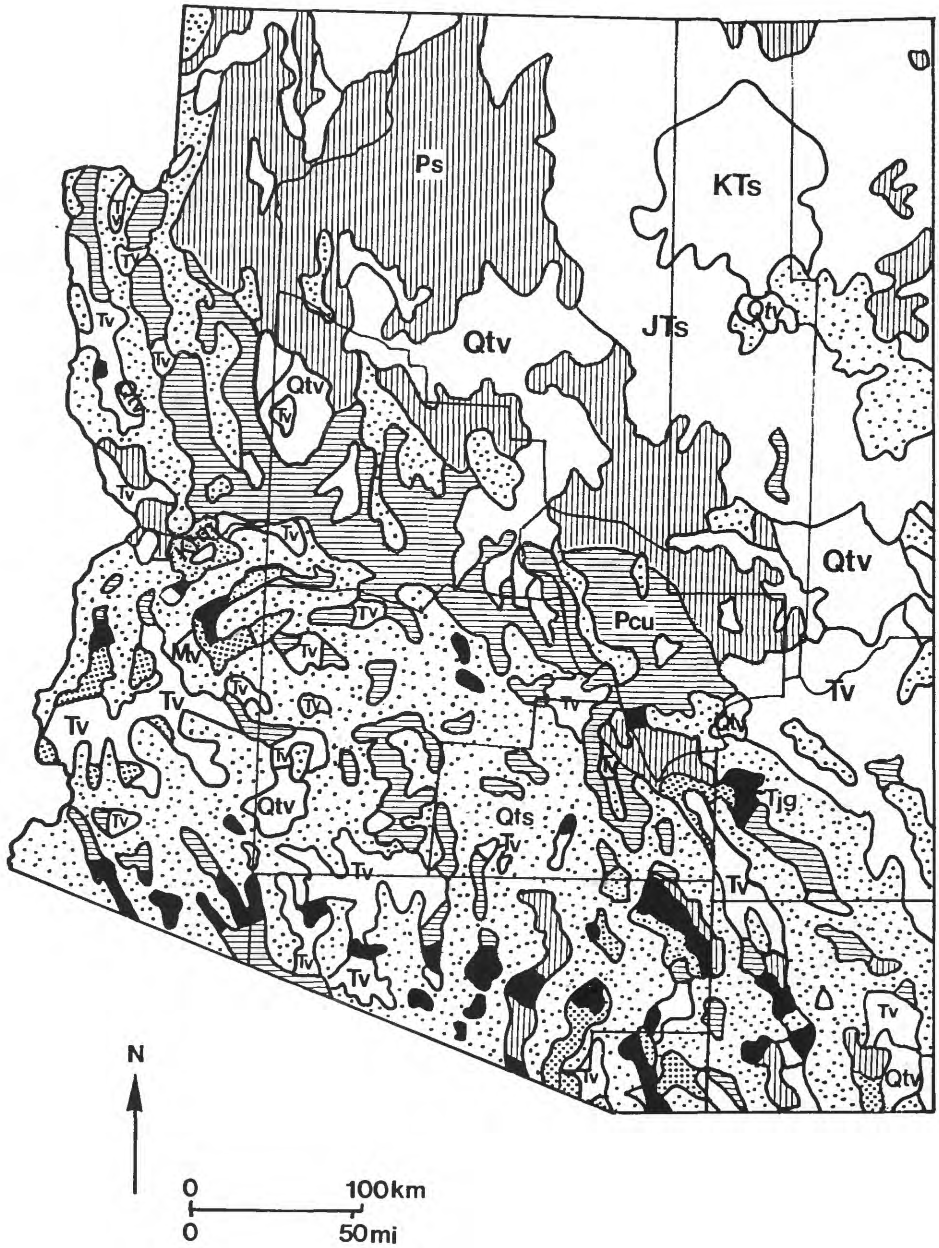
Ruby in Santa Cruz County and near Arivaca in southeastern Pima County. Many of the Lower Jurassic to mid-Tertiary silicic volcanic rocks in southern Arizona are poorly mapped in detail and are little studied to date; preliminary work (Scarborough, 1981; Wenrich and others, 1989) indicates that many 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.



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 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.

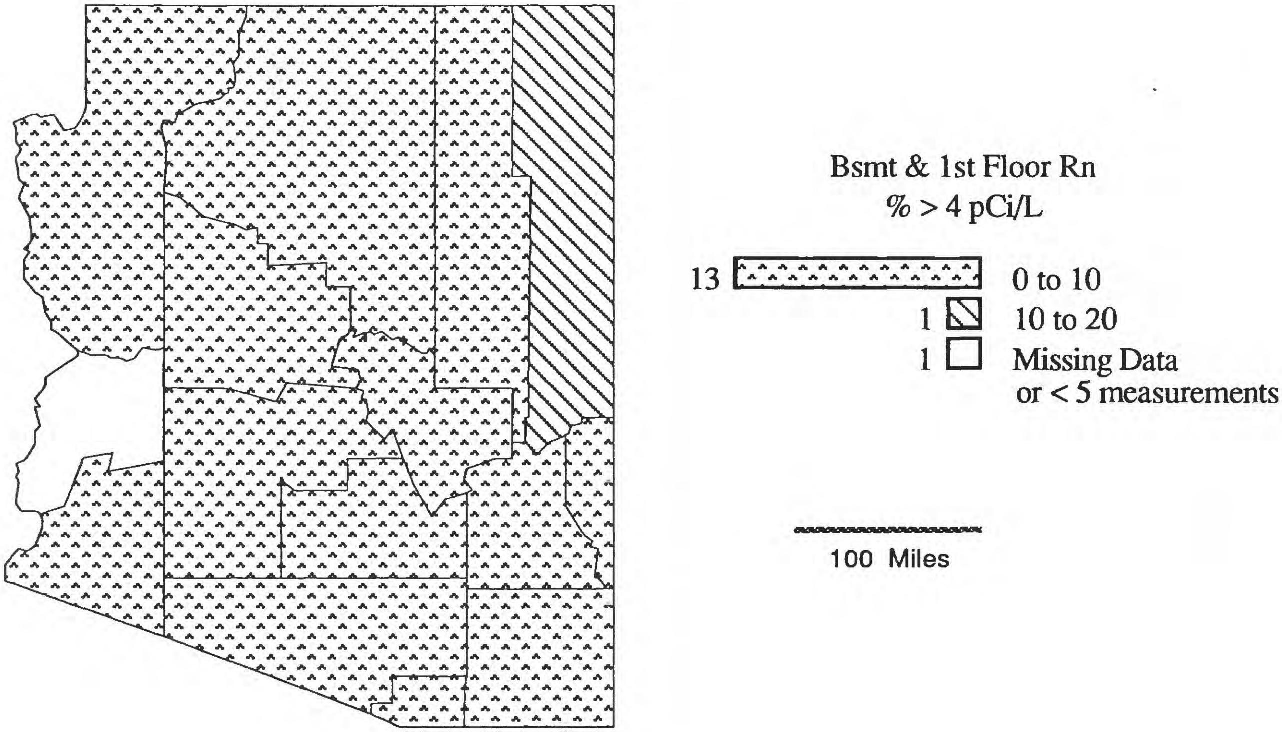
Many homes in Arizona are built on concrete slabs (Spencer, 1986), and only 3 counties (Maricopa, Navajo, and Yavapai) had more than 5 basement measurements in the State/EPA survey. County average screening indoor radon concentrations were between 0.3 and 1.9 pCi/L in the State/EPA Residential Radon 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



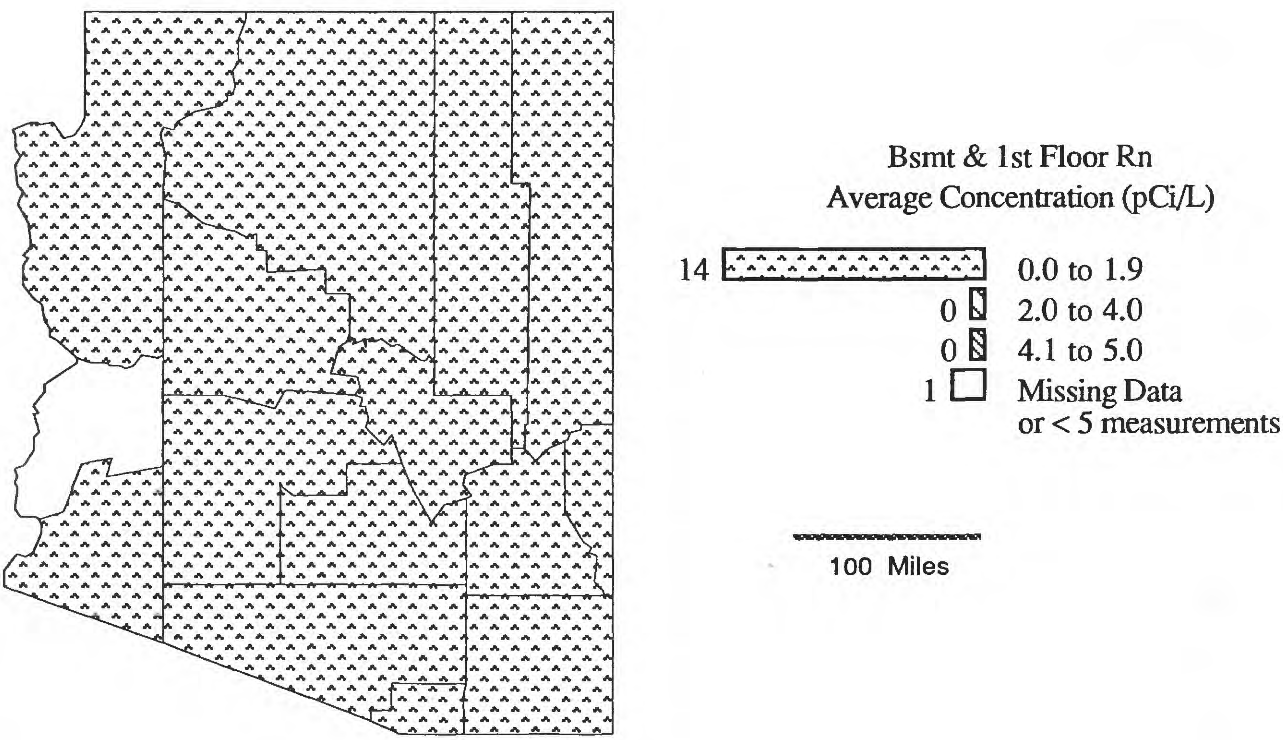


Figure 9. Screening indoor radon data from the EPA/State Residential Radon Survey of Arizona, 1987-88, for counties with 5 or more measurements. Data are from 2-7 day charcoal canister tests. Histograms in map legends show the number of counties in each category. The number of samples in each county (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

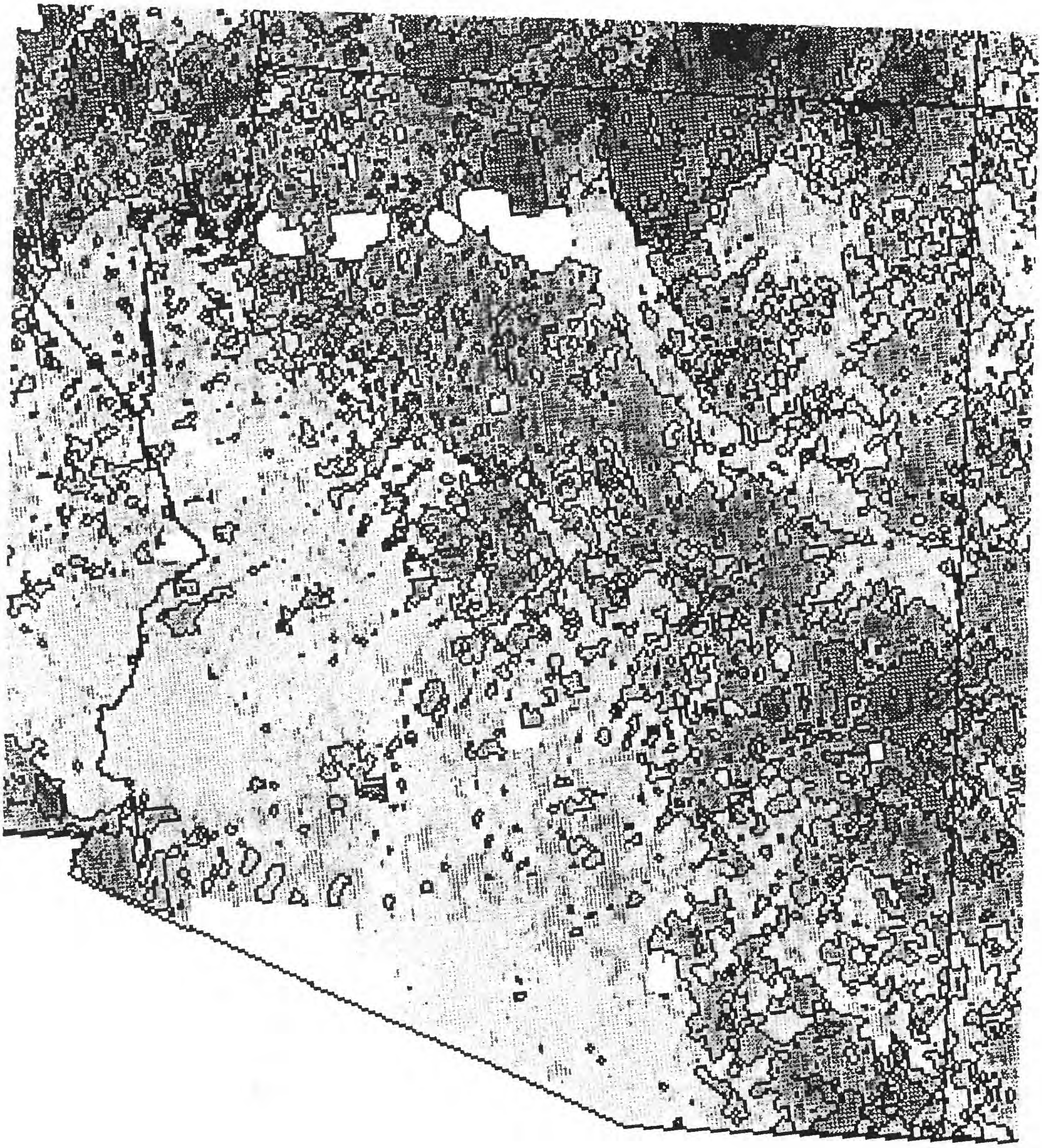


Figure 10. Aerial radiometric map of Arizona (after Duval and others, 1989). Contour lines at 1.5 and 2.5 ppm equivalent uranium (eU). Pixels shaded from 0 to 6.0 ppm eU at 0.5 ppm eU increments; darker pixels have lower eU values; white indicates no data.

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

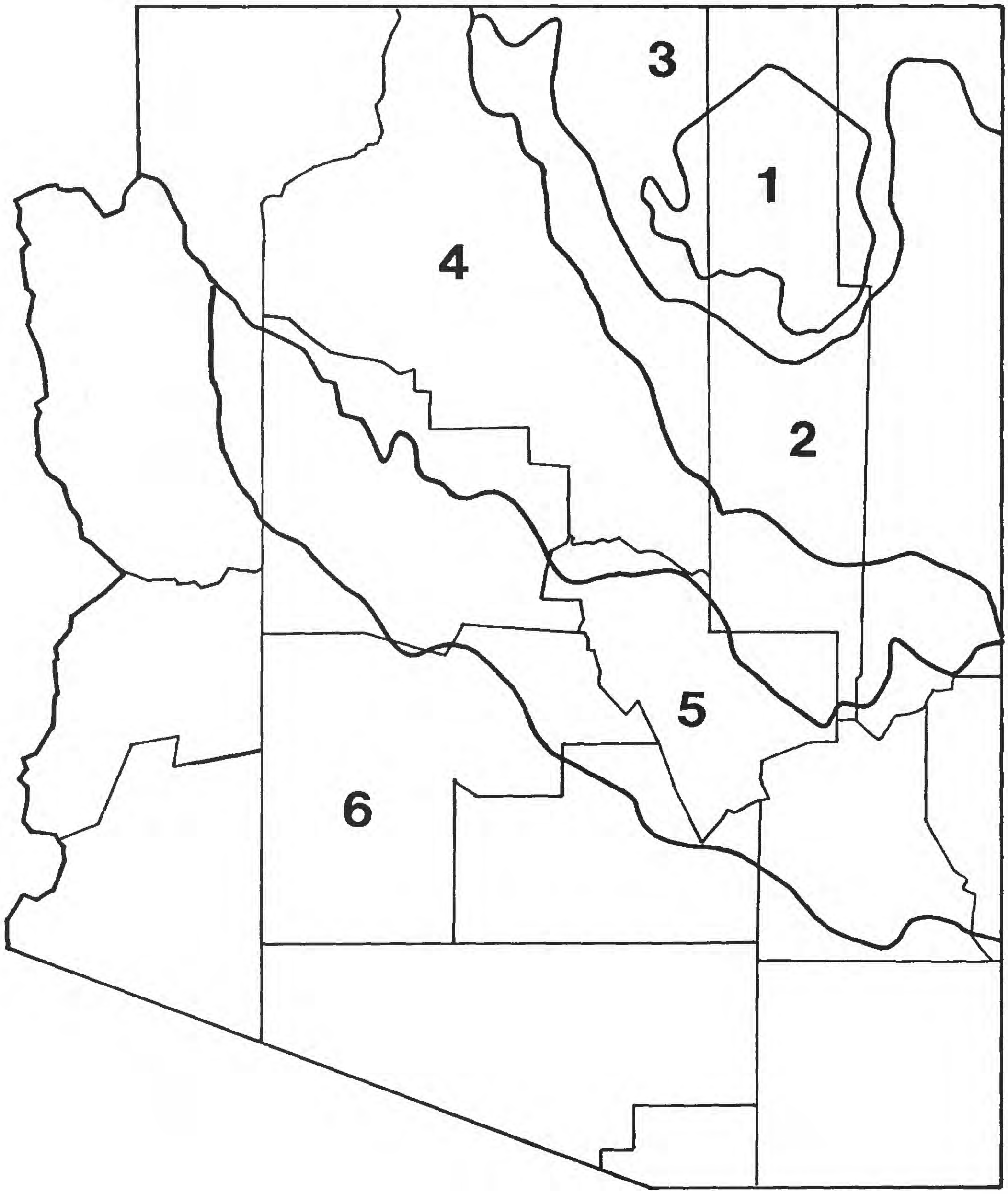


Figure 11. Map showing radon potential areas in Arizona (see Table 1 and text for discussion of areas).

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 <u>not</u> be made without consulting all available local data. For additional information on radon and how to test, contact your State radon program or EPA regional office. More detailed information on state or local geology may be obtained from the State geological survey. Addresses and phone numbers for these agencies are listed in chapter 1 of this booklet.

TABLE 2. Radon Index (RI) and Confidence Index (CI) scores for geologic radon potential areas of 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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PRELIMINARY GEOLOGIC RADON POTENTIAL ASSESSMENT OF CALIFORNIA

by
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INTRODUCTION

This assessment of the radon potential of California relies heavily on geologic information derived from publications of the California Division of Mines and Geology, from publications of the U.S. Geological Survey, from previous work by personnel at Lawrence Berkeley Laboratory (Moed and others, 1984), from an analysis of indoor radon data from the State/EPA Indoor Radon Survey of California conducted during 1989-1990, and from a study of radon potential in California by the California Air Resources Board (Liu and others, 1990). Much information in the geographic setting section is derived from The National Atlas of the United States of America and from the Atlas of California (Donley and others, 1979).

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

GEOGRAPHIC SETTING

California lies at the western edge of North America. Twelve physiographic provinces are discussed here (slightly modified from the 11 of Donley and others, 1979): the Klamath Mountains, the Cascade Range, the Modoc Plateau, the Northern Coast Ranges, the Southern Coast Ranges, the Great Valley, the Sierra Nevada, the Basin and Range, the Mojave Desert, the Transverse Ranges, the Peninsular Ranges, and the Colorado Desert (fig. 1).

The Klamath Mountains form an area of high mountains where the relief generally ranges 3000-5000 feet except in coastal areas where the relief is 1000-3000 feet. Less than 20 percent of the surface area is gently sloped. The Cascade Range is characterized by open high mountains where the relief is 3000-5000 feet and 20-50 percent of the land's surface is gently sloped. The Modoc Plateau is an area of tablelands of moderate relief (300-500 feet) and plains with low mountains (relief 1000-3000 feet). Gentle slopes occupy 50-80 percent of the land.

The Northern Coast Ranges comprise mostly low mountains with open low mountains in the southern part. Relief ranges from about 1000-3000 feet. The Southern Coast Ranges are mostly open low mountains, but high mountains lie along the coast south of Monterey Bay and

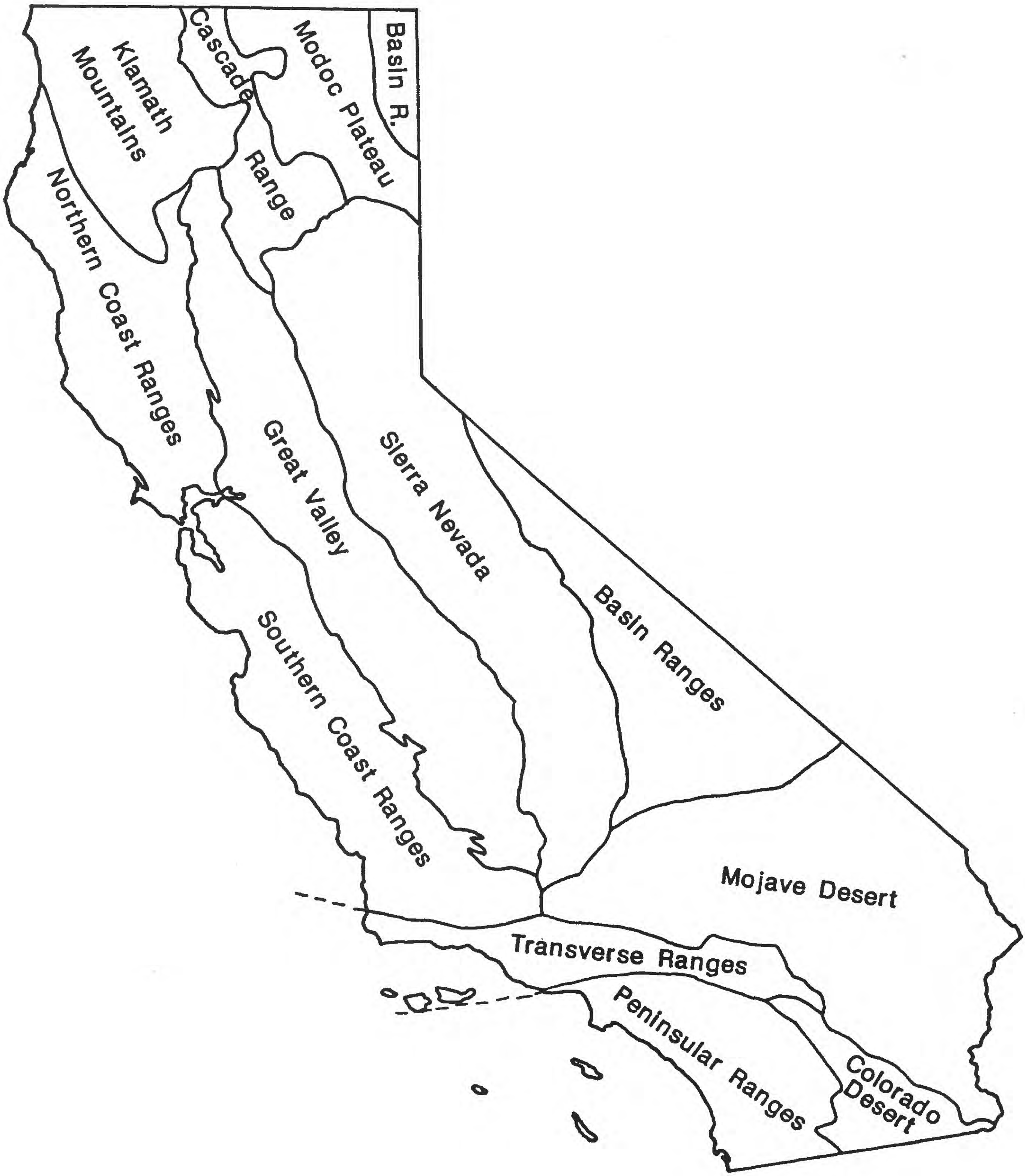


Fig. 1- Physiographic provinces of California. Modified from Donley and others, 1979.

low mountains flank the Great Valley along the eastern side of this province. Relief is 1000-3000 feet except in the high mountains where it is 3000-5000 feet.

The Great Valley is an area of flat plains where local relief is less than 100 feet. Greater then 80 percent of the area is gently sloping. Large wetlands occupy the central parts of the northern and south-central Great Valley. Irregular plains or irregular plains and hills flank the Great Valley to the north and east and form a transition to adjacent mountains.

The Sierra Nevada is the largest and highest mountain range in the State. High mountains with relief ranging 3000-5000 feet form the western two-thirds of this range and low mountains with 1000-3000 feet of relief lie between the higher mountains to the east and the adjacent Great Valley. The Basin and Range is characterized by plains with high mountains and open high mountains where relief ranges 3000-5000 feet. The Mojave Desert is an area of plains with low mountains and, in its western parts, plains with hills. Relief is 1000-3000 feet in the east and 300-500 feet in the west.

The Transverse Ranges are composed of high mountains (relief 3000-5000 feet) and open low mountains (relief 1000-3000 feet). The Peninsular Ranges are characterized by high mountains to the east (relief 3000-5000 feet), open low mountains in the central part (relief 1000-3000 feet) and tablelands of moderate relief (300-500 feet) along the coast. Plains with high hills occupy the area around Los Angeles (relief 1000-3000 feet). The Colorado Desert is an area of smooth plains where relief ranges 100-300 feet. The central part of this area is occupied by the Salton Sea. Large sand dunes occur in the eastern and western part of this province.

Precipitation in the mountains of the Cascade Range, the Klamath Mountains, the Northern Coast Ranges, and the Sierra Nevada ranges from 20 to more than 80 inches per year with the higher amounts occurring at the higher elevations. Some of the lower valleys in the eastern Klamath Mountains and the Cascade Range receive only 10-20 inches of precipitation per year. The Modoc Plateau receives 10-20 inches of precipitation per year. In the Southern Coast Ranges the high mountains near the coast receive 20-80 inches per year, but the rest of the area receives only 4 to 30 inches per year with the driest areas being the western interior valleys.

The Great Valley receives 4-30 inches of precipitation per year with the lower and southern parts of the valley being the driest. The Basin and Range province receives less than 4 to as much as 30 inches of precipitation per year, but only the mountains receive more than 10 inches. Most of the Mojave Desert receives less than 4 inches per year.

The Transverse Ranges receive 10 to 60 inches per year with altitude strongly controlling the amounts received. The Peninsular Ranges receive 4 to as much as 40 inches per year but only the higher mountains in the east part of the Province receive more than 20 inches per year. The Colorado Desert generally receives less than 4 inches of precipitation per year.

Most of the population of the State is concentrated in counties in coastal bay and valley areas and in the Great Valley (fig. 2, see fig. 3 for county names). Most of the desert areas of the Modoc Plateau, the Basin and Range, and the Mojave Desert, and the mountain areas of the Klamath Mountains, Cascade Range, Northern Coast Range, and the Sierra Nevada, are very sparsely populated.

The Klamath Mountains, the Northern Coast Ranges, the Cascade Range, and the Sierra Nevada are dominated by forest and woodland, some grazed and some ungrazed. Grazed open woodlands and desert shrublands are present throughout most of the Modoc Plateau. The Great Valley is one of the heavily developed agricultural areas of the world. Irrigated croplands and croplands with grazing occur throughout the Great Valley. The Southern Coast Ranges are a mix of grazed open woodland, ungrazed forest and woodland, and, in the valleys, cropland and

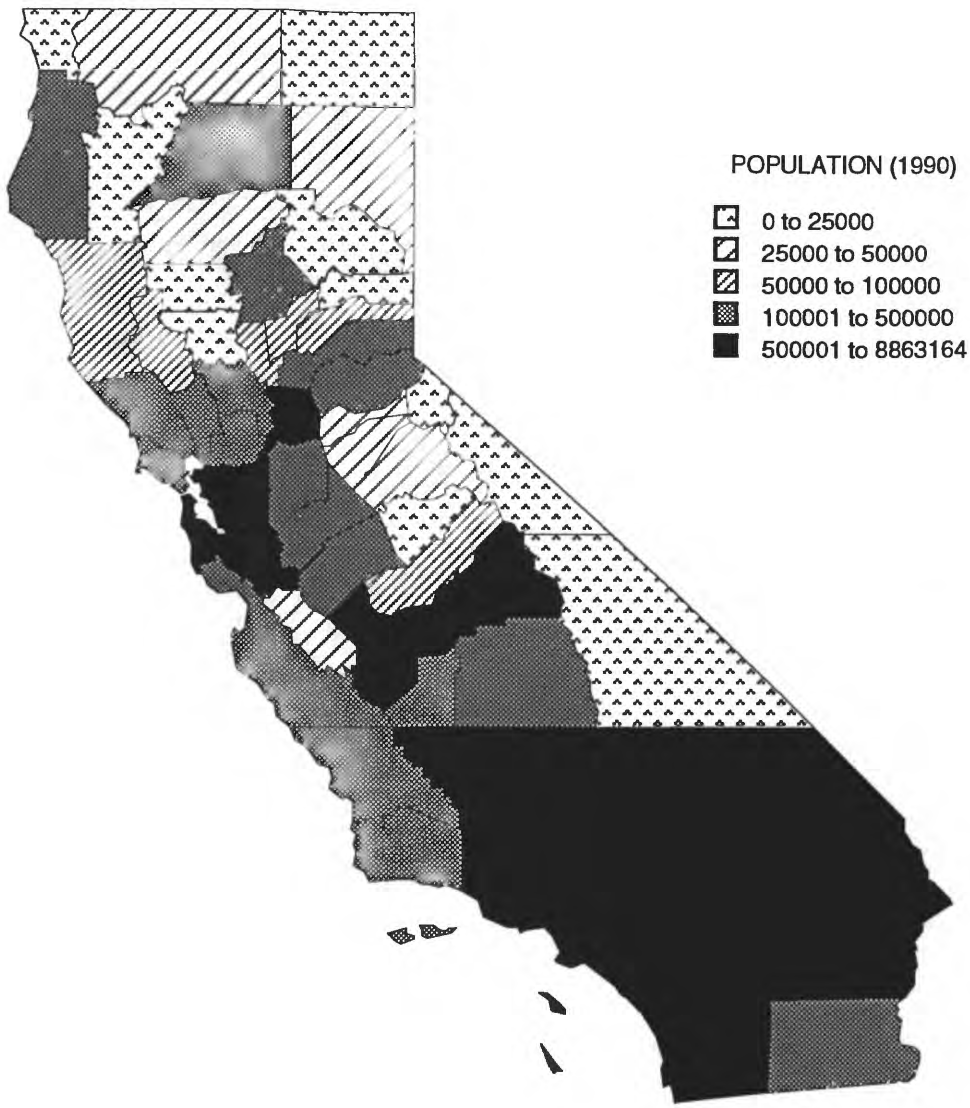


Figure 2. Population of counties of California (1990 U.S. Census data).

Fig. 3- Map showing location and names of counties in California.

grazing land. The Transverse Ranges are dominantly forestland and woodland and grazed open woodland. The Basin and Range, the Mojave Desert, and the Colorado Desert are dominated by ungrazed desert shrubland. However, grazed desert shrubland occurs at the western edge of these three areas and in the area closest to Las Vegas. A large area of irrigated cropland occurs in the lower Colorado Desert area. The Peninsular Ranges are mostly open grazed woodland.

Most of the housing in California is slab-on-grade which generally results in lower indoor radon levels because there is less contact between the structure and the underlying soil. However, houses on hillslopes commonly have lower floors which are recessed into the hillslope, creating a lower level partly below grade. Such below-grade floors are more susceptible to elevated indoor radon levels and measurements of such areas in houses may contribute many of the higher values.

GEOLOGIC SETTING

The geology of California is diverse and geologic provinces are often separated by sharp structural and geomorphic boundaries (fig. 4). The Klamath Mountains are underlain by Paleozoic and Mesozoic metavolcanic and metasedimentary rocks, Jurassic ultramafic rocks, and Mesozoic granitic intrusive rocks. The Cascade Range is underlain primarily by upper Tertiary and Quaternary extrusive rocks, mainly basalt and lesser andesite and rhyolite. The Modoc Plateau is underlain by Tertiary basalt flows, upper Tertiary to Quaternary basalt flows, and lesser amounts of andesite and rhyolite.

The Northern Coast Ranges 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. The Southern Coast Ranges 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.

The Great Valley is underlain by surficial materials composed of Quaternary alluvium, largely derived from the Sierra Nevada to the east and the Coast Ranges to the west. The northern part of the Sierra Nevada is underlain by Paleozoic and Mesozoic metamorphic rocks with lesser Mesozoic granitic rocks, whereas in the southern part Mesozoic granitic rocks predominate, with lesser Mesozoic metamorphic rocks. In the northern part, Tertiary volcanic rocks, including basalt, rhyolite and sedimentary rocks derived from them, crop out along the crests of many ranges.

The Basin and Range is tectonically active. It is separated from the Sierra Nevada by normal faults of large displacement and corresponding mountain fronts of great relief. The ranges are composed of Precambrian metamorphic rocks, late Precambrian and Paleozoic metamorphosed and unmetamorphosed sedimentary rocks, Mesozoic and Tertiary intrusive rocks, and Tertiary sedimentary and volcanic rocks. The basins are filled with alluvium derived from the adjacent ranges. Upper Tertiary and Quaternary volcanic rocks occur around Mono Lake. The Mojave Desert is underlain by rocks similar to those of the Basin and Range except the ranges are smaller and more deeply eroded and the alluvial valleys are wider.

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

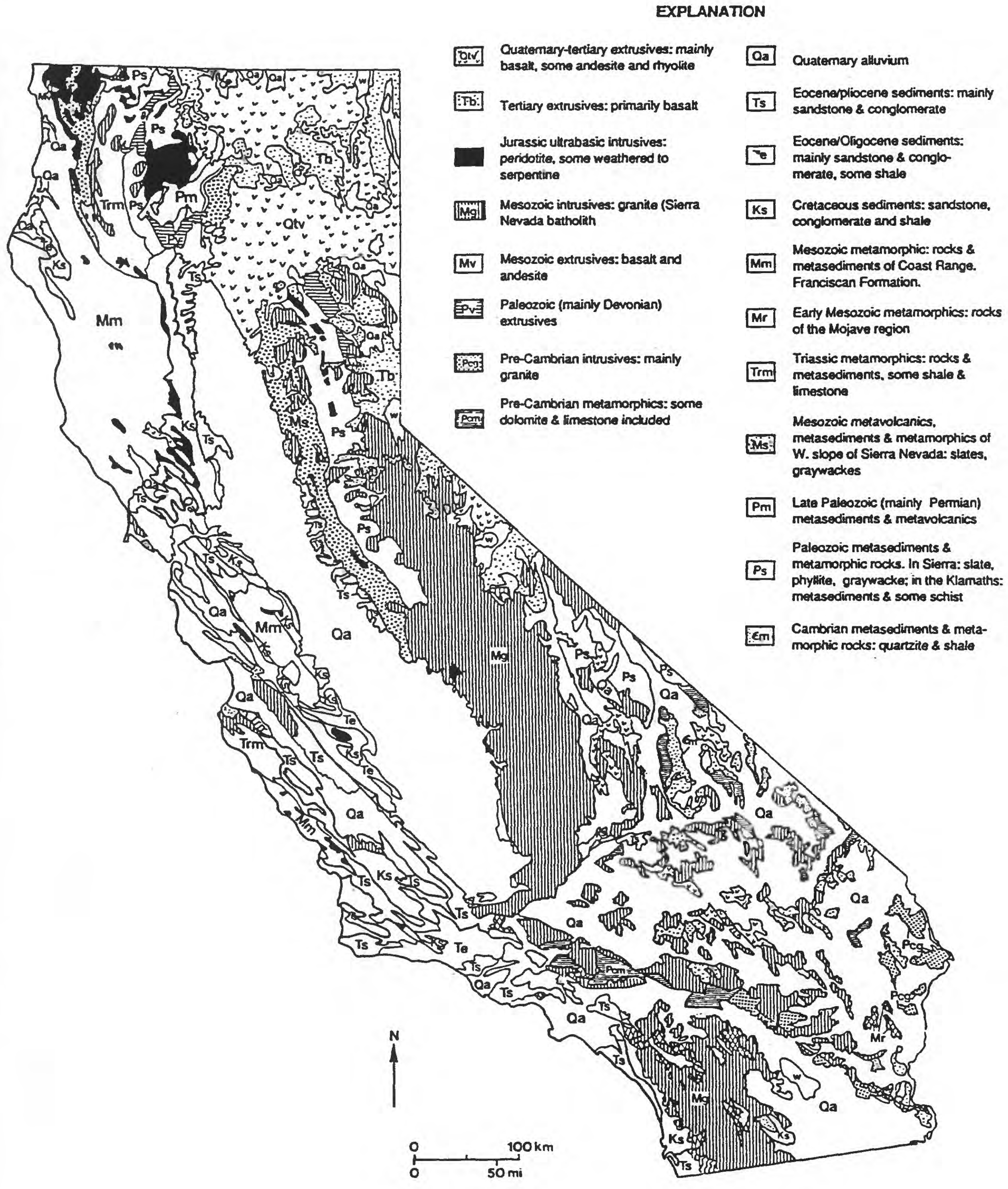


Fig. 4- Generalized geologic map of California. Modified from Donley and others, 1979.

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 Peninsular Ranges are dominated by Mesozoic granitic rocks with lesser Mesozoic metamorphic rocks. Tertiary sedimentary rocks lie along the coast. The Colorado Desert (Salton trough) is underlain by Quaternary alluvium derived from the adjacent mountains.

Aeroradioactivity exhibits considerable variation across the State (fig. 5). For the purposes of this report, "uraniferous" or "high uranium values" refers to uranium concentrations or equivalent uranium (eU) concentrations sufficient to generate indoor radon concentrations exceeding 4 pCi/L, defined here as greater than 2.5 ppm. Equivalent uranium (eU) values range from less than 0.5 ppm over ultramafic rocks of the Klamath Mountains to greater than 5.5 ppm over metamorphic and granitic terranes in the eastern Mojave Desert. The Klamath Mountains overall exhibit the lowest eU signatures in the State. Ultramafic rocks and Paleozoic metasedimentary rocks in the Klamath Mountains typically have less than 0.5 ppm eU. The other rocks range from 0.5 to 1.5 ppm eU. Only one small granitic pluton in the Klamaths has more than 1.5 ppm eU.

The Cascade Range and the Modoc Plateau generally range from less than 0.5 ppm to 1.5 ppm eU, however local eU values of as much as 4.5 ppm are interpreted to result from outcrops of silicic volcanic rocks. 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 values of as much as 4.5 ppm were measured.

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. From Lake Tahoe southward, however, the granitic rocks and the thin volcanic cover of most of the Sierra Nevada have 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.

Equivalent uranium values for rocks and soils in the Great Valley are strongly influenced 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, reflecting the relatively low uranium content of rocks in the nearby northern Sierra Nevada and Northern Coast Ranges. However, Sutter Buttes, prominent hills in the middle of the northern Great Valley that are underlain mostly by volcanic rocks, exhibits 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 as the uraniferous granitic and volcanic rocks from the Sierra Nevada have contributed more detritus to the valley alluvium. 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 uraniferous sedimentary rocks of the Southern Coast Ranges contribute alluvium to the valley floor.

Equivalent uranium values vary significantly for the Southern Coast Ranges. Franciscan metamorphic rocks, Triassic metamorphic rocks, and Tertiary sedimentary rocks derived from

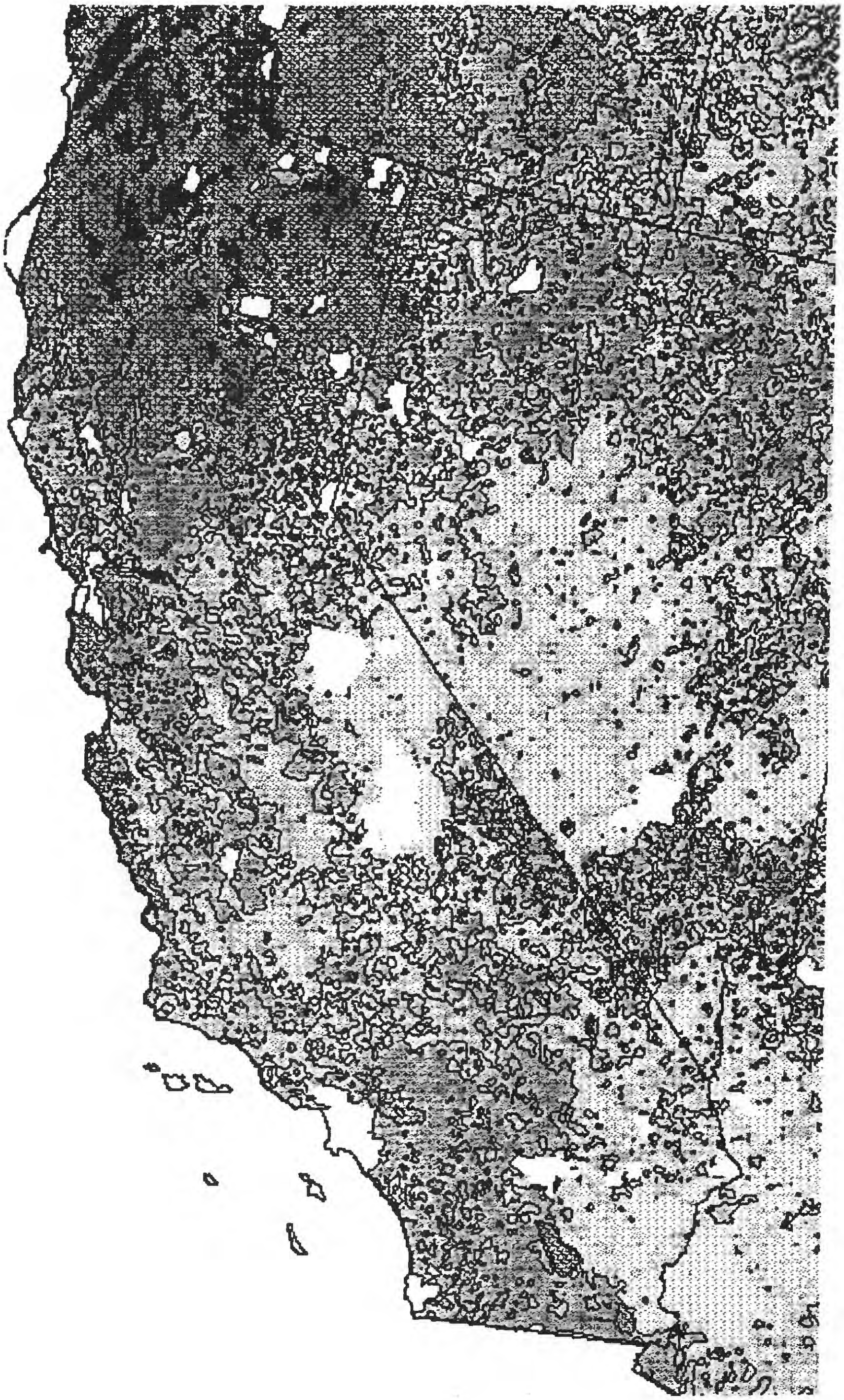


Figure 5 - Aerial radiometric map of California (after Duval and others, 1989). Contour lines at 1.5 and 2.5 ppm equivalent uranium (eU). Pixels shaded from 0 to 6.0 ppm eU at 0.5 ppm eU increments; darker pixels have lower eU values; white indicates no data.

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 Basin and Range also exhibits variation in eU related to mapped rock units. Precambrian metamorphic rocks, most Mesozoic granitic rocks and Tertiary silicic volcanic rocks have elevated eU. 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.

In the Mojave Desert the apparent uranium content of the rocks decreases from east to west. Much of the eastern half of the Mojave Desert has more than 2.5 ppm eU, with a broad area of mountains and adjacent valley alluvium in southeasternmost California above 5.5 ppm eU. In the western Mojave much of the area has lower eU (1.0-2.5 ppm) 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.

The Transverse Ranges generally exhibit low eU in the eastern part (1.0-2.0 ppm), which is underlain by Precambrian metamorphic rocks and Mesozoic intrusive rocks, but in the western Transverse Ranges many of the sedimentary units are more uraniferous (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.

Mesozoic intrusive rocks of the Peninsular Ranges are generally low in uranium, with eU values ranging 1.0-2.5 ppm eU. Some areas of Tertiary sedimentary rocks and Mesozoic granitic rocks are more uraniferous. Equivalent uranium signatures over the Colorado Desert vary significantly. Some Quaternary alluvium derived from rocks in the Mojave Desert are elevated in eU (>2.5 ppm), but other areas range from 1.0-2.5 ppm eU.

Uranium occurrences have been found widely in the southern two-thirds of California and are generally co-extensive with areas of aeroradioactivity exceeding 2.5 ppm eU. Tertiary silicic volcanic rocks, Tertiary sedimentary rocks rich in volcanic ash, Tertiary arkosic sandstones with abundant plant debris, marine gray to black phosphatic shales, and sheared and faulted uraniferous granites and metamorphic rocks are common hosts for uranium occurrences in California. Uraniferous Tertiary sedimentary rocks are common in the western Transverse Ranges and the Southern Coast Ranges.

SOILS

Soils in several areas are likely to be excessively well-drained, very rapidly permeable, or both. Because of the generally mountainous terrain of much of California, coarse-grained alluvial soils are common in many areas including most mountain valleys, the margins of valleys in the Basin and Range and the Mojave Desert, and the margins of larger valleys such as the Great Valley. High permeability in such soils increases the radon potential of structures built on them. Steep slopes are also common in much of California. Steep slopes tend to be well-drained and drier, even in areas of high precipitation, and thus tend to transmit radon more effectively either by diffusion or flow.

Swelling clay soils are common in parts of California (Donley and others, 1979), including the north-central part of the Great Valley, the eastern slopes of the northern part of the Southern Coast Ranges, and the Los Angeles Basin area. Such soils may have enhanced permeability during dry periods of the year due to cracking.

Inceptisols or entisols are common throughout California (Donley and others, 1979). Both Entisols and Inceptisols are poorly developed, lack or have poorly developed genetic horizons, and often develop on or are composed of transported materials. In poorly developed soils only modest amounts of uranium or radium have leached from mineral grains in the soil. Thus uranium and radium are less likely to occur on the surfaces of mineral grains and more likely to be found within mineral grains. In immature soils the grains have not broken down to smaller sizes so the specific surface area remains small. Where this occurs, less radon can escape from mineral matter and reach pore spaces. The radon potential of such soils is lower than for soils of similar radium content that have been heavily weathered.

The effect of caliche and hardpan soils on radon potential in semiarid to arid areas is not well understood. In such soils radium tends to accumulate in the calcium-rich caliche and hardpan, but such material is often highly cemented and radon in these soils may not reach pore spaces readily unless the parent radium is concentrated in surface coatings. The dryness of many of these soils may also inhibit radon emanation.

Soil moisture-temperature regimes in California vary systematically with altitude, latitude, and distance from the coastline (Rose and others, 1990). Soils in most of the Klamath Mountains, the northern Cascade Range and the crest of the Sierra Nevada are frigid xeric and thus are very moist in the wintertime (56-96 percent pore space saturation in a sandy loam and 74-99 percent saturation in a clay loam) and moderately moist in the summertime (44-56 percent saturation in a sandy loam and 58-74 percent saturation in a clay loam). Soils in the more southerly parts of the Klamath Mountains and the Cascade Range, the Modoc Plateau, the inland parts of the Northern Coast Ranges, the western foothills of the Sierra Nevada, and the eastern parts of the Transverse Ranges and the Peninsular Ranges are mesic xeric. These soils are very moist in the wintertime (56-96 percent pore space saturation in a sandy loam and 74-99 percent saturation in a clay loam) and slightly moist in the summertime (24-44 percent pore saturation in a sandy loam and 39-58 percent pore saturation in a clay loam).

The soils of the coastal parts of the Northern Coast Range and the Klamath Mountains are mesic udic. These soils are very moist in the wintertime (56-96 percent pore space saturation in a sandy loam and 74-99 percent saturation in a clay loam) and moderately moist in the summertime (44-56 percent saturation in a sandy loam and 58-74 percent saturation in a clay loam).

Soils of the Great Valley, the Southern Coast Ranges, the western part of the Transverse Ranges, and the coastal parts of the Peninsular Ranges are thermic xeric. They are moderately moist in the wintertime (44-56 percent saturation in a sandy loam and 58-74 percent saturation in a clay loam) and slightly dry in the summertime (4-24 percent saturation in a sandy loam and 6-39 percent saturation in a clay loam). Soils of the Basin and Range are generally thermic aridic except in lower altitudes near Death Valley where they are hyperthermic aridic. Soils throughout the Mojave Desert and the Colorado Desert are hyperthermic aridic. Thermic aridic soils are slightly moist in the wintertime (24-44 percent pore saturation in a sandy loam and 39-58 percent pore saturation in a clay loam) and slightly dry in the summertime (4-24 percent saturation in a sandy loam and 6-39 percent saturation in a clay loam). Hyperthermic aridic soils are slightly dry all year (4-24 percent saturation in a sandy loam and 6-39 percent saturation in a clay loam).

INDOOR RADON DATA

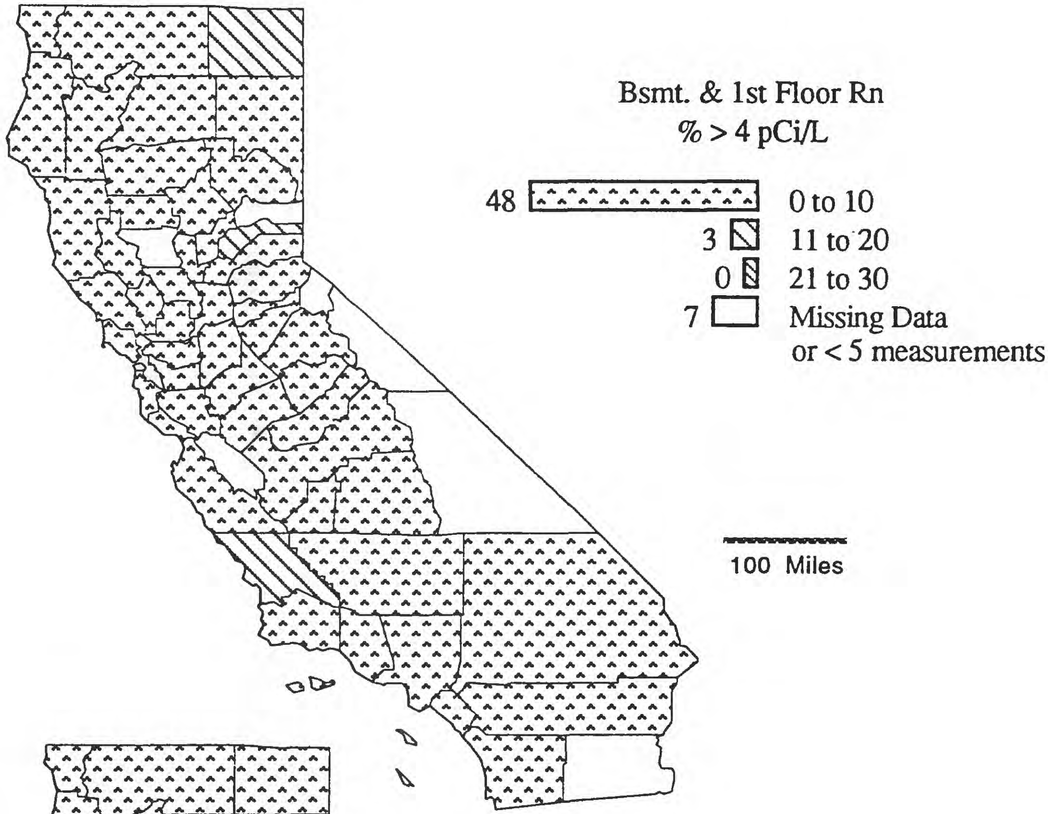
The U.S. Environmental Protection Agency (EPA), in cooperation with the State of California, completed a random, population-based, screening survey of indoor radon levels in 1885 homes across California during the winter of 1989-1990 (Table 1, fig. 6). All data represent 2-7 day charcoal canister measurements. Colusa, San Benito, Alpine, Sierra, Mono, Inyo, and Imperial Counties have 5 or fewer indoor radon measurements (fig. 6) and only limited conclusions should be drawn from these data. Geologic interpretations of population-based data must be made with caution because the measured houses are typically only from a relatively few population centers within a given county and do not provide good geographic coverage of the county's surface area. This has a significant impact in interpreting the radon potential of the Basin and Range and the Mojave Desert provinces, in which nearly all of the measured houses are in the populated parts in westernmost Riverside County, southwesternmost San Bernadino County, and eastern Kern County.

Average indoor radon readings for counties vary from 0.3 pCi/L in Del Norte and Riverside Counties (8 and 24 measurements, respectively) to 2.7 pCi/L in San Luis Obispo County (15 measurements). Counties averaging less than 1.0 pCi/L generally occur in the northern Coast Ranges, the Klamath Mountains, the northern part of the southern Coast Ranges, the San Francisco Bay area, the Peninsular Ranges, and the Mojave Desert. Counties averaging 1.5 to 2.7 pCi/L occur in the southern part of the Great Valley, the Sierra Nevada, the southern part of the Southern Coast Ranges and the western part of the Transverse Ranges. Houses in the Basin and Range and Mojave Desert may average 1.5 pCi/L or more, but only limited data are available. Only Madera, Nevada, San Joaquin, Merced, and San Luis Obispo Counties average 2.0 pCi/L or more.

Twenty-four counties had no houses that measured 4 pCi/L or more in the State/EPA dataset. They occur in the Northern Coast Range, the Peninsular Range, the westernmost Mojave Desert, parts of the Modoc Plateau, parts of the northernmost and central Sierra Nevada, and parts of the northern Great Valley.

Readings above 4 pCi/L tend to be clustered (fig. 7). Some clustering coincides with high sampling density, simply because sampling a larger number of homes in a limited area is more likely to identify those houses whose indoor radon levels fall in the upper part of the distribution of values. This occurs in the San Francisco Bay area, for example, but not in the Los Angeles or San Diego areas. However, some clusters are related to geology. Most of the elevated indoor radon values were measured in the following areas: 1) along the California coast from the western part of Los Angeles County northward to southwestern San Luis Obispo County; 2) along the northeastern flank of the Great Valley and along the adjacent Sierra foothills from Tulare County to Sacramento County; 3) in the southern San Francisco Bay area in the alluvial valley surrounding San Jose; 4) in the hilly terrane north and south of the Bay area; 5) on the west side of Lake Tahoe and in mountain communities between Lake Tahoe and the northern Great Valley; and 6) in the upper Sacramento River Valley in Shasta and Tehama Counties.

Clustering of values over 4 pCi/L seems to be associated with areas of elevated aeroradioactivity in the central and southern Great Valley, in Santa Barbara and Ventura Counties, and in some localities north of the Bay area. Perhaps slightly more than half of the elevated values may be attributed to radium-rich rocks and soils. Elsewhere, highly permeable soils, excessively well-drained soils on steep slopes, and soils with high radon emanation may be responsible for many of the other elevated indoor radon levels. For example, four houses in the study around the



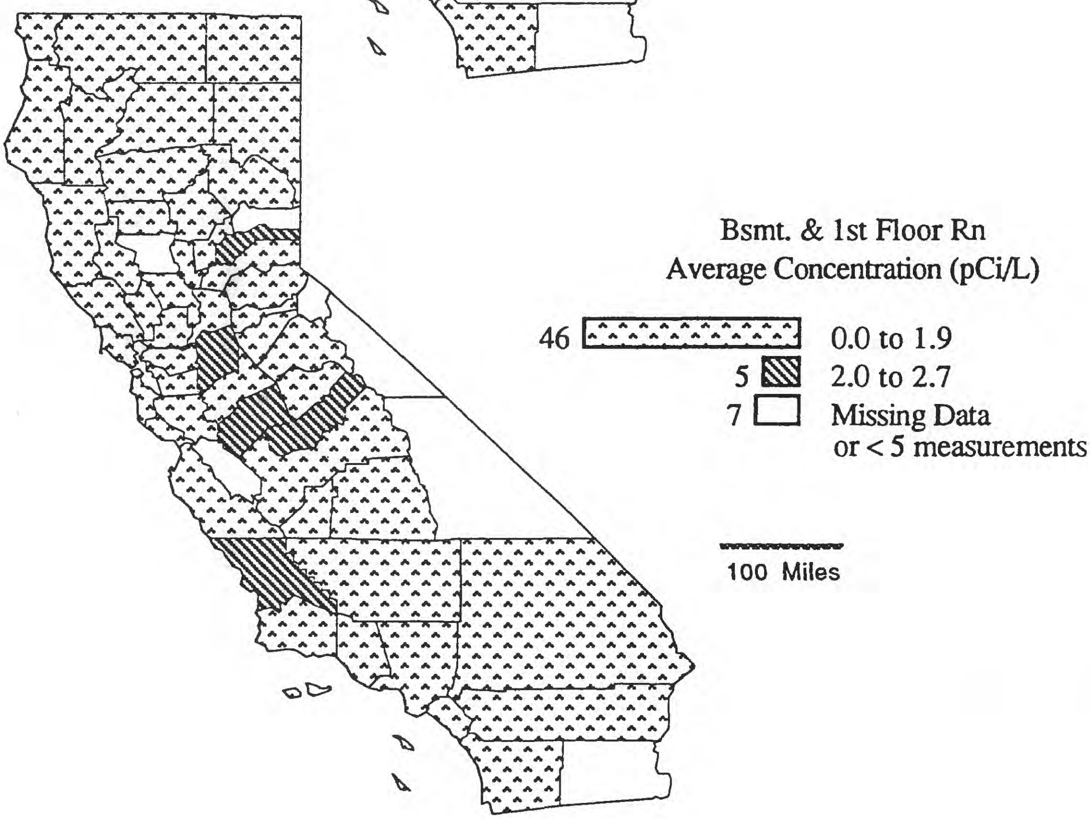


Figure 6. Screening indoor radon data from the EPA/State Residential Radon Survey of California, 1989-90, for counties with 5 or more measurements. Data are from 2-7 day charcoal canister tests. Histograms in map legends show the number of counties in each category. The number of samples in each county (See Table 1) may not be sufficient to statistically characterize the radon levels of the counties, but they do suggest general trends. Unequal category intervals were chosen to provide reference to decision and action levels.

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

COUNTY	NO. OF MEAS.	MEAN	GEOM. MEAN	MEDIAN	STD. DEV.	MAXIMUM	%>4 pCi/L	%>20 pCi/L
ALAMEDA	60	0.8	0.5	0.7	1.0	4.0	0	0
AMADOR	15	1.5	0.8	1.3	1.3	3.9	0	0
BUTTE	44	0.5	0.3	0.5	1.1	3.2	0	0
CALAVERAS	18	1.2	0.7	1.1	1.1	3.2	0	0
COLUSA	2	0.6	0.3	0.6	0.6	1.0	0	0
CONTRA COSTA	60	0.8	0.4	0.7	0.9	4.0	0	0
DEL NORTE	8	0.3	0.3	0.5	0.8	1.1	0	0
EL DORADO	34	1.3	0.7	0.9	1.6	5.7	9	0
FRESNO	106	1.3	0.8	0.9	1.3	9.4	2	0
GLENN	10	0.4	0.3	0.4	0.6	1.8	0	0
HUMBOLDT	36	0.4	0.2	0.1	1.6	8.6	3	0
IMPERIAL	2	1.5	1.4	1.5	0.5	1.8	0	0
INYO	1	1.7	1.7	1.7	0.0	1.7	0	0
KERN	100	1.4	1.0	1.3	1.2	8.5	2	0
KINGS	12	1.5	0.9	1.2	1.5	5.3	8	0
LAKE	16	1.4	0.5	0.8	2.7	11.1	6	0
LASSEN	18	1.1	0.8	1.0	0.9	3.4	0	0
LOS ANGELES	69	0.7	0.4	0.5	1.0	5.6	1	0
MADERA	24	2.6	1.3	1.4	5.7	29.1	4	4
MARIN	58	0.8	0.4	0.4	1.3	6.4	3	0
MARIPOSA	9	1.0	0.6	0.9	1.0	3.3	0	0
MENDOCINO	17	0.4	0.2	0.3	0.5	1.3	0	0
MERCED	10	2.1	1.3	1.7	1.8	6.1	10	0
MODOC	5	1.0	0.4	0.5	2.2	4.6	20	0
MONO	2	1.9	1.8	1.9	0.4	2.1	0	0
MONTEREY	20	1.0	0.2	0.2	2.2	7.4	10	0
NAPA	29	1.0	0.5	0.7	2.1	9.7	7	0
NEVADA	26	2.4	0.7	1.1	5.3	27.3	12	4
ORANGE	31	0.7	0.5	0.6	0.7	2.2	0	0
PLACER	82	0.9	0.4	0.6	1.7	9.1	5	0
PLUMAS	11	1.3	0.7	1.0	1.3	3.7	0	0
RIVERSIDE	24	0.3	0.3	0.5	0.8	1.7	0	0
SACRAMENTO	55	1.0	0.4	0.7	2.3	15.9	2	0
SAN BENITO	2	0.4	0.2	0.4	0.5	0.7	0	0
SAN BERNARDINO	17	0.7	0.5	0.7	1.0	2.9	0	0
SAN DIEGO	39	0.6	0.4	0.6	0.6	2.4	0	0
SAN FRANCISCO	20	0.6	0.4	0.6	0.6	2.1	0	0
SAN JOAQUIN	22	2.5	1.3	1.5	3.8	18.0	9	0
SAN LUIS OBISPO	15	2.7	0.7	0.7	5.7	22.1	13	7
SAN MATEO	38	0.8	0.4	0.5	1.3	6.6	3	0
SANTA BARBARA	90	1.5	0.7	0.9	2.6	19.5	7	0

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

COUNTY	NO. OF MEAS.	MEAN	GEOM. MEAN	MEDIAN	STD. DEV.	MAXIMUM	%>4 pCi/L	%>20 pCi/L
SANTA CLARA	77	1.4	0.7	1.0	1.9	9.2	9	0
SANTA CRUZ	10	1.2	0.5	0.8	1.4	4.8	10	0
SHASTA	79	1.1	0.5	0.6	1.9	11.5	4	0
SIERRA	2	1.4	1.3	1.4	0.1	1.4	0	0
SISKIYOU	27	0.9	0.5	0.8	1.5	6.8	4	0
SOLANO	43	0.9	0.4	0.5	1.5	8.6	5	0
SONOMA	82	0.6	0.3	0.3	0.9	4.1	1	0
STANISLAUS	14	1.8	1.2	1.3	1.5	5.9	7	0
SUTTER	15	1.1	0.4	0.4	2.0	7.7	7	0
TEHAMA	17	0.9	0.3	0.8	1.8	7.5	6	0
TRINITY	6	0.4	0.2	0.2	0.8	1.7	0	0
TULARE	63	1.9	1.5	1.5	1.4	8.0	5	0
TUOLUMNE	24	1.2	0.7	0.9	1.0	3.2	0	0
VENTURA	140	1.2	0.8	0.9	1.3	8.2	4	0
YOLO	14	1.4	0.8	1.2	1.5	5.8	7	0
YUBA	15	1.3	0.6	0.8	2.0	8.3	7	0

Fig. 7- Approximate location of zipcodes in California with houses measuring greater than or equal to 4 pCi/L in the State/EPA Indoor Radon Survey (the data used in this figure are from an extended version of the dataset which includes 2321 measurements).

western side of Lake Tahoe had screening indoor radon readings greater than 4 pCi/L. Although the geologic setting of the individual houses in the study is not known, this area is characterized by housing on highly permeable alluvial soils and on steep slopes with thin, coarse, sandy soils and shallow bedrock.

Fourteen readings of 4 pCi/L or more occur in Santa Barbara and Ventura Counties (fig. 7). Although no precise location information is available for the measured homes in the State/EPA study, an independent study conducted in Santa Barbara County found that indoor radon screening readings ranging from 4-50 pCi/L occur in about three-fourths of the homes sited on the Rincon Shale in Santa Barbara County (D. Carlisle, 1991, written commun.). This unit is widely scattered across Santa Barbara and Ventura Counties, is probably responsible for the elevated eU signature in these two counties (see general geologic map, fig. 4), and is likely responsible for many of the elevated indoor readings in the State/EPA study.

Los Angeles, Orange, and San Diego Counties combined contain only 1 reading above 4 pCi/L in spite of the high population density and the corresponding high sample density. In the Basin and Range, the Mojave Desert, and the Colorado Desert in southeastern California, no values over 4 pCi/L were measured. However, the sampling is sparse and all of the sampled homes in the five counties (Mono, Inyo, San Bernadino, Riverside, and Imperial) come from the westernmost part of the Basin and Range and the Mojave Desert and many houses are actually in the adjacent Peninsular and Transverse Ranges Provinces. Only two houses were sampled in the Colorado Desert (the town of Brawley in Imperial County). No houses were measured in the eastern Mojave Desert where substantial parts of the area have high eU values.

The California Air Resources Board (CARB) conducted a study of outdoor radon, soil radon, and indoor radon across the state (Liu and others, 1990). Thirty-eight houses were sampled in a pretest in the Salinas/Santa Cruz area (Santa Cruz and Monterey Counties); 310 houses were sampled across the entire state in the main study; and 37 residences were sampled in the Sierra Nevada foothills (Fresno, Mono, and Tulare Counties) in a followup study. Residences were selected randomly for participation from Department of Motor Vehicles registration lists. Annual average values in the pretest area had geometric means of about 0.9 pCi/L in living areas with the highest value at 5.9 pCi/L. Statewide, the "whole house" geometric mean was about 0.85 pCi/L with the highest measured value being 16 pCi/L. The geometric mean of 27 basements measured in the statewide study was 2.17 pCi/L. In the Sierra Nevada foothills, the whole house annual average geometric mean was 1.28 pCi/L and the highest value was 8.8 pCi/L. The authors of the CARB study concluded that the Sierra Nevada foothills and Ventura County were areas of elevated indoor radon.

Analysis of these indoor radon data sets suggests that elevated indoor readings in California are the result of elevated radium content in soils on which homes are located, locally highly permeable soils, local steep slopes, and unusual housing circumstances. Basement measurements in the various studies average 2 to 3 times that of first floor or "whole house" measurements. This suggests that homes with basements or parts of the structure below grade are more likely to have elevated indoor radon levels than homes built above grade.

GEOLOGIC RADON POTENTIAL

The geologic radon potential of the state seems to be lowered overall by the relatively mild climate, especially in the most populous areas, and the predominance of above grade, slab housing. In the two indoor radon studies discussed here, only a few values exceed 20 pCi/L and a relatively small percentage exceed 4 pCi/L. However, no area in California appears to be completely free from indoor radon levels above 4 pCi/L.

Elevated indoor radon can be expected in several geologic settings in California. Uraniferous granites, uraniferous Tertiary silicic volcanic and sedimentary rocks, uraniferous dark marine shales, and residual soils and alluvium derived from these units are likely to have significant percentages of homes with indoor radon levels exceeding 4 pCi/L. The most likely areas for such rock formations to occur are those where elevated eU values occur in the aeroradiometric data (fig. 5). Where structures are sited on excessively drained soils or steep slopes, the radon potential is higher. Extreme indoor radon levels (greater than 100 pCi/L) may be expected where structures are inadvertently sited on uranium occurrences. In those areas where the eU values are moderate to low, excessively well-drained soils or soils with unusually high emanating power may locally cause some indoor radon levels to exceed 4 pCi/L. The presence of steep slopes may also influence radon potential because, in many cases, the structure is built partly below grade. The below-grade parts of the house are more likely to draw soil-gas radon indoors. Where the slope is accommodated by placing the structure on stilts rather than cutting into the hillslope, the radon potential of the structure is low.

Areas of the State along the northern coast, where precipitation and soil moisture are high and where eU values are low, are expected to have low radon potential. Only those localities where soils are excessively well drained are likely to yield a few homes over 4 pCi/L. The eastern part of the Transverse Ranges and all of the Peninsular Ranges (including the Los Angeles Basin in the northern part of the Peninsular Ranges) have relatively low eU which, coupled with the mild climate and predominance of slab-on-grade housing, also suggests low radon potential. Those parts of the eastern Mojave Desert and various areas of the Basin and Range where eU values are unusually high may have increased indoor radon potential, but the effects of highly cemented, often immature, soils on radon potential in these areas are uncertain and houses there have not been adequately sampled.

SUMMARY

California was divided into twelve geologic provinces for which geologic radon potential may be evaluated. A relative index of radon potential (RI) and an index of the level of confidence in the available data (CI) (see discussion in chapter 1, the introductory section of this volume) have been applied to each of these areas (Table 2).

The Cascade Range and Modoc Plateau are thought to have low geologic radon potential overall in spite of the locally moderate eU signature across these two provinces. The indoor data are sparse in this lightly populated area and little is known about the processes that control radon emanation and migration in soils derived from volcanic rocks. In Susanville (8 measurements), Lassen County, the average of all measurements was 1.8 pCi/L. In Modoc County, the average of all measurements (6) was 2.1 pCi/L and two readings were above 4.0 pCi/L. Soils are drier here than in areas closer to the coast and this may contribute to the apparent locally elevated indoor radon levels in spite of relatively low eU. Steep topography and excessively well-drained soils may also contribute to the locally moderate to elevated values.

The Northern Coast Range province has low geologic radon potential overall; however, missing aeroradiometric data for the central part of this province lowers the confidence in this evaluation slightly. Areas of elevated eU occur along the east side of the southern half of this province and these are areas where some indoor radon levels exceeding 4 pCi/L are likely to occur, especially where steep, excessively well-drained, or highly permeable soils coincide with the elevated eU in soils.

The Southern Coast Range has moderate geologic radon potential overall; however, much of the radon potential is associated with areas of elevated radioactivity inland from the coast, from Monterey Bay southward, and this area is less populated than areas elsewhere in this province. Houses sited directly on radium-rich marine sedimentary rocks in this province, such as the Monterey Formation, are very likely to exceed 4 pCi/L.

The Great Valley has low geologic radon potential overall; however, the area along the east side of the valley from Sacramento southward seems more likely to have elevated average indoor radon levels and a greater percentage of homes over 4 pCi/L, as indicated by higher eU values, than the rest of the Great Valley. The Sierra Nevada has moderate radon potential overall owing to high eU throughout much of the province and the predominance of soils that are likely to favor radon transport. Indoor radon data are sparse in this province because of the low population density, thus the confidence in this assessment is lower than elsewhere. The Basin and Range has moderate radon potential overall, but the paucity of indoor radon data lowers the confidence in this assessment.

The Transverse Ranges have moderate geologic radon potential overall. The potential is higher in the western two-thirds of the province as indicated by higher eU and the presence of radium-rich marine sedimentary rocks such as the Rincon Shale. Indoor radon levels in houses sited on these marine sedimentary rocks are very likely to exceed 4 pCi/L, especially where homes are sited on steep slopes and parts of the home are below grade. The Mojave Desert also has moderate radon potential but, like the Basin and Range, the paucity of indoor radon data lowers the confidence in this assessment. Of particular concern are the eU values exceeding 5.5 ppm in the mountains and alluvial valleys near Blythe. Although this area is very sparsely populated, any structures in this area may have elevated indoor radon levels.

The Peninsular Ranges have low geologic 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 indoor radon. The Los Angeles metropolitan area at the north end of the Peninsular Ranges has low radon potential. The Colorado Desert province has low geologic radon potential but, similarly to the Basin and Range and the Mojave Desert, lack of indoor radon data lowers the confidence in this assessment.

This is a generalized assessment of the State's geologic radon potential and there is no substitute for having a home tested. The conclusions about radon potential presented in this report cannot be applied to individual homes or building sites. Indoor radon levels, both high and low, can be quite localized, and within any radon potential area there will likely be areas with higher or lower radon potential that assigned to the area as a whole. Any local decisions about radon should <u>not</u> be made without consulting all available local data. For additional information on radon and how to test, contact your State radon program or EPA regional office. More detailed information on state or local geology may be obtained from the State geological survey. Addresses and phone numbers for these agencies are listed in chapter 1 of this booklet.

TABLE 2. Radon Index (RI) and Confidence Index (CI) for geologic radon potential areas of California. See figure 1 for locations of areas. See the introductory chapter for discussion of RI and CI.

FACTOR	Klamath Mountains RI	Klamath Mountains CI	Cascade Range RI	Cascade Range CI	Modoc Plateau RI	Modoc Plateau CI	Northern Coast Range RI	Northern Coast Range CI
INDOOR RADON	1	3	2?	1	2?	1	1	3
RADIOACTIVITY	1	3	1	3	1	3	1	2
GEOLOGY	1	2	2	2	2	2	1	2
SOIL PERMEABILITY	2	3	2	2	2	2	2	3
ARCHITECTURE	1	-	1	-	1	-	1	-
GFE POINTS	0	-	0	-	0	-	0	-
TOTAL	6	11	8?	8	8?	8	6	10
RANKING	Low	High	Low	Mod	Low	Mod	Low	High

FACTOR	Southern Coast Range RI	Southern Coast Range CI	Great Valley RI	Great Valley CI	Sierra Nevada RI	Sierra Nevada CI	Basin & Range RI	Basin & Range CI
INDOOR RADON	1	3	1	3	1	1	2	1
RADIOACTIVITY	2	3	2	3	3	3	2	3
GEOLOGY	2	2	2	2	2	2	2	1
SOIL PERMEABILITY	2	3	2	3	2	2	2	2
ARCHITECTURE	1	-	1	-	1	-	1	-
GFE POINTS	+1	-	0	-	0	-	0	-
TOTAL	9	11	8	11	9	8	9	7
RANKING	Mod	High	Low	High	Mod	Mod	Mod	Mod

TABLE 2 (continued).

FACTOR	Transverse Ranges RI	Transverse Ranges CI	Mojave Desert RI	Mojave Desert CI	Peninsular Ranges RI	Peninsular Ranges CI	Colorado Desert RI	Colorado Desert CI
INDOOR RADON	1	3	2	1	1	3	1	1
RADIOACTIVITY	2	3	3	3	1	3	2	3
GEOLOGY	2	2	2	1	2	2	2	1
SOIL PERMEABILITY	2	3	2	2	2	3	2	2
ARCHITECTURE	1	-	1	-	1	-	1	-
GFE POINTS	+1	-	0	-	0	-	0	-
TOTAL	9	11	10	7	7	11	8	7
RANKING	Mod	High	Mod	Mod	Low	High	Low	Mod

- Not used in CI.

RADON INDEX SCORING:

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

Possible range of points = 3 to 17

CONFIDENCE INDEX SCORING:

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

Possible range of points = 4 to 12

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PRELIMINARY GEOLOGIC RADON POTENTIAL ASSESSMENT OF HAWAII

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INTRODUCTION

The radon potential for Hawaii has been determined primarily from considerations of the parent rock from which the islands are formed, the climate, and the open-air construction of houses. The State of Hawaii consists of 8 principal islands composed primarily of basaltic volcanic rock, ashes, and tuffs. There are also minor carbonate and clastic marine sediments, alluvium, colluvium, dune sands, and mudflow deposits. The common outdoor activities of the inhabitants and local architecture, combined with volcanic rock and soils low in uranium and thorium, indicate that Hawaii, overall, has low radon potential for its inhabitants. In some areas, particularly where a combination of mechanical and chemical weathering has concentrated uranium and uranium decay-series progeny on the surface of soil grains, soil-gas radon concentrations can be in excess of 1000 pCi/L. This concentration would normally be sufficient to cause some indoor radon concentrations to be greater than 4 pCi/L if houses were in contact with the soil, and homes were persistently closed to outside air. Hawaii had the lowest state-average indoor radon, 0.1 pCi/L, of the State/EPA Residential Radon Survey program. Although the state has a low radon potential for the inhabitants and could be summarized briefly with simplified figures, this booklet contains maps that are consistent in detail with geologic, soil, and physiographic delineation maps provided in other booklets in this series.

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

PHYSIOGRAPHIC AND GEOGRAPHIC SETTING

The Hawaiian archipelago, which is about 1,400 miles long, is composed of numerous seamounts, atolls, and islands that are summits of volcanic domes built up from the ocean floor through repeated volcanic eruptions. Eight major islands at the southeast end of this chain make up the State of Hawaii (fig. 1). The state is 2,300 miles from the mainland U.S., the nearest continental land mass, and is the southernmost U.S. state. In order of decreasing size, the islands are Hawaii, Maui, Oahu, Kauai, Molokai, Lanai, Niihau, and Kahoolawe. The population distribution and land use in Hawaii reflect, in part, the geology, topography, and climate of the state. Only seven of the islands are populated–Kahoolawe is closed and had been utilized as a

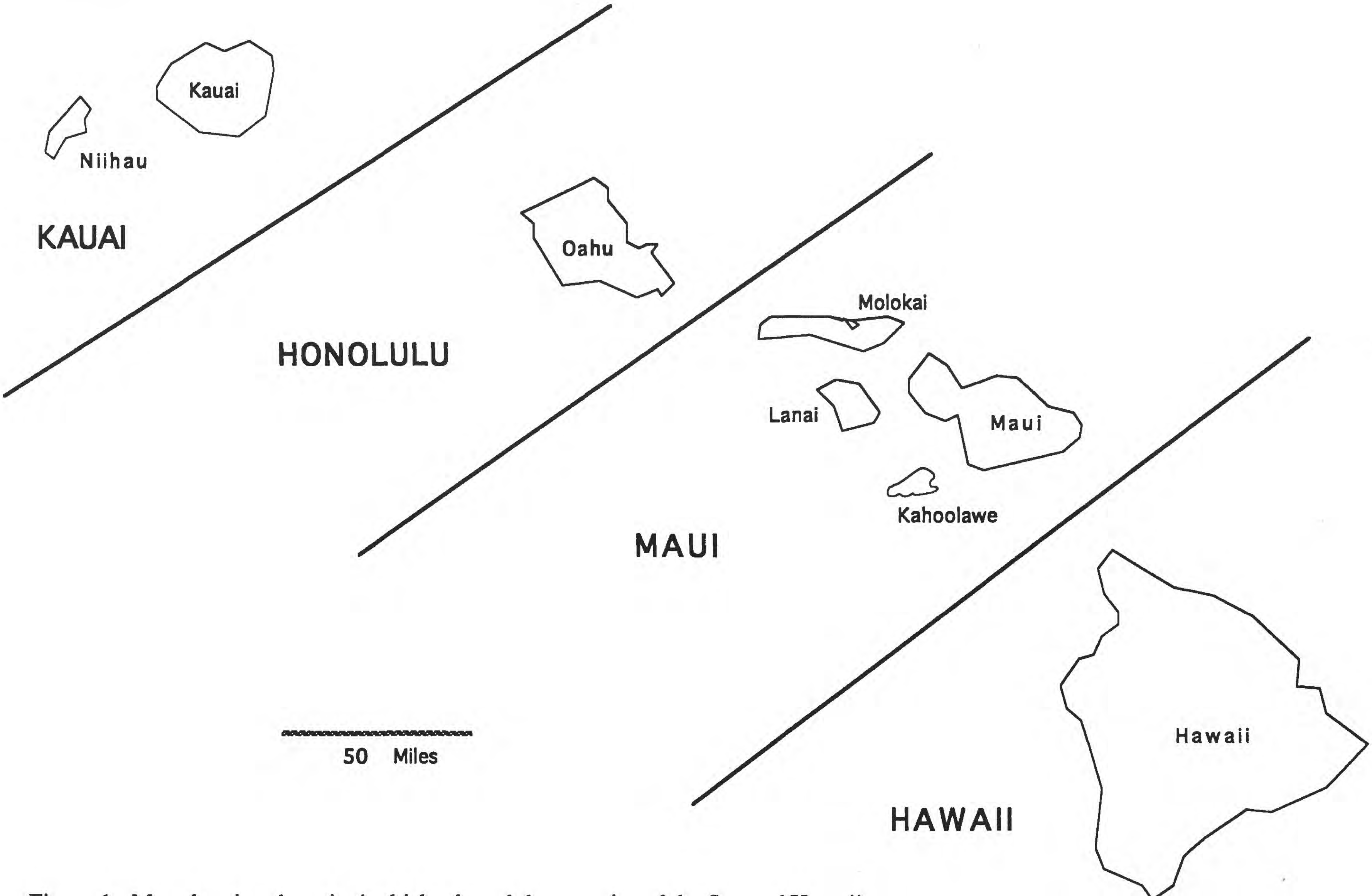


Figure 1. Map showing the principal islands and the counties of the State of Hawaii.

military bombing range, and Niihau is sparsely populated. The topography is extreme for most islands, with the six larger islands all having mountains over 3,000 feet above sea level, and over 13,000 feet above sea level on Maui and Hawaii. Numerous physiographic terrains are present on the islands (figs. 2 and 3). The total area of the islands is 6,425 square miles, making Hawaii the 47th largest state. In 1990, the population of Hawaii was 1,108,000 (fig. 4). Average population density is 172.5 people per square mile but 75 percent live in metropolitan areas. The state capitol is Honolulu, in Honolulu County, and has about 35 percent of the state's population. The climate is subtropical, with large variations in rainfall, ranging from 10 to over 400 inches per year. Northeasterly trade winds dominate the climate and, coupled with the topographic contrasts, create rainfall extremes over small distances. Erosion, caused by large rainfall amounts, creates spectacular landscapes of steep, deeply grooved, verdant cliffs with numerous waterfalls. The Waimea Canyon on Kauai has a relief of several thousand feet and is often referred to as the "Grand Canyon of the Pacific." Average annual temperatures in Honolulu range from 72° F to 79° F. Principal industries include tourism, agriculture, cattle ranching, defense and other government activities, and fishing. Primary crops are sugar, pineapples, and macadamia nuts. Much of the agricultural land is irrigated. Hawaii is the only U.S. state in which coffee is grown. There are 4 counties; from northwest to southeast they are, Lanai, Honolulu, Maui, and Hawaii (fig. 1). In this booklet, Kalawao is considered to be part of Maui County (Armstrong, 1973; Information Please Almanac, Atlas and Yearbook, 1990; Statistical Abstract of the United States, 1991).

GEOLOGIC SETTING

The island chain was formed from volcanic eruptions as the Pacific Plate passed over a mantle hot spot. The age of the islands decreases from northwest to the southeast. Niihau and Lanai are about 5 million years old and the oldest parts of Hawaii are 0.5 million years old. The lava that formed the islands is basaltic and has a chemical composition related to one of the 4 eruptive stages of the island building sequence. The stages and predominant lava type are preshield (alkalic), shield (tholeiitic), postshield (alkalic) and rejuvenated (alkalic). Preshield is confined to submarine volcanic events, and the young, big island of Hawaii has not yet experienced a rejuvenated stage. Other rock types are present in addition to the basalt, including volcanic ash and tuff, windblown sands, carbonates from reef building, and the clastics that form marine sediments (figs. 5 to 11) (Macdonald and others, 1983; Langenheim and Clague, 1986).

SOILS

Soils on the islands are classified into 11 orders by the U.S. Department of Agriculture Soil Conservation Service (SCS) and are shown in Figures 12 to 18 (Foote and others, 1972; Sato and others, 1973). The SCS does not provide a soil map for Niihau or Kahoolawe so those maps were derived from data in the Atlas of Hawaii (Armstrong and others, 1973). Occasionally, on some of the soil maps, there are separations for adjacent, similarly numbered units. These represent slight differences in soil sub-groups that are indicated on the map from the original source and are simply left in place on these modified renditions. The lavas and marine sediments, and hence the soils formed from them, are generally extremely low in uranium and thorium compared to continental rocks (Clark and others, 1966). Very few analyses exist for uranium and thorium but those that do indicate that the concentrations are low. Ranges from 0.06 ppm to 3.22 ppm for uranium and

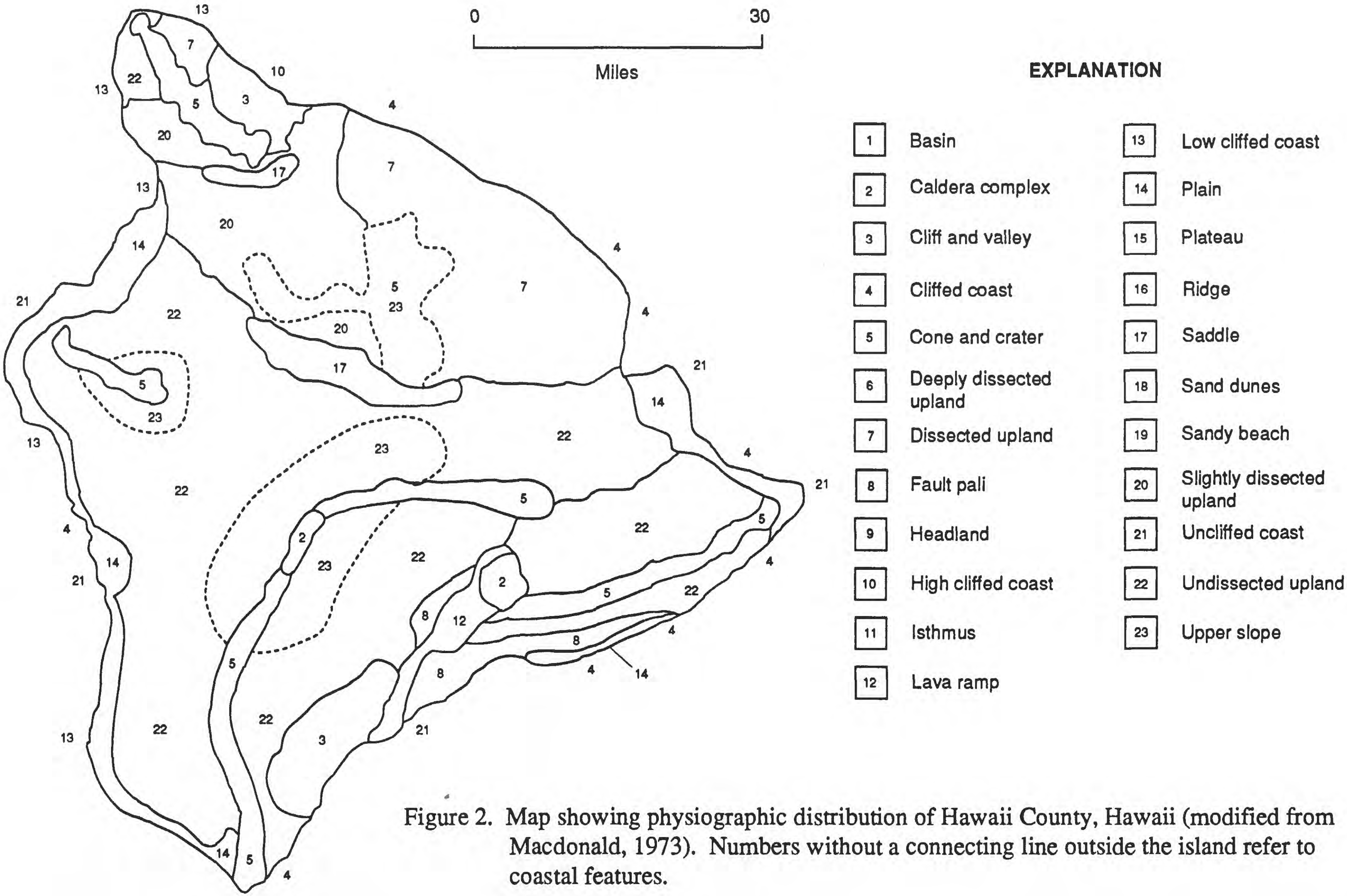


Figure 2. Map showing physiographic distribution of Hawaii County, Hawaii (modified from Macdonald, 1973). Numbers without a connecting line outside the island refer to coastal features.

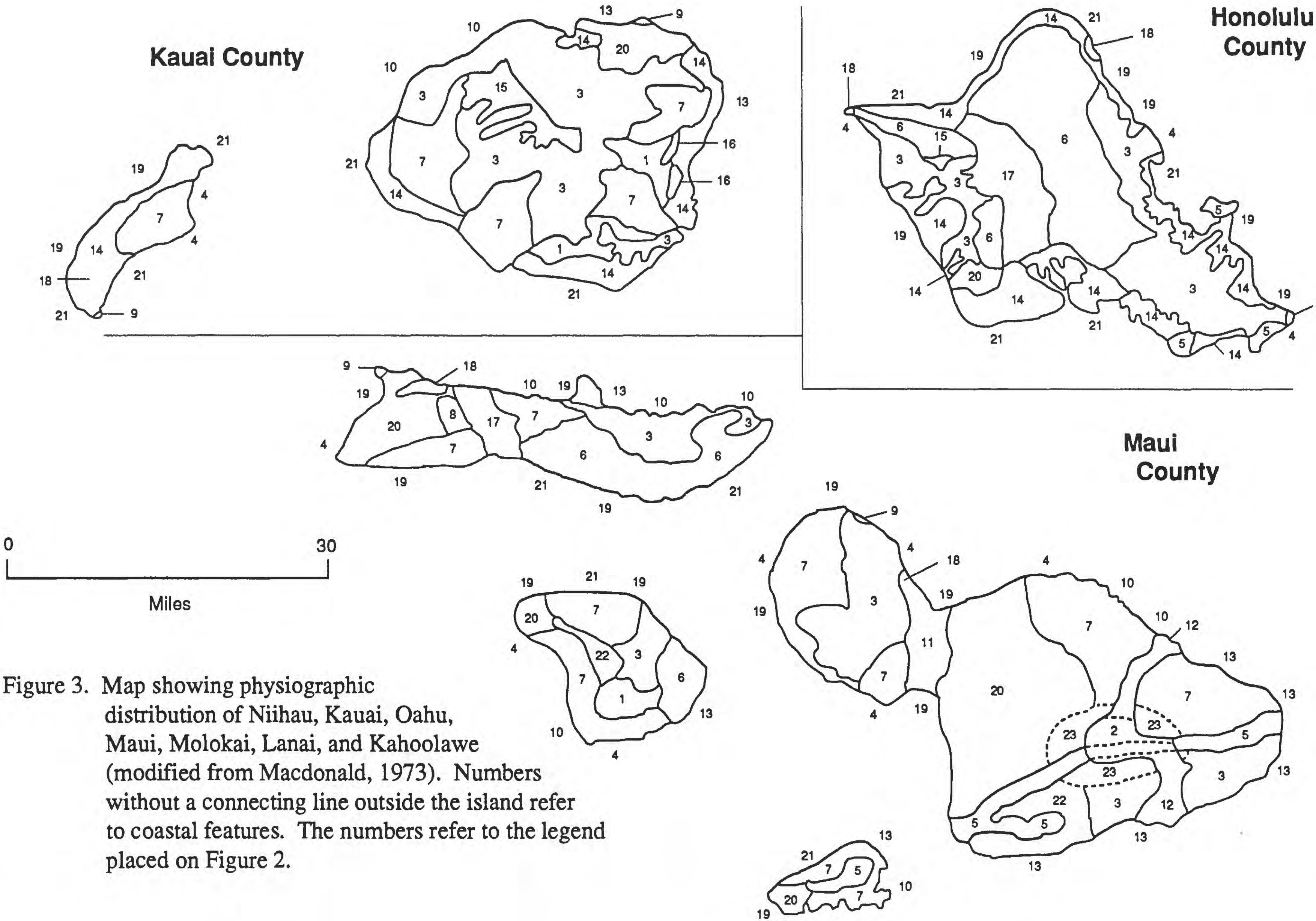


Figure 3. Map showing physiographic distribution of Niihau, Kauai, Oahu, Maui, Molokai, Lanai, and Kahoolawe (modified from Macdonald, 1973). Numbers without a connecting line outside the island refer to coastal features. The numbers refer to the legend placed on Figure 2.

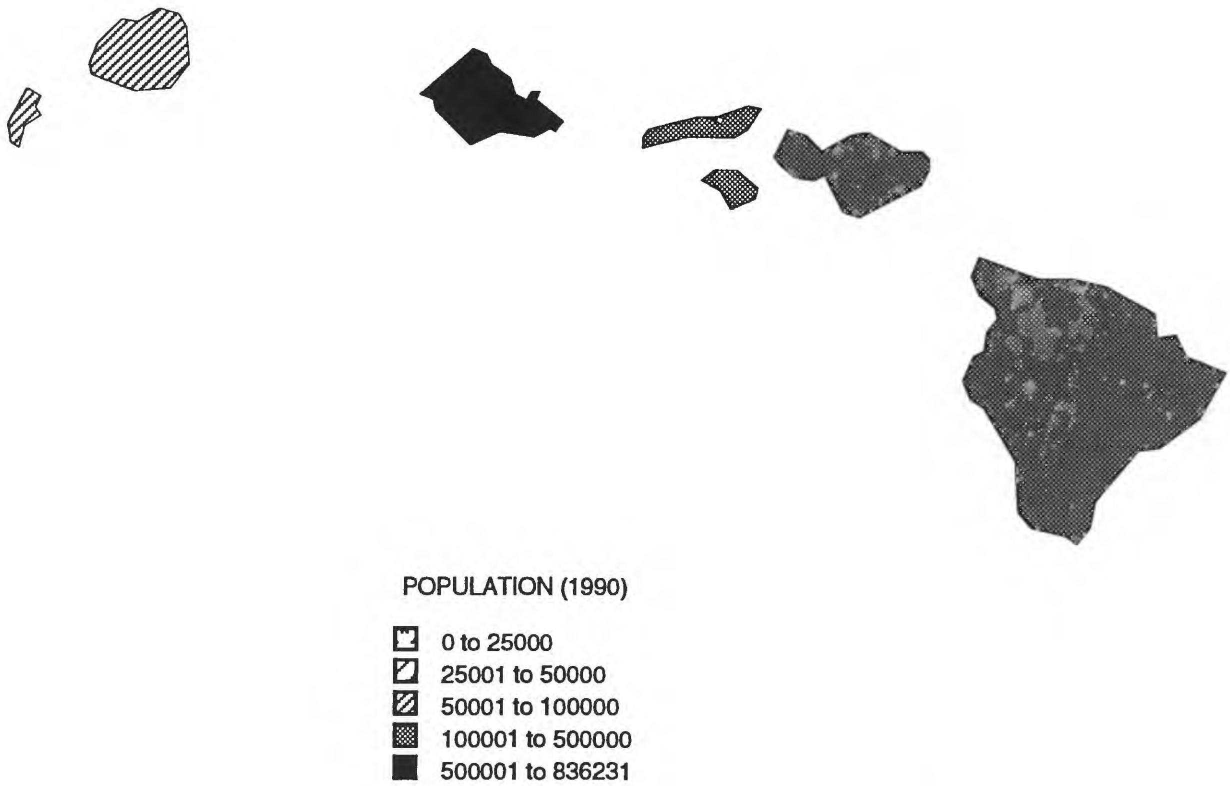
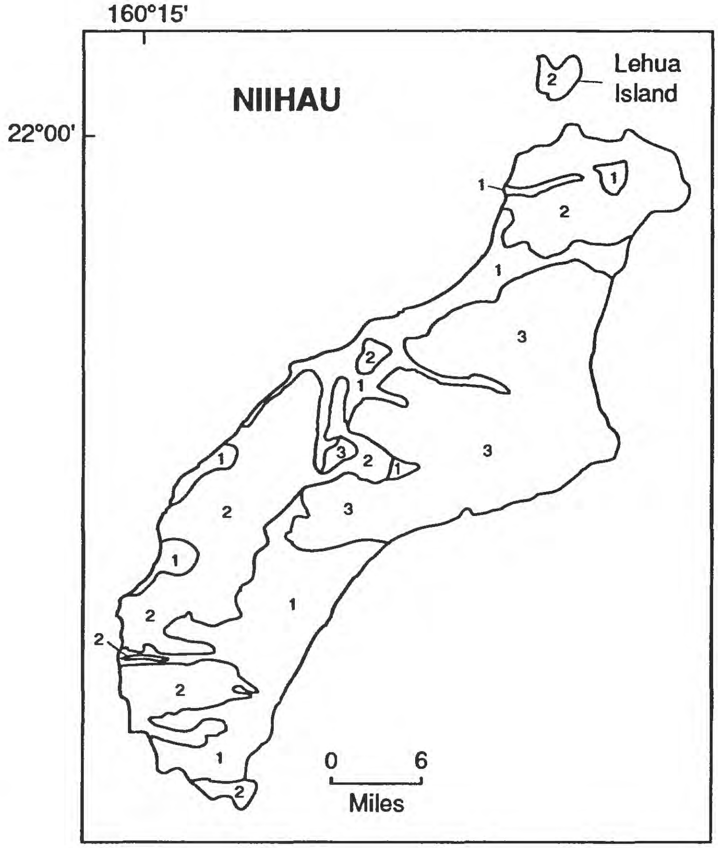


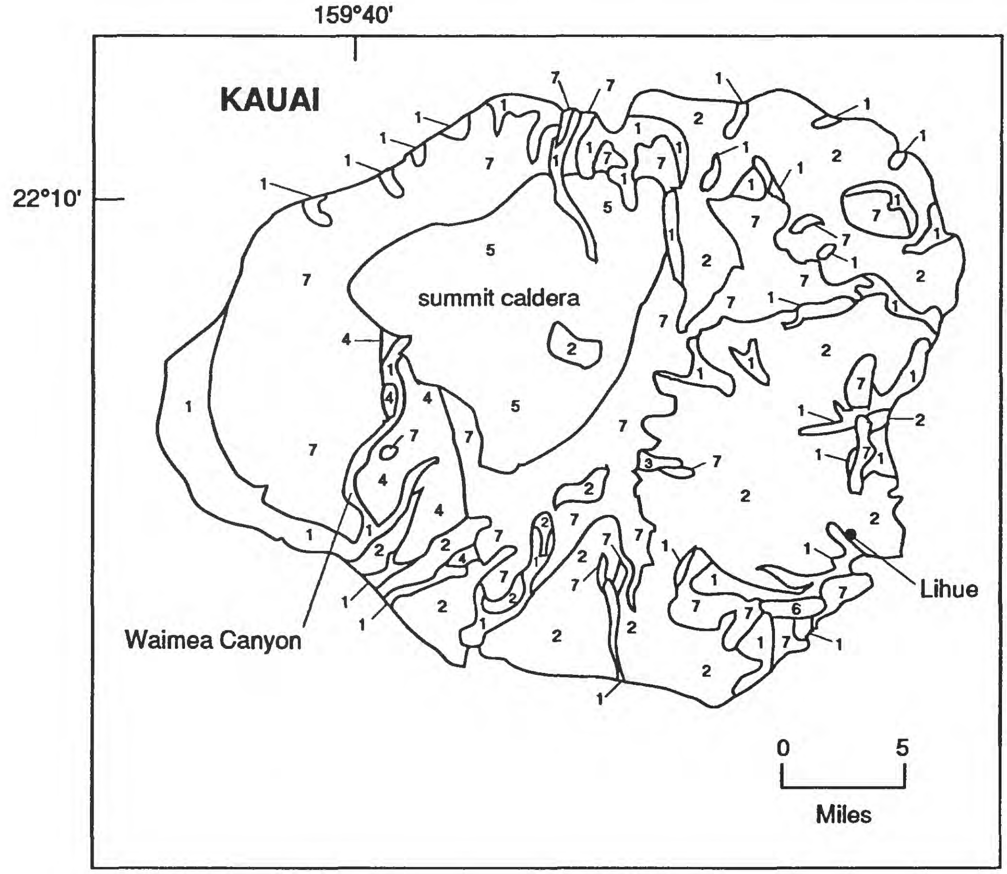
Figure 4. Population of counties in Hawaii (1990 U.S. Census data).



EXPLANATION

1	Sedimentary deposits (Holocene and Pleistocene)
2	Kiekie Basalt (Pleistocene and Pliocene)
3	Paniau Basalt (Pliocene and Miocene)

Figure 5. Map showing generalized geology of Niihau, Kauai County, Hawaii (modified from Langenheim and Clague, 1986).



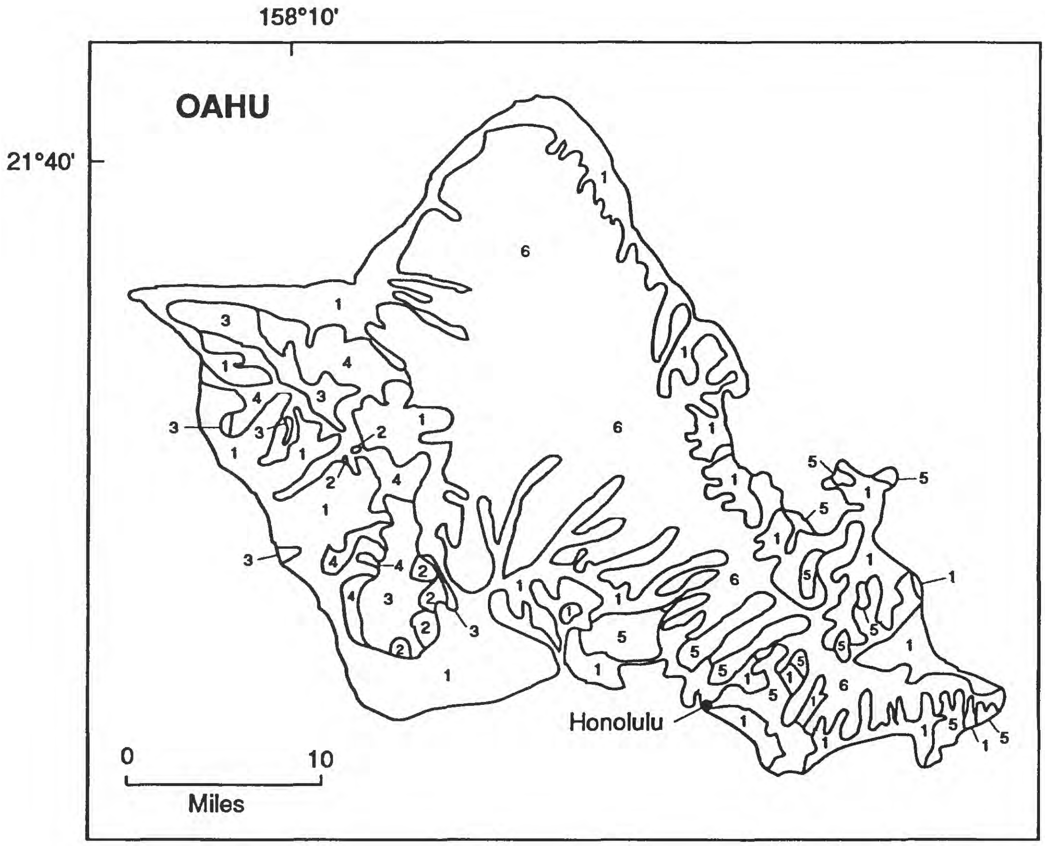
EXPLANATION

- 1 — Sedimentary deposits (Holocene)
- 2 — Koloa Volcanics (Pleistocene and Pliocene)
- 3 — Palikea Breccia Member (Pleistocene? and Pliocene?)

Waimea Canyon Basalt

- 4 — Makaweli Member (Pliocene) (flank graben) (includes Mokuone Breccia Beds)
- 5 — Olokele Member (Pliocene)
- 6 — Haupu Member (Pliocene) (flank caldera)
- 7 — Napali Member (Pliocene and Miocene?) (lava flows)

Figure 6. Map showing generalized geology of Kauai, Kauai County, Hawaii (modified from Langenheim and Clague, 1986).



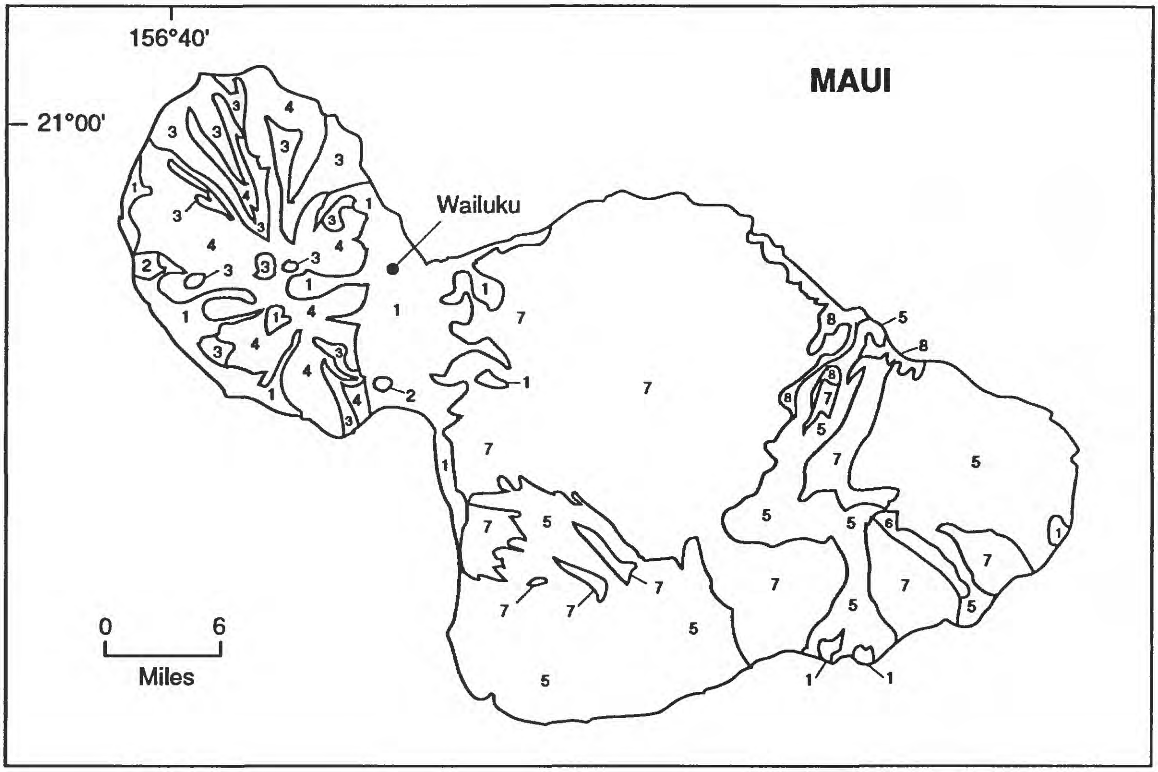
EXPLANATION

- [1] Sedimentary deposits (Holocene and Pleistocene)
- [2] Kolekole Volcanics (Pleistocene)

Waianae Volcanics (Pleistocene)

- [3] Palehua Member
- [4] Kamaileunu and Lualualei Members, undivided (Kamaileunu Member includes Mauna Kuwale Rhyodacite Flow)
- [5] Honolulu Volcanics (Holocene? and Pleistocene)
- [6] Koolau Basalt (Pleistocene? and Pliocene) (includes Kailua Member)

Figure 7. Map showing generalized geology of Oahu, Honolulu County, Hawaii (modified from Langenheim and Clague, 1986).



EXPLANATION

1	Sedimentary deposits (Holocene and Pleistocene)	5	Hana Volcanics (Holocene and Pleistocene?)
2	Lahaina Volcanics (Pleistocene)	6	Kipahulu Member (Pleistocene?)
3	Honolua Volcanics (Pleistocene)	7	Kula Volcanics (Pleistocene)
4	Wailuku Basalt (Pleistocene)	8	Honomanu Basalt (Pleistocene)

Figure 8. Map showing generalized geology of Maui, Maui County, Hawaii (modified from Langenheim and Clague, 1986).

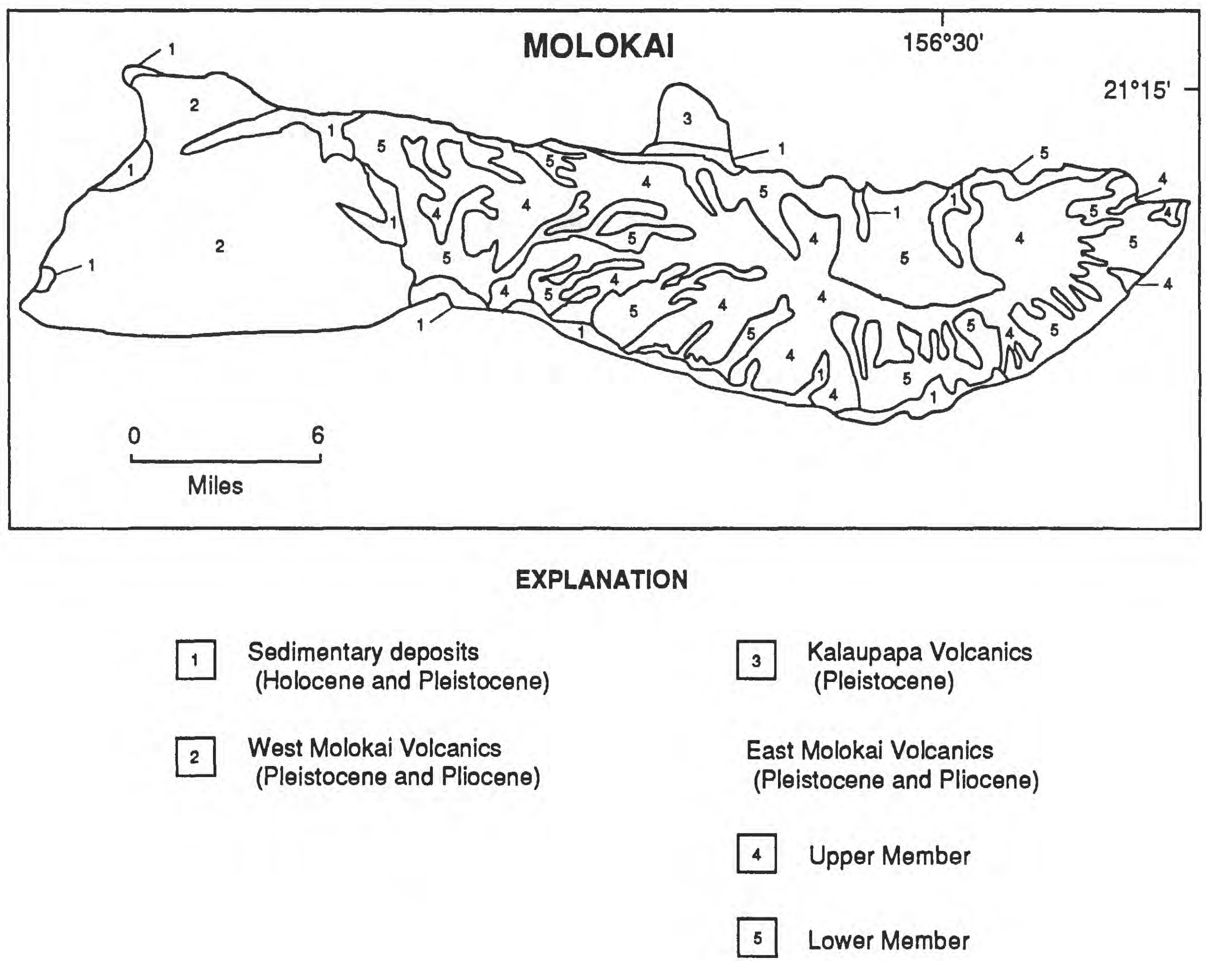
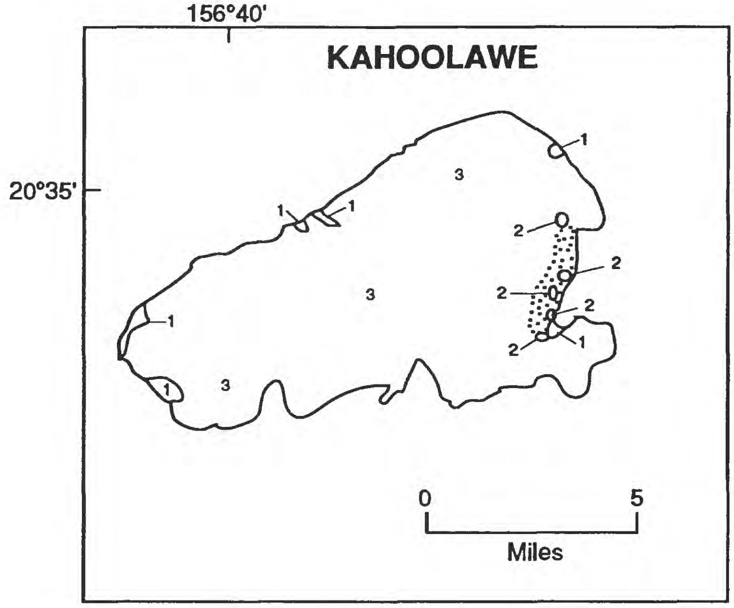


Figure 9. Map showing generalized geology of Molokai, Maui County, Hawaii (modified from Langenheim and Clague, 1986).

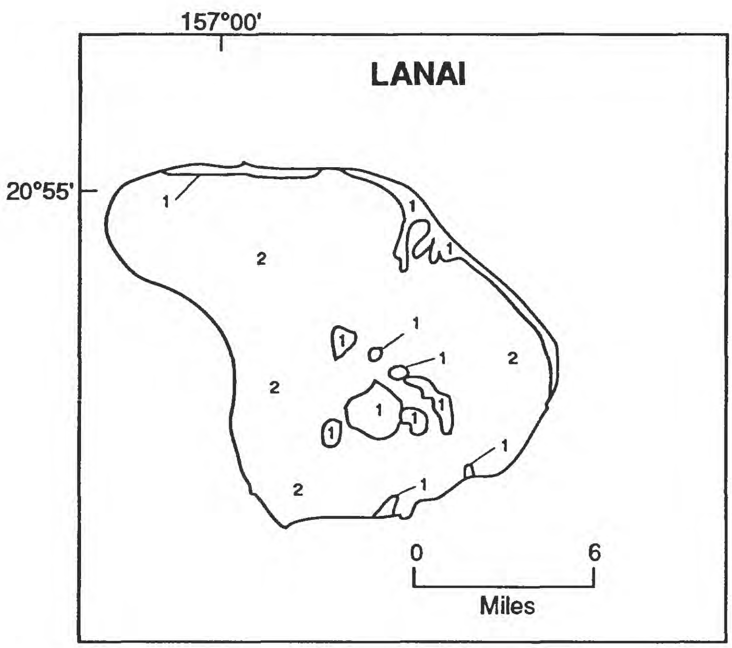


EXPLANATION

1 Sedimentary deposits (Holocene)

2 Volcanic rocks (rejuvenated-stage vents) (Holocene or Pleistocene)

3 Kanapou Volcanics (Pleistocene) (caldera-filling lava, stippled)

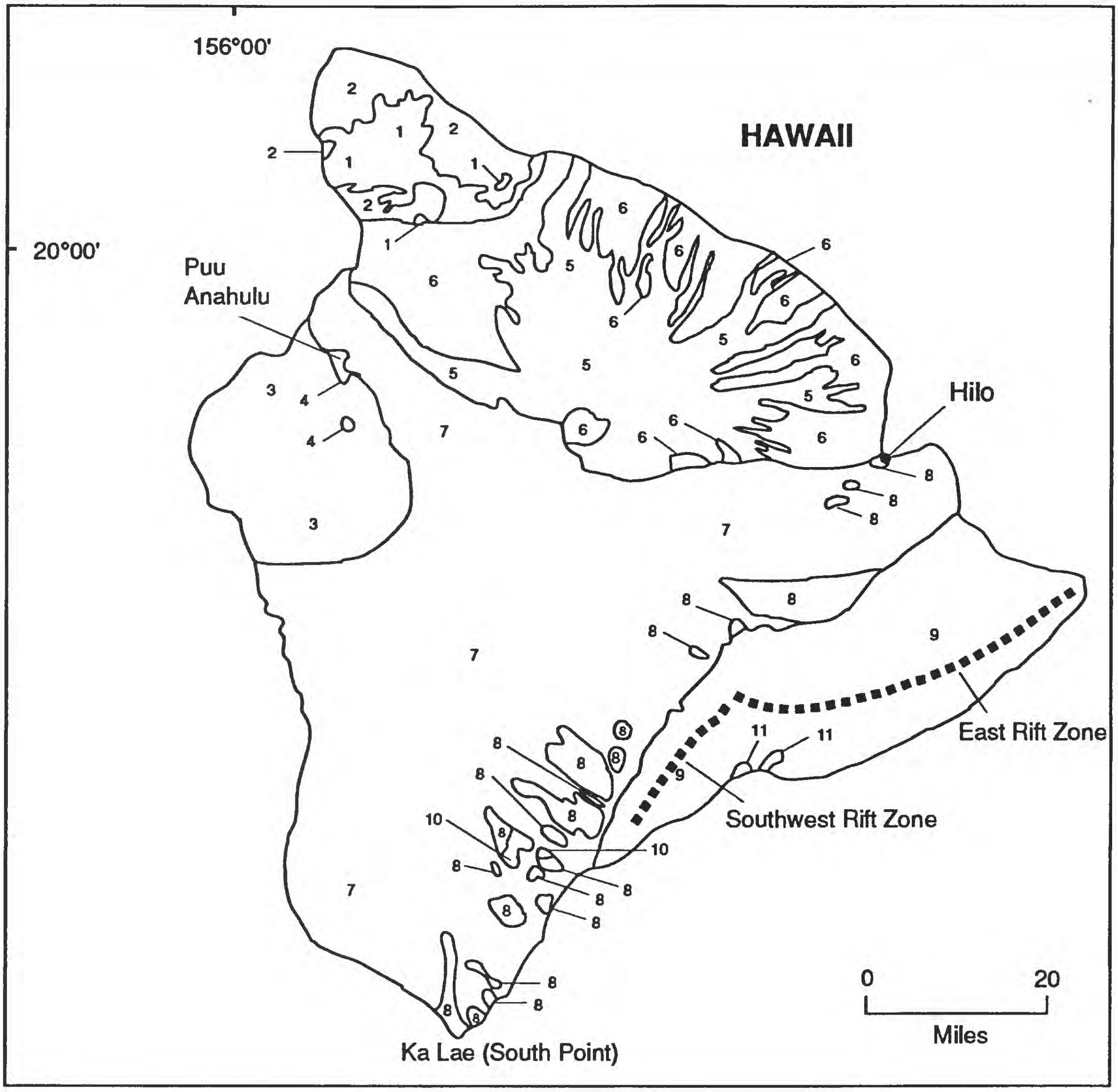


EXPLANATION

1 Sedimentary deposits (Holocene and Pleistocene)

2 Lanai Basalt (Pleistocene)

Figure 10. Map showing generalized geology of Kahoolawe and Lanai, Maui County, Hawaii (modified from Langenheim and Clague, 1986).



EXPLANATION

1	Hawi Volcanics (Pleistocene)
2	Pololu Basalt (Pleistocene)
3	Hualalai Volcanics (Holocene and Pleistocene)
4	Waawaa Trachyte Member (Pleistocene)
5	Laupahoehoe Volcanics (Holocene and Pleistocene) (Waikahalulu Volcanic and Makanaka and Waihu Glacial Members, undivided)
6	Hamakua Volcanics (Pleistocene) (Hopukani Volcanic and Pohakuloa Glacial Members and lower member, undivided)
7	Kau Basalt (Holocene and Pleistocene)
■■■■■■	Rift zone
8	Kahuku Basalt (Pleistocene)
9	Puna Basalt (Holocene and Pleistocene) (includes Keanakakoi and Uwekahuna Ash Members)
10	Ninole Basalt (Pleistocene)
11	Hilina Basalt (Pleistocene) (includes Moo, Pohakaa, Kahele, and Halape Ash Members)

Figure 11. Map showing generalized geology of Hawaii, Hawaii County, Hawaii (modified from Langenheim and Clague, 1986).

0.41 to 10.9 ppm for thorium have been reported (Heier and Rogers, 1963; Heier and others, 1964; Hamilton, 1965; Clague and Frey, 1982). Only a few values for uranium are greater than 1 ppm. Concentrations for some basaltic sequences can be inferred by using a reasonable range of ratios of uranium and thorium to other elements (Hamilton, 1965; Stille and others, 1983), and those inferred values are within the range of samples actually analyzed. A few ground-based measurements to determine equivalent uranium were performed on Oahu and Hawaii in 1989 using a gamma spectrometer (Reimer and Thomas, unpublished data), and those results indicated equivalent uranium to be less than 1.0 ppm.

Because of the climate in Hawaii, many of the soils are mechanically and chemically deeply weathered. Some soils are especially iron rich, with Fe_2O_3 concentrations of 10 to 20 percent or more (Aguilera and Jackson, 1953). As weathering oxidizes and leaches the iron from the soils, it is available for coating the grains. This action is what causes the bright red color of many of the Hawaiian soils on the more northwestern islands. Soils developed on the big island of Hawaii do not have the same maturity as the other islands to have developed the deeply weathered, lateritic type of soil (Sato and others, 1973). Uranium and some progeny of the uranium decay series, including radium, will chemically redeposit with iron on the surface of the soil grains. Consequently, even though the uranium concentration is very low, it is not uniformly distributed throughout the minerals that make up the soil, and it is enhanced on the soil-grain boundaries. This increases the emanation coefficient of the soil because the recoil of radon from alpha-particle-emitting radium, a member of the uranium decay series and immediate progenitor of radon, near the grain surfaces gives a higher probability that radon will enter the pore space and become available for transport (Reimer and Tanner, 1991).

Permeability of Hawaiian soils is quite variable. Typically, soils are well drained because of the slope and fabric of the soils. Some soils with higher clay and organic content, or associated with flat or gently sloping terrain, such as found in the summit caldera of Kauai, are poorly drained (Foote and others, 1972).

NURE AIRBORNE RADIOMETRIC DATA

The National Uranium Resource Evaluation (NURE) program did not include Hawaii. Consequently, there is no information for aeroradiometric data or stream sediment analyses.

OUTDOOR AND SOIL-GAS RADON CONCENTRATIONS

There are few data available on outdoor and soil-gas radon concentrations. The ambient atmospheric radon concentration for Hawaii is very low because Hawaii is an island; there is no surrounding continental mass contributing a soil flux of radon to the atmospheric concentration (Wilkening and Clements, 1975). Radon fluxes have been measured and are found to be low (Wilkening, 1964). Radon samples collected in an eruptive Kilauea plume and elsewhere on the big island of Hawaii have shown concentrations only of 0.007 pCi/L (Larson, 1974; Moore and others, 1974). Gas samples collected directly from Kilauea vents have not contained radon concentrations greater than 200 pCi/L. Long-term studies of soil-gas radon at Kilauea and the East Rift Zone have shown variations in relation to meteorological, seismic and volcanic activity (Cox, 1980; Cox and others, 1980; Cox, 1983; Thomas and others, 1986). Soil-gas concentrations in that study ranged from about 10 to 1000 pCi/L. The higher concentrations may be attributed to

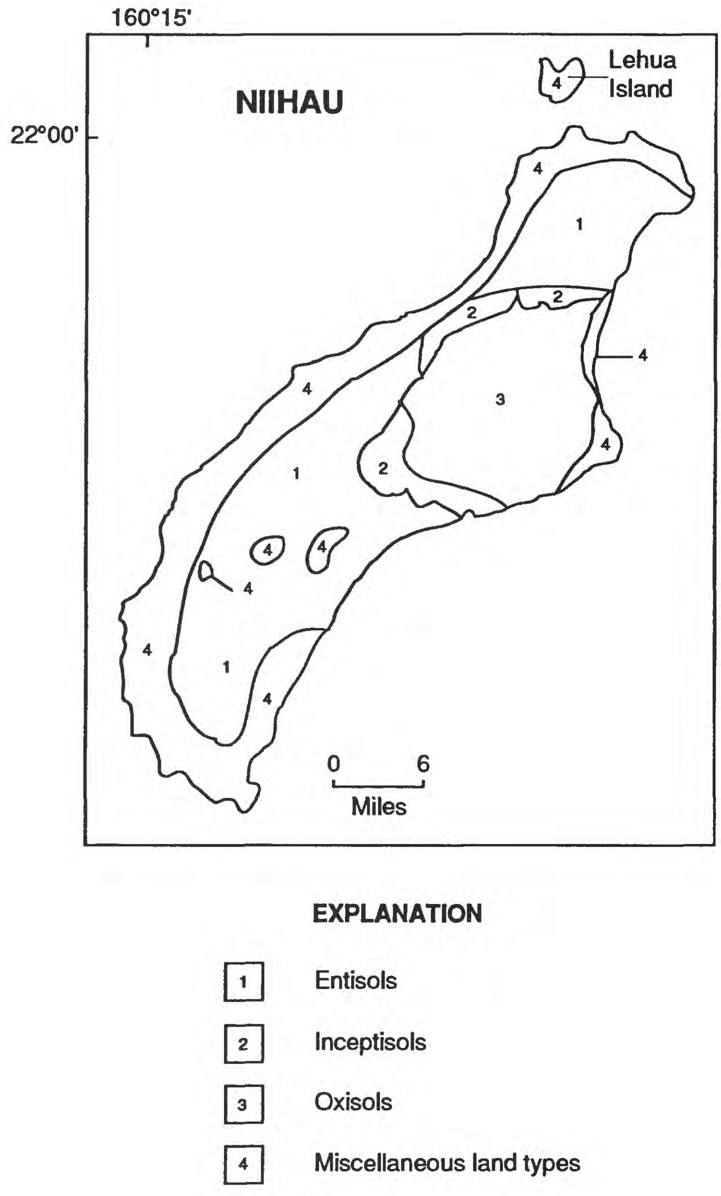
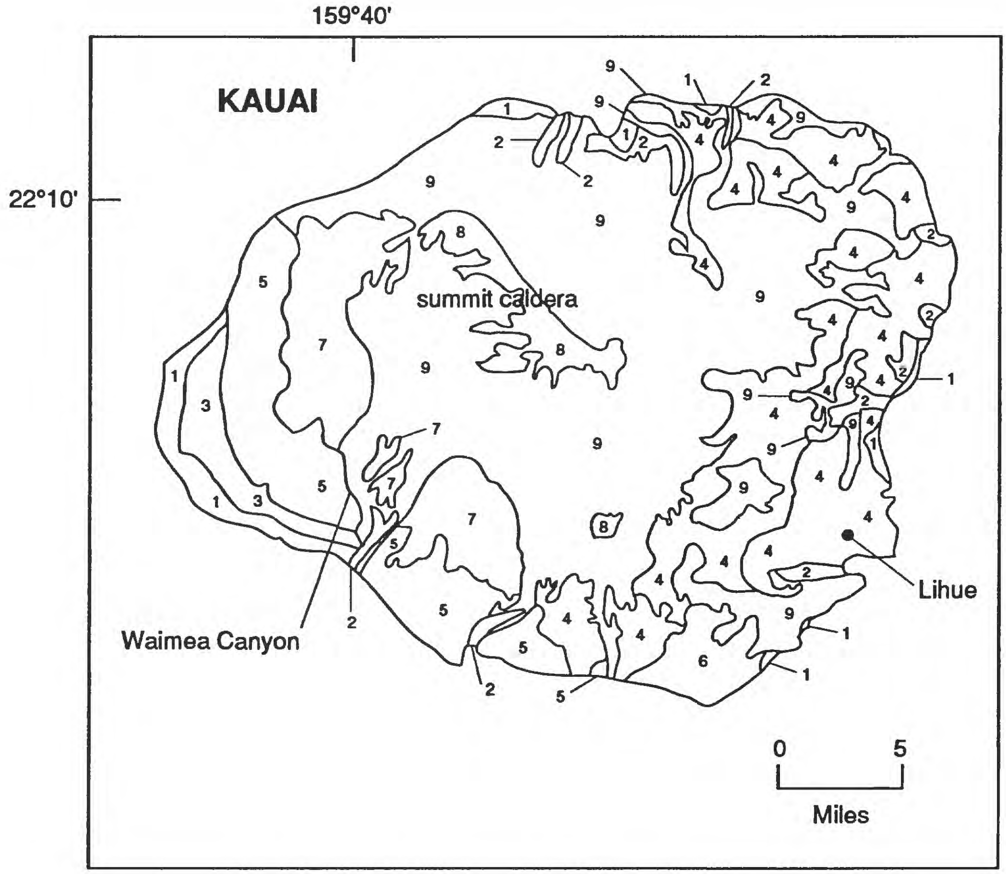


Figure 12. Map showing generalized soil classification of Niihau, Kauai County, Hawaii (modified from Macdonald, 1973). Occasionally, on some of the soil maps, there are separations for adjacent, similarly numbered units. These represent slight differences in soil sub-groups that are indicated on the map from the original source and are simply left in place on these modified renditions.



EXPLANATION

1	Entisols-Mollisols
2	Inceptisols
3	Mollisols
4	Oxisols
5	Oxisols-Mollisols
6	Mollisols-Inceptisols-Oxisols
7	Rough broken land-Inceptisols-Ultisols
8	Spodosols-Histosols
9	Rough mountainous land-Rough broken land-Rock outcrop

Figure 13. Map showing generalized soil classification of Kauai, Kauai County, Hawaii (modified from Foote and others, 1972). Occasionally, on some of the soil maps, there are separations for adjacent, similarly numbered units. These represent slight differences in soil sub-groups that are indicated on the map from the original source and are simply left in place on these modified renditions.

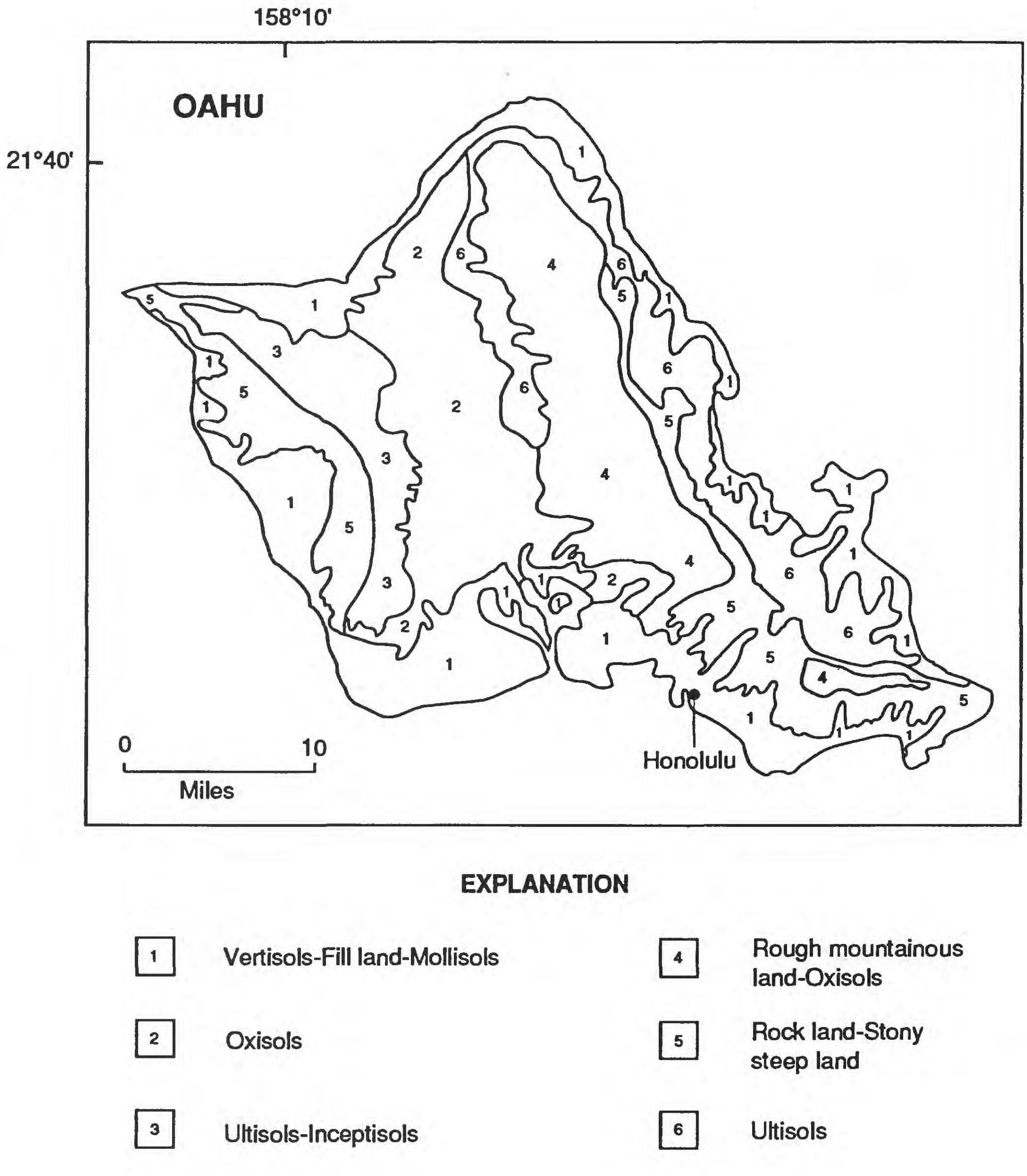
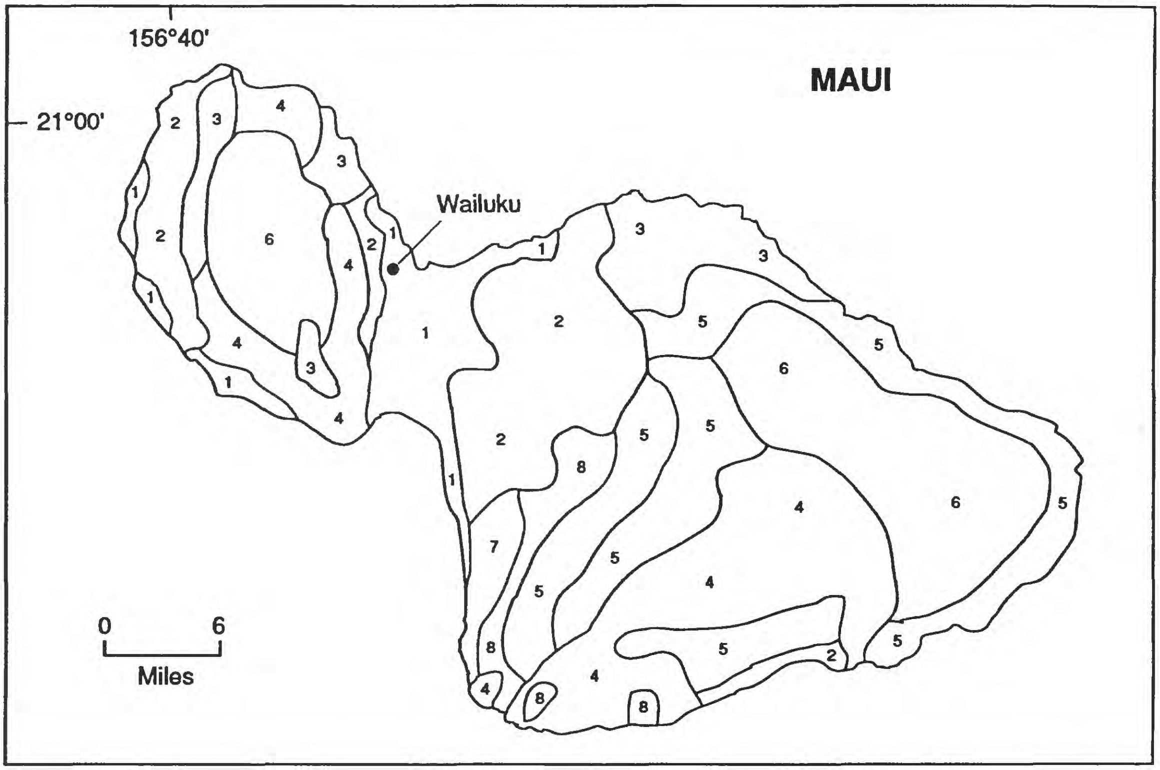


Figure 14. Map showing generalized soil classification of Oahu, Honolulu County, Hawaii (modified from Foote and others, 1972). Occasionally, on some of the soil maps, there are separations for adjacent, similarly numbered units. These represent slight differences in soil subgroups that are indicated on the map from the original source and are simply left in place on these modified renditions.



EXPLANATION

- 1 Mollisols-Entisols
- 2 Mollisols-Oxisols
- 3 Ultisols
- 4 Rock land-Rough mountainous land
- 5 Inceptisols
- 6 Inceptisols-Spodosols
- 7 Mollisols
- 8 Mollisols-Inceptisols

Figure 15. Map showing generalized soil classification of Maui, Maui County, Hawaii (modified from Foote and others, 1972). Occasionally, on some of the soil maps, there are separations for adjacent, similarly numbered units. These represent slight differences in soil sub-groups that are indicated on the map from the original source and are simply left in place on these modified renditions.

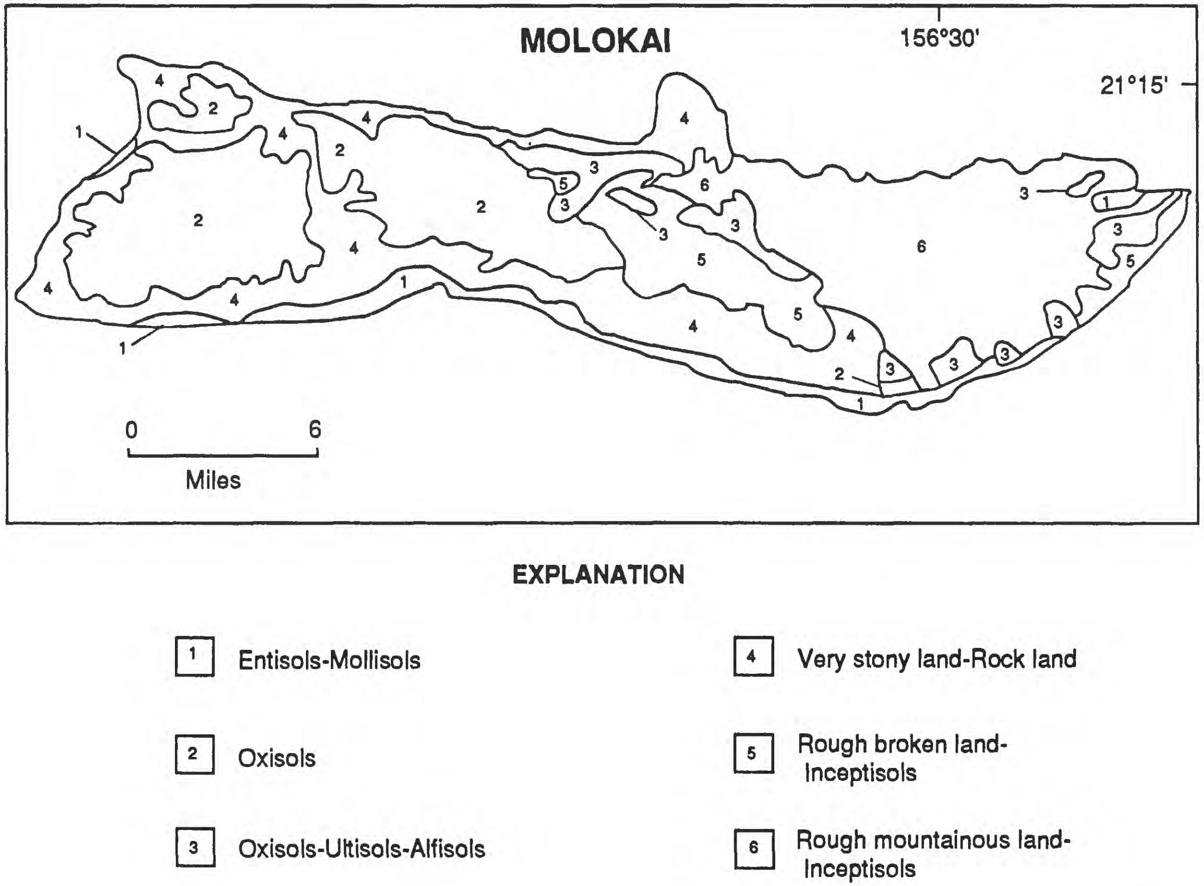


Figure 16. Map showing generalized soil classification of Molokai, Maui County, Hawaii (modified from Foote and others, 1972). Occasionally, on some of the soil maps, there are separations for adjacent, similarly numbered units. These represent slight differences in soil sub-groups that are indicated on the map from the original source and are simply left in place on these modified renditions.

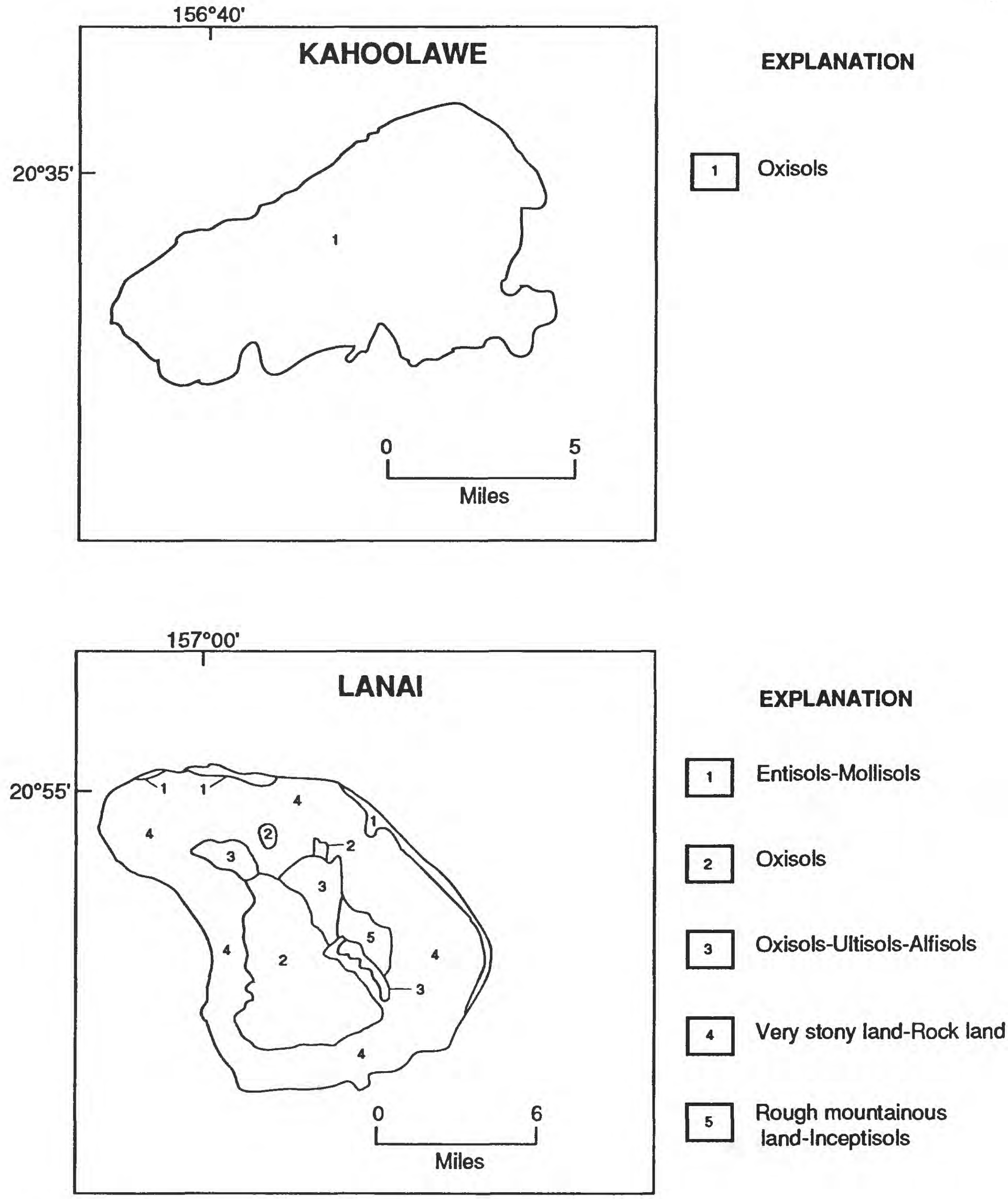
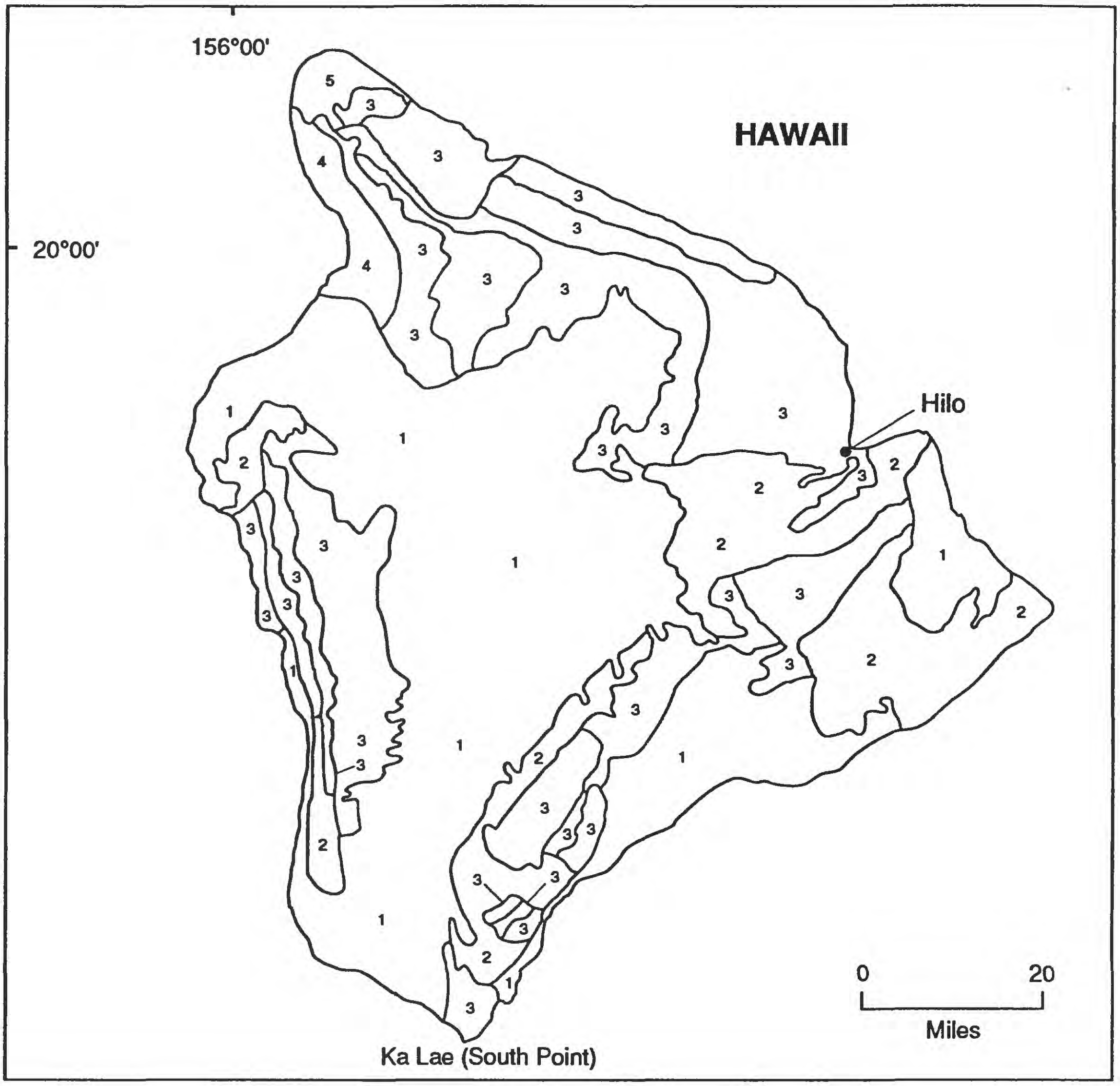


Figure 17. Map showing generalized soil classification of Kahoolawe and Lanai, Maui County, Hawaii (modified from Foote and others, 1972). Occasionally, on some of the soil maps, there are separations for adjacent, similarly numbered units. These represent slight differences in soil sub-groups that are indicated on the map from the original source and are simply left in place on these modified renditions.



EXPLANATION

1 Lava flows	4 Aridisols
2 Histosols	5 Inceptisols-Mollisols
3 Inceptisols	

Figure 18. Map showing generalized soil classification of Hawaii, Hawaii County, Hawaii (modified from Sato and others, 1973). Occasionally, on some of the soil maps, there are separations for adjacent, similarly numbered units. These represent slight differences in soil subgroups that are indicated on the map from the original source and are simply left in place on these modified renditions.

additional concentration and redistribution of uranium in structurally active areas, such as faults or shear zones (Gundersen, 1991).

Soil-gas radon concentrations are moderate in some locations, with up to 1000 pCi/L being recorded on deeply weathered soils on Oahu (Reimer and Thomas, 1989, unpublished data). A few sites have been measured on Oahu and Hawaii as part of a DOE-funded program to understand meteorological effects on radon availability and transport. Concentrations of 1000 pCi/L and less were found (Cuff and others, 1985; Thomas and others, 1992).

INDOOR RADON DATA

A number of studies have shown a distinct correlation between geology and indoor radon (Hawthorne and others, 1984; Gundersen and others, 1988a, 1988b; Reimer, 1990). Underlying rock and the soils derived from it are the primary factors in determining the radon availability. The potential for indoor radon exposure by occupants is then based on a number of additional factors including house construction and occupant usage, which are themselves often influenced by climate.

Indoor radon data from 523 homes sampled in the State/EPA Residential Radon Survey conducted in Hawaii during the winter of 1989-1990 are listed in Table 1 and shown in figure 19. Indoor air samples were collected using short-term charcoal canisters. This sampling technique provides an estimate of the indoor radon concentration which then can be used to estimate the concentration of indoor radon progeny to which the occupants may be exposed during their long-term occupation of the dwelling (Nazaroff and Nero, 1988). Data are available only on a county-wide basis and are not subject to finer analysis. Because results are reported by county, all islands are not represented equally. For example, to the best of our knowledge, no samples included in this study were obtained from the counties of Kahoolawe and Niihau, and only three were from Molokai and one from Lanai. Kauai County had 49 samples; Honolulu County had 257 samples; Maui County had 79 samples; and Hawaii County had 138 samples (Table 1). The average for the state was 0.1 pCi/L and only 2 homes exceeded 4 pCi/L. A distribution of the indoor concentrations is shown in figure 20. The highest concentrations recorded in the survey were 5.6 pCi/L in Hawaii County and 4.8 pCi/L in Honolulu County. Therefore, only 0.4 percent of the homes in this survey exceeded 4 pCi/L.

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

COUNTY	NO. OF MEAS.	MEAN	GEOM. MEAN	MEDIAN	STD. DEV.	MAXIMUM	%>4 pCi/L	%>20 pCi/L
HAWAII	138	0.1	0.1	0.0	0.6	5.6	1	0
HONOLULU	257	0.1	0.1	0.0	0.6	4.8	0	0
KAUAI	49	0.2	0.2	0.3	0.5	2.3	0	0
MAUI	79	0.1	0.1	0.0	0.7	2.3	0	0

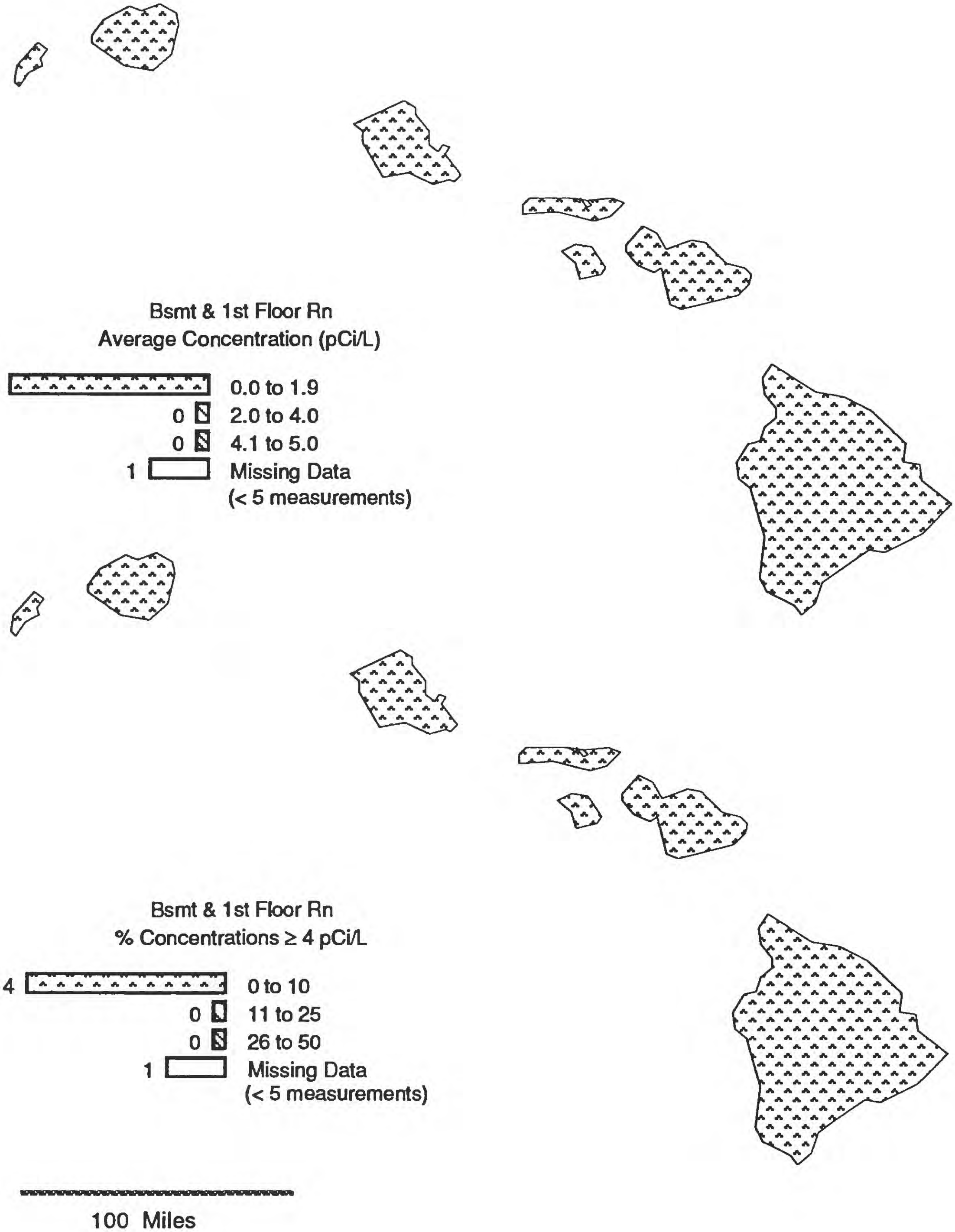


Figure 19. Screening indoor radon data from the State/EPA Residential Radon Survey of Hawaii, 1989-90, for counties with 5 or more measurements. Data are from 2-7 day charcoal number of samples in each county (see Table 1) may not be sufficient to statistically characterize the radon levels of the counties, but they do suggest general trends. Unequal category intervals were chosen to provide reference to decision and action levels.

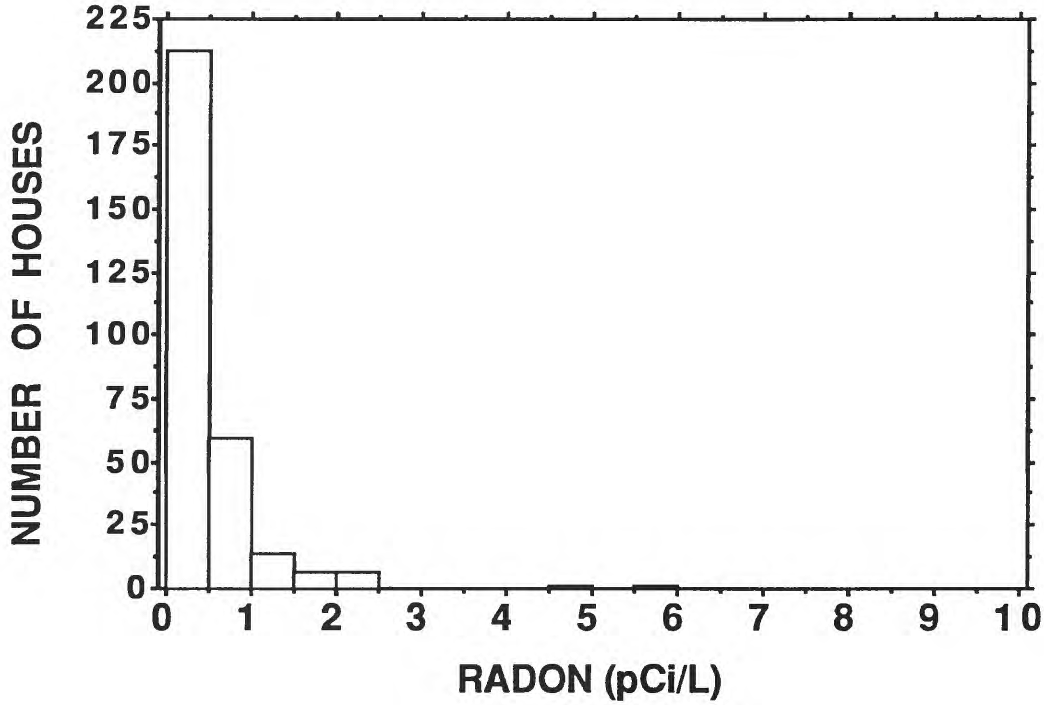


Figure 20. Frequency distribution of indoor radon concentrations measured in the winter of 1989 to 1990 by the State/EPA sampling program. There were a total of 523 homes measured in 4 counties. Only 299 of the total number of homes are plotted here because the remainder were below the measurable lower detection limit of the charcoal canister sampling technique. Concentrations from all house construction types are included.

GEOLOGIC RADON POTENTIAL

Basalt, derived from oceanic and mantle sources, is low in uranium and thorium (Clark and others, 1966). Weathering processes can concentrate what little uranium and thorium are present on the surface of soil grains. In addition, the permeability of most soils in Hawaii is high. This would increase the radon availability for transport but that would only be a factor in increased radon potential if the houses have contact with the ground or are built with a basement or underground. As previously mentioned, there is no NURE data available for the state of Hawaii.

RADON INDEX AND CONFIDENCE INDEX

For the purpose of this assessment, Hawaii has been characterized on the basis of two geologic factor ratings and has been assigned respective Radon Indices (RI) and Confidence Indices (CI) scores (Table 2). The RI is a semi-quantitative measure of radon potential based on geology, soils, radioactivity, architecture, and indoor radon. For this study, radioactivity refers not to aeroradioactivity measurements but rather to the actual chemical measurements of uranium in some rock types. Architecture is assigned 1 point although the majority of homes are built above ground contact, although a few homes in this study did have basements or on-grade slabs. The CI is a measure of the relative confidence of the RI assessment based on the quality and quantity of the data used to assess geologic radon potential. See the Introduction chapter to this regional booklet for more information.

SUMMARY

The radon potential for inhabitants of Hawaii is low, based on geology, soil, limited radiometric determinations, and climate. This appraisal is confirmed from indoor measurements from the State/EPA Residential Radon Survey of 1989-1990, which resulted in a state average of 0.1 pCi/L, a value even lower than average continental ambient air concentrations (Nazaroff and Nero, 1988). The common open-air style house construction methods are paramount in determining the low potential. Because soil-gas radon measurements are moderate in some locations, more than would be normally expected from the bulk uranium and thorium determinations, underground facilities or houses with basements would be suspect for higher radon potential. The higher soil-gas radon concentrations are typically found in moderately- to deeply-weathered lateritic soils characterized by iron oxide coating of the soil grains.

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 Hawaii. The Pu'u Anahulu area is shown on Figure 11.

	Entire state[1]		Pu'u Anahulu Hawaii County	
FACTOR	RI	CI	RI	CI
INDOOR RADON	1	3	1	1
RADIOACTIVITY	1	1	3	1
GEOLOGY	1	3	1	3
SOIL PERMEABILITY	1	2	1	2
ARCHITECTURE	1	-	1	-
GFE POINTS	0	-	0	-
TOTAL	5	9	7	7
RANKING	LOW	MOD	LOW	MOD

[1]The total area of the state of Hawaii is included in this category with the exception of the Pu'u Anahulu lava flow on the island of Hawaii. The separate distinction for this small area is based upon the reported uranium concentration of 3.2 ppm (Heier and others, 1964).

RADON INDEX SCORING:

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

Possible range of points = 3 to 17

CONFIDENCE INDEX SCORING:

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

Possible range of points = 4 to 12

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PRELIMINARY GEOLOGIC RADON POTENTIAL ASSESSMENT OF NEVADA

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U.S. Geological Survey

INTRODUCTION

Nevada is an arid western state bordered by Utah and Arizona on the east, California on the south and west, and by Oregon and Idaho on the north. Most of Nevada receives less than 10 inches (25 cm) of precipitation per year (Manahan, 1990). Nevada is subdivided into 17 counties, most of which cover vast land areas (fig. 1). Most of Nevada has a sparse population; 8 of the counties have less than 10,000 inhabitants, and only 2 counties have more than 100,000 people (fig. 2). The population is concentrated in two clusters, one in the vicinity of Las Vegas and the other in the Reno/Carson City area (fig. 2).

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

GEOGRAPHIC SETTING

Almost all of Nevada lies within the Basin and Range Province, and most of Nevada is in the Great Basin Section of this province (fig. 3). The Great Basin Section is characterized by isolated mountain ranges separated by aggraded desert plains (Peterson, 1981). The southern tip of Nevada is in the Sonoran Desert Section of the Basin and Range Province (fig. 3), and is characterized by widely separated mountain ranges in desert plains (Peterson, 1981). The mountainous western side of Nevada, where the state line turns to the north, lies within the Sierra Nevada Province. The Owyhee Upland is adjacent to the Snake River Plain and extends into Nevada along the State's border with Idaho. The Owyhee Upland is an area of low relief and moderate elevation (Stewart, 1980).

Mountain ranges in Nevada generally rise 1,000 to 5,000 feet (300 to 1,500 m) above the adjacent valleys and have widths that range from 5 to 15 miles (8 to 24 km) (Stewart, 1980). The valleys tend to be similar in width to their corresponding mountain ranges. Typically the mountain ranges are elongate with a north-northeast orientation and many of the ranges extend for more than 50 miles (80 km) (Stewart, 1980). The lowest elevations in the State are found along the Colorado River in the south. Boundary Peak, the highest point in the State, has an elevation of 13,145 feet (4,006 m) and is located in the White Mountains near the California-Nevada state line.

Fig. 1. Counties

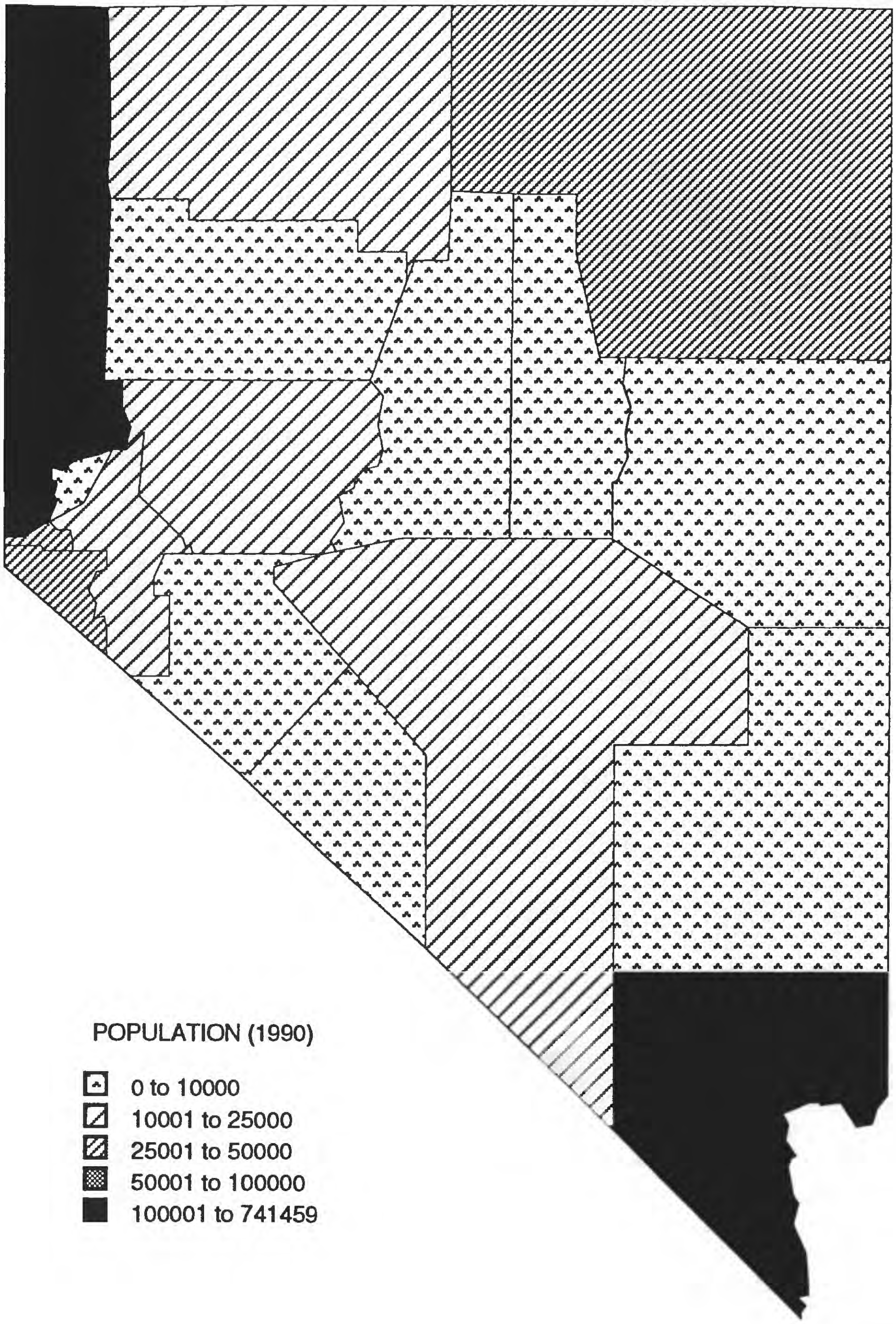


Figure 2. Population of counties in Nevada (1990 U.S. Census data).

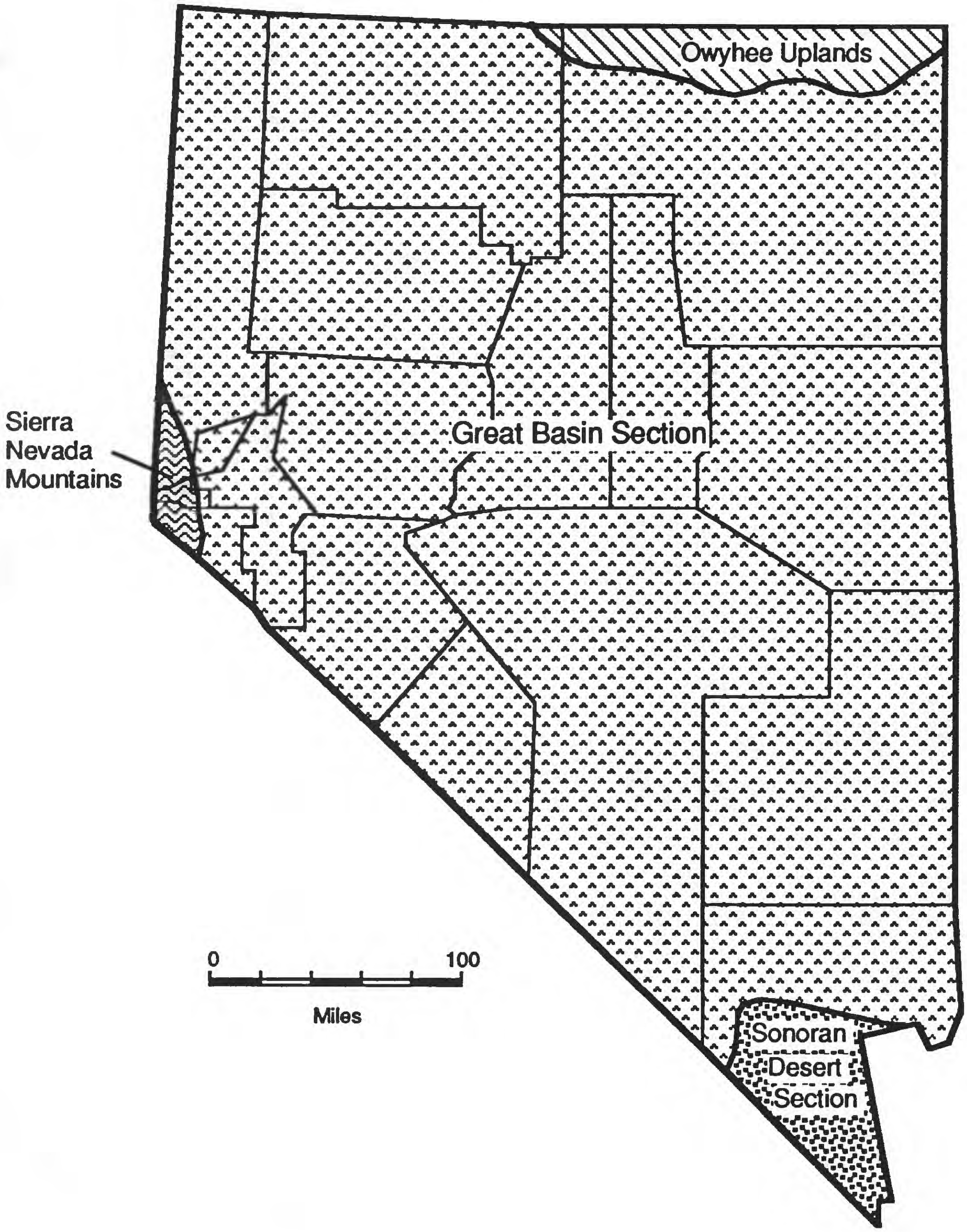


Figure 3. Physiographic provinces of Nevada (after Peterson, 1981).
Areas listed as "sections" are subdivisions of the Basin and Range Province.

GEOLOGIC SETTING

Nevada is a large state with a complex, fault-dominated geology consisting of rocks and sediments that range in age from Precambrian to Holocene. Stewart (1980) gives the following summary of the geology and geologic history of Nevada:

> "Nevada has had a long and complex geologic history that includes major episodes of sedimentation, igneous activity, orogenic deformation [mountain building], and continental rifting. The record of this history starts in the Precambrian and is well documented throughout the Phanerozoic [Cambrian and later time].
>
> The oldest rocks in Nevada crop out in the southernmost part of the State and consist of metamorphic and intrusive rocks of Precambrian age containing folded granite lenses dated as 1,740 m.y. [million years] old. These rocks are intruded by porphyritic rapakivi granite [granite that is characterized by alkali feldspar phenocrysts that are mantled with plagioclase] dated as 1,450 m.y. old.
>
> The next youngest rocks in Nevada are uppermost Precambrian to Upper Devonian shallow-water subtidal to supratidal terrigenous detrital and carbonate strata deposited on a broad shelf along the western margin of North America. This deposition created a prism of sediment (the Cordilleran miogeocline) that thickens from a few thousand feet in cratonic areas [areas that have obtained stability and have had little deformation for a long time] in central Utah to nearly 30,000 feet (10,000 m) in central Nevada. Coeval [same age] rocks in western Nevada are considered to be mainly deep-water strata and consist predominantly of shale, radiolarian chert, quartzite, and mafic pillow lava.
>
> During the Late Devonian and Early Mississippian, wide-spread orogenic activity of the Antler orogeny affected Nevada and resulted in the emplacement of the Roberts Mountains allochthon [a mass of rock that has been moved from its place of origin by tectonic processes], a sheet of oceanic siliceous and volcanic assemblage rocks thrust eastward as much as 90 miles (145 km) over coeval shelf carbonate rocks. This orogeny produced the Antler highland, an upland belt trending north-northeast medially in Nevada along what was formerly the edge of the shelf.
>
> During the late Paleozoic, the sedimentary and tectonic provinces in Nevada were, from east to west, (1) a shallow-water carbonate shelf; (2) a foreland basin containing coarse detrital material derived from the west as well as more widespread shallow-water carbonate sediments; (3) the Antler highland, overlapped in Pennsylvanian and Permian time by thin coarse detrital marine sediments; (4) a western deep-water basin containing fine to coarse detrital rocks, radiolarian chert, silty limestone, and mafic lava; and (5) a Permian magmatic arc terrane, largely of mafic lava.
>
> During the Late Permian and Early Triassic, Nevada was subjected to another major orogeny (the Sonoma orogeny) during which ocean-floor sediments were thrust eastward as part of the Golconda allochthon for perhaps as much as 60 miles (100 km) over shallow-water deposits on the Antler highland.

Mesozoic sedimentary rocks in Nevada are largely of Triassic and Early Jurassic age and occur in an eastern and a western region. In the eastern region, strata are the western continuation of shallow-water marine and continental, largely terrigenous detrital deposits that are extensively exposed to the east in the Colorado Plateau region of Utah and Arizona. In the western region, shallow-water marine carbonate and deeper water mudstone give way westward into a complex of volcanogenic sediments and lavas and fine-grained detrital rocks. Sedimentary rocks of Cretaceous age occur at scattered localities in Nevada and consist of continental sediments deposited in local basins.

Jurassic and Cretaceous igneous rocks occur widely in western Nevada and at scattered localities elsewhere in the State. Those in western Nevada are along the eastern margin of the Sierra Nevada batholith.

During the Mesozoic, tectonic activity was widespread in Nevada. After the Sonoma orogeny, folding and thrusting may have started again as early as the Late Triassic or Early Jurassic and by the mid-Jurassic, were extensive in western Nevada. During the remainder of the Mesozoic, tectonic activity probably prevailed throughout much of the State, culminating in the major tectonic deformation of the late Mesozoic Sevier orogeny in western Utah and easternmost Nevada.

Rocks of early Cenozoic age are sparse in Nevada. During this time, the State was probably high and undergoing erosion. During middle Cenozoic time, volcanic activity was widespread in Nevada, starting about 43 m.y. ago in the northernmost part of the State and moving gradually southward. Voluminous siliceous ash-flow tuffs were erupted about 34 to 17 m.y. ago in an east-trending belt across the central part of the State.

About 17 m.y. ago, a major change occurred in the tectonic setting of Nevada with the onset of extensional faulting and the eruption of basalt or bimodal assemblages of basalt and rhyolite. During the past 17 m.y., the major basins and ranges that characterize the present-day physiography of the State formed by extensional block faulting, and continental sediments were trapped in fault-related basins."

Figure 4 is a small-scale geologic map of Nevada generalized from the geologic map of Nevada (Stewart and Carlson, 1977). The complex and varied geology of a state like Nevada cannot be satisfactorily shown on a page size map; see Stewart and Carlson (1977) for a more detailed geologic map and Stewart (1980) for a more detailed discussion of the geology of Nevada.

SOILS

Most of the soils in the basins of Nevada are arid soils (fig. 5). These soils are usually light colored, but are often reddish and calcareous. Except where carbonate buildup is heavy, the soils formed on alluvium and colluvium shed from the mountain ranges are probably at least moderately permeable. The surficial geology map of Hunt (1979) shows the basin deposits as fan gravels, an indication that the basin soils typically have high permeabilities. However, many of the basins or valleys also contain broad areas of lacustrine and playa deposits with lower permeability. Most of the soils developed on the uplands are shallow or immature (fig. 5). The semiarid soils in

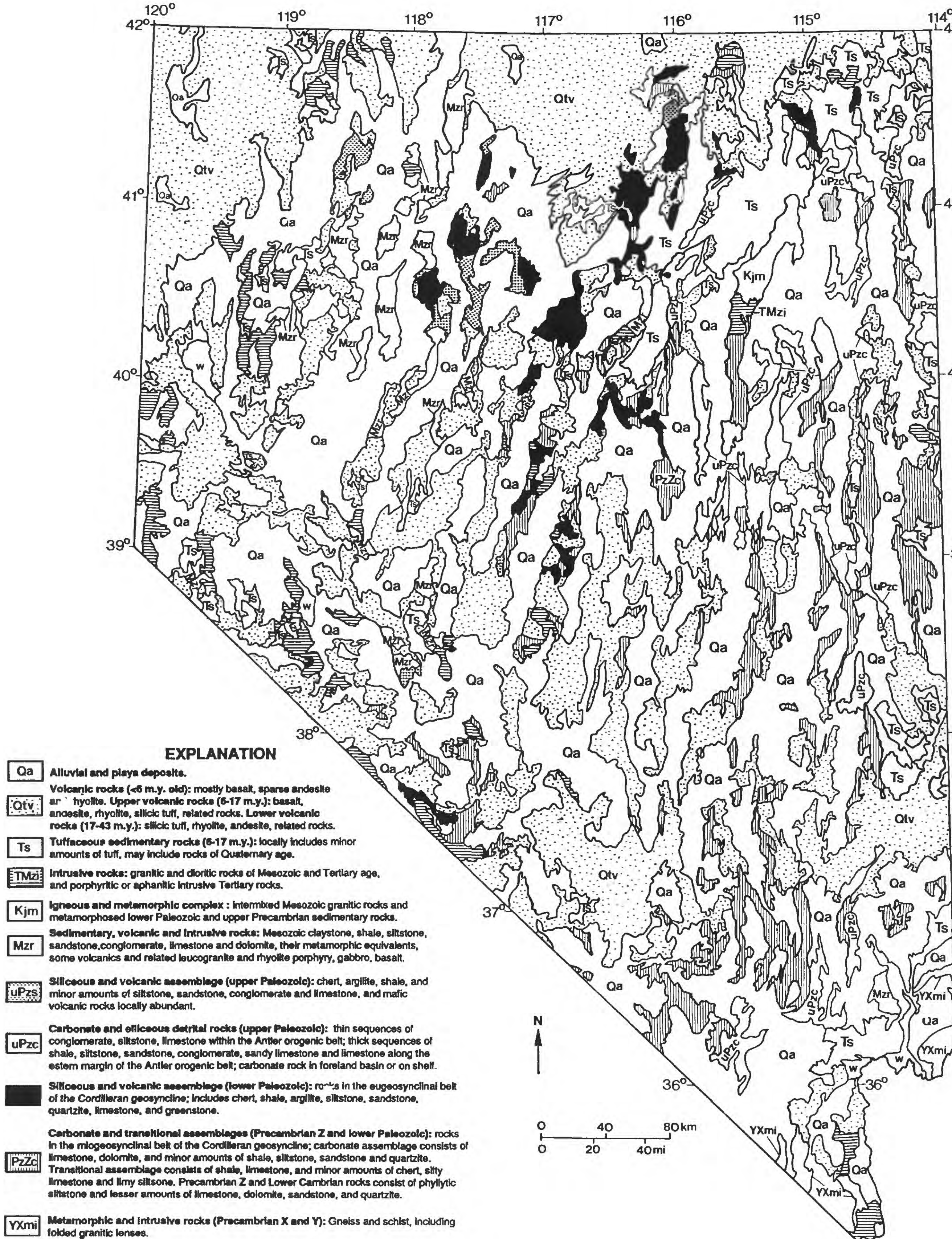
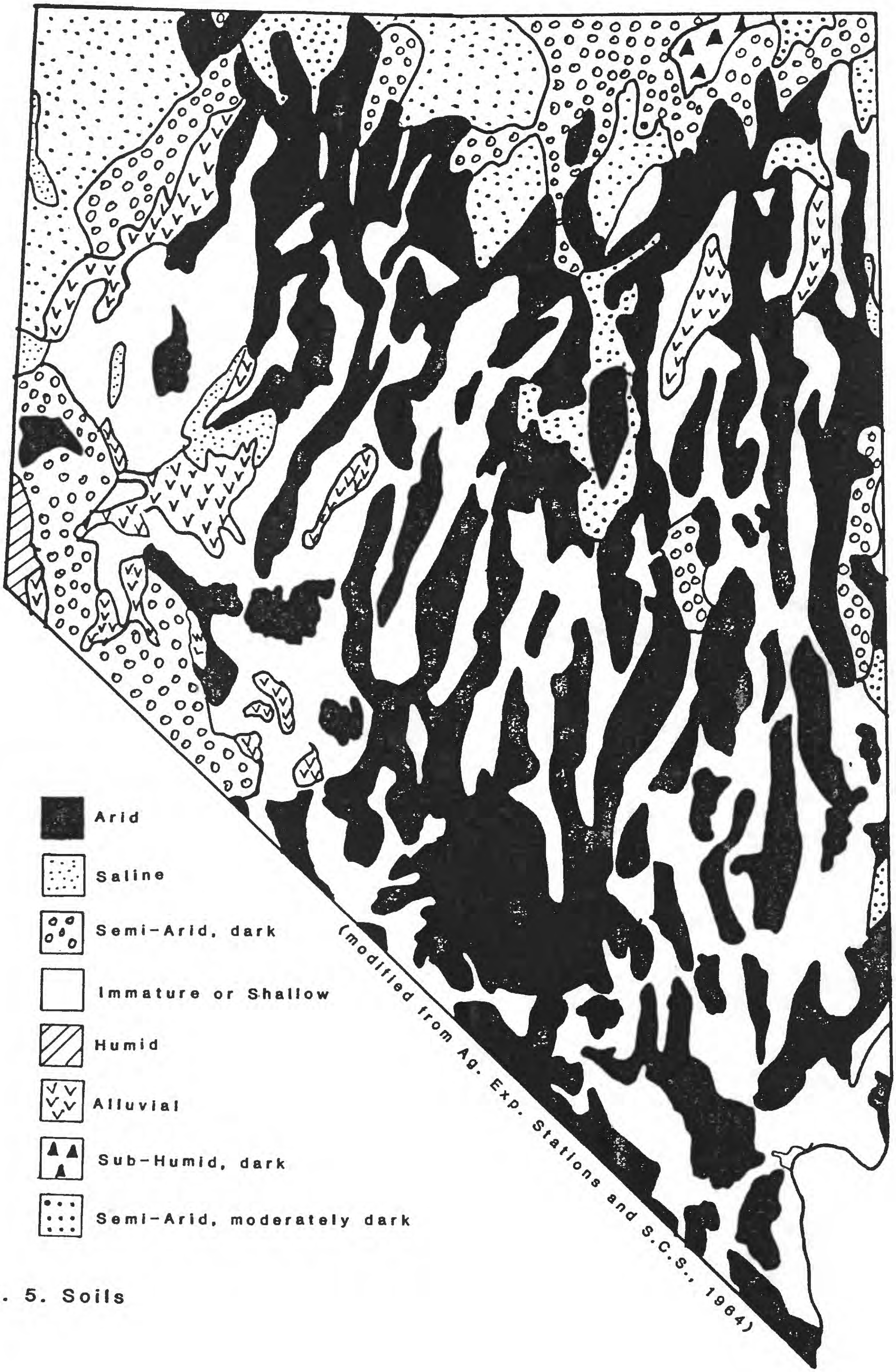


Fig. 4. Geologic Map of Nevada

(Generalized from Stewart and Carlson, 1977)



Arid
Saline
Semi-Arid, dark
Immature or Shallow
Humid
Alluvial
Sub-Humid, dark
Semi-Arid, moderately dark
(modified from Ag. Exp. Stations and S.C.S., 1964)

Fig. 5. Soils

Nevada are moderately dark to dark in color and occur primarily in the western and northern parts of the State (fig. 5).

INDOOR RADON DATA

Figure 6 shows the indoor radon data for the State/EPA Residential Radon Survey of Nevada. Table 1 shows the number of measurements and other statistics for the data set. Two counties, Douglas and Lincoln, had average radon concentrations greater than 4 pCi/L for the homes measured (fig. 6). In three counties (Douglas, Lincoln, and Mineral), between 30 and 40 percent of the homes tested had screening indoor radon concentrations greater than 4 pCi/L (fig. 6 and Table 1). [**Note**: The indoor radon data base for the State continues to grow, and since the data was provided for figure 6 there have been more measurements made in Pershing County that would significantly change the results depicted for that county. Out of 15 measurements, 6 are above 4 pCi/L with the maximum being 40.7 pCi/L.]

The Nevada Bureau of Mines and Geology (1991) analyzed the 1989 and 1990-1991 radon survey data for communities that had at least 10 indoor radon measurements (Table 2). In the following communities, 10 percent or less of the homes tested had screening indoor radon concentrations greater than 4 pCi/L: Alamo, Battle Mountain, Boulder City, Fallon, Fernley, Gabbs, Goldfield, Henderson, Las Vegas, Lund, McDermitt, McGill, North Las Vegas, Parhrump, Paradise Valley, Round Mountain, Sparks, and Tonopah. Eleven to 50 percent of the homes tested had indoor radon concentrations greater than 4 pCi/L in Austin, Beatty, Caliente, Carlin, Carson City, Dayton, Elko, Ely, Eureka, Gardnerville, Hawthorne, Minden, Pioche, Reno, Ruby Valley, Ruth, Wells, Wendover, Winnemucca, and Yerington. Only the following communities had screening indoor radon levels greater than 4 pCi/L in more than 50 percent of the homes tested: Lovelock, Orvada, Panaca, and Zephyr Cove. In year-long studies conducted in the Las Vegas area, Nyberg and Bernhart (1983) found that indoor radon levels showed a seasonal trend with the highest radon levels occurring in the month of October.

During the relatively cold winter of 1989, the Nevada Bureau of Mines and Geology conducted a survey of indoor radon in 238 Nevada homes, which were widely distributed across the State, and found that 21 percent of the homes had indoor radon concentrations greater than 4 pCi/L (Rigby, 1989a; Rigby 1989b; Rigby, 1990a). Additional measurements were made, and with a data base of 1,950 indoor radon measurements the percentage of the homes with greater than 4 pCi/L was 17.7 percent (Rigby, 1990b). In 1991, with a data base of 2,355 measurements (Nevada Bureau of Mines and Geology, 1991), the percentage of homes with greater than 4 pCi/L stood at 19 percent. When weighted to compensate for variability in sampling intensity (giving more weight to urban areas), the Bureau concluded that about 10 percent of Nevadans live in houses with radon levels greater than 4 pCi/L (Nevada Bureau of Mines and Geology, 1991).

GEOLOGIC RADON POTENTIAL

High radon potential is generally linked to rocks with relatively high uranium contents and is not limited to areas around known uranium-mineral occurrences. Nonetheless, areas in the vicinity of known uranium occurrences have a high radon potential for several reasons other than the unlikely occurrence that homes would be built over an ore body itself. These reasons are: (1) noncommercial concentrations of uranium are often also present in an area that contains ore-grade deposits; (2) even minor mineralization of uranium (primary or secondary) along faults and

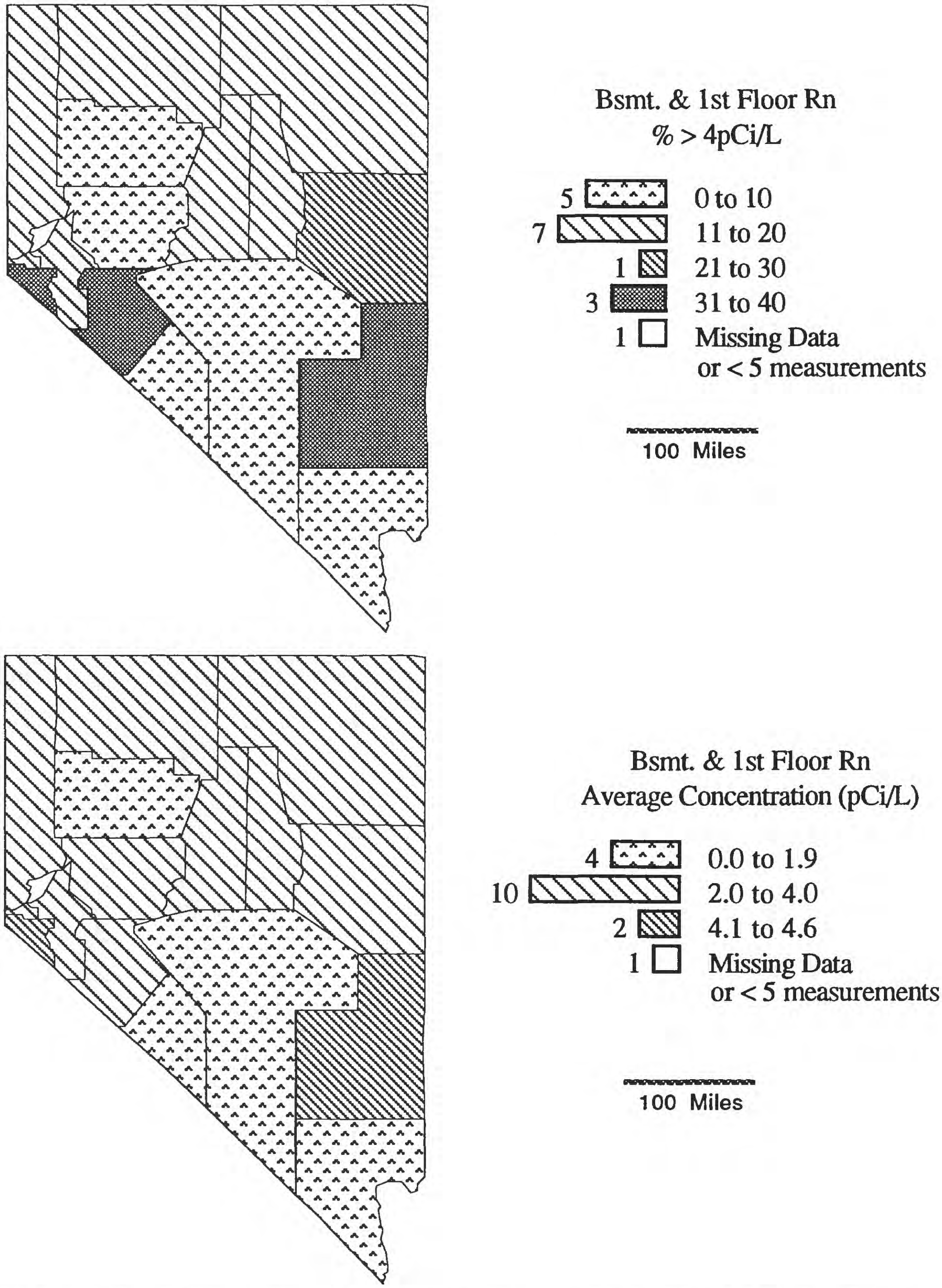


Figure 6. Screening indoor radon data from the State/EPA Residential Radon Survey of Nevada, 1989-90, for counties with 5 or more measurements. Data are from 2-7 day charcoal canister tests. Histograms in map legends show the number of counties in each category. The number of samples in each county (See Table 1) may not be sufficient to statistically characterize the radon levels of the counties, but they do suggest general trends. Unequal category intervals were chosen to provide reference to decision and action levels.

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

COUNTY	NO. OF MEAS.	MEAN	GEOM. MEAN	MEDIAN	STD. DEV.	MAXIMUM	%>4 pCi/L	%>20 pCi/L
CARSON CITY	64	3.0	2.1	2.5	2.9	17.5	16	0
CHURCHILL	110	2.3	1.6	1.8	2.8	20.1	9	1
CLARK	188	1.1	0.6	0.8	1.3	11.0	4	0
DOUGLAS	52	4.2	2.2	2.1	4.9	21.9	35	2
ELKO	185	2.7	1.6	1.8	2.7	13.8	16	0
ESMERALDA	11	1.3	1.0	1.2	1.0	3.0	0	0
EUREKA	21	3.5	1.6	1.4	6.2	29.1	19	5
HUMBOLDT	204	2.3	1.3	1.3	3.9	43.4	12	1
LANDER	40	3.1	1.1	1.2	8.2	46.7	13	5
LINCOLN	103	4.6	2.0	2.7	6.8	41.8	32	3
LYON	53	2.3	1.4	1.6	2.0	8.8	11	0
MINERAL	54	4.0	2.5	3.1	4.2	23.6	31	2
NYE	120	1.8	1.1	1.2	2.2	17.5	7	0
PERSHING	6	0.8	0.6	0.8	0.6	1.7	0	0
STOREY	3	2.1	2.1	2.1	0.5	2.6	0	0
WASHOE	154	2.7	1.2	1.3	4.9	32.0	16	3
WHITE PINE	194	3.3	2.1	2.3	3.2	20.1	26	1

TABLE 2. Screening indoor radon data for cities in Nevada with 10 or more usable indoor radon measurements. Data represent charcoal-canister tests made between 1989 and 1991.

CITY	NO. OF MEAS.	HIGH pCi/L	LOW pCi/L	AVERAGE pCi/L	% > 4 pCi/L
Alamo	30	7.0	0.0	1.3	10.0
Austin	22	46.7	0.0	6.7	40.9
Battle Mountain	48	7.7	0.0	1.3	6.3
Beatty	14	10.0	0.0	2.3	14.3
Boulder City	21	5.3	0.0	1.8	9.5
Caliente	44	41.8	0.0	5.1	34.1
Carlin	25	11.5	0.0	2.9	24.0
Carson City	105	31.6	0.0	4.1	30.5
Dayton	17	8.1	0.0	1.9	11.8
Elko	173	17.2	0.0	2.6	17.9
Ely	163	23.7	0.0	4.3	39.3
Eureka	30	35.4	0.0	5.5	33.3
Fallon	141	20.1	0.0	2.2	8.5
Fernley	18	7.0	0.3	1.5	5.6
Gabbs	13	2.6	0.0	1.1	0.0
Gardnerville	44	21.9	0.0	4.2	34.1
Goldfield	17	2.8	0.0	1.0	0.0
Hawthorne	67	23.6	0.0	4.5	37.3
Henderson	22	3.4	0.1	1.1	0.0
Las Vegas	193	11.0	0.0	0.9	3.1
Lovelock	32	40.7	0.7	7.9	56.3
Lund	15	4.0	0.7	2.1	6.7
McDermitt	10	43.4	0.1	5.8	10.0
McGill	47	3.8	0.0	1.2	0.0
Minden	15	8.9	0.4	2.8	26.7
North Las Vegas	10	2.9	0.6	1.5	0.0
Orovada	13	30.5	0.0	6.9	61.5
Pahrump	67	17.5	0.0	1.8	7.5
Panaca	29	16.8	1.0	5.2	55.2
Paradise Valley	10	5.8	0.4	1.7	10.0
Pioche	31	39.8	0.0	5.4	38.7
Reno	311	40.6	0.0	3.3	21.2
Round Mountain	12	3.1	0.0	1.4	0.0
Ruby Valley	10	18.0	0.5	5.0	40.0
Ruth	15	6.6	0.3	1.8	13.3
Sparks	82	9.0	0.0	1.4	6.1
Tonopah	42	7.6	0.0	1.5	7.1
Wells	23	13.3	0.0	4.3	39.1
Wendover	14	6.4	0.1	2.0	14.3
Winnemucca	210	20.8	0.0	2.0	11.0
Yerington	23	11.0	0.5	3.8	34.8
Zephyr Cove	13	19.1	1.4	7.4	69.2

fractures is enough to produce a radon hazard in homes built above them; (3) sediments eroded and transported from rocks with elevated uranium and the soils that develop on them are also likely to have elevated uranium levels. There are 442 radioactive mineral occurrences in Nevada described by Garside (1973). The number of radioactive mineral occurrences found in each county is shown in figure 7. Every county in Nevada has at least one occurrence and most counties have many (fig. 7). Additional information on radioactive mineral occurrences in Nevada can be found in Garside (1979).

Figure 8 is an equivalent uranium (eU) map for Nevada. A contour map of eU at a scale of 1:750,000 can be found in Duval (1988). Based on these maps (fig. 8 & Duval, 1988), most of Nevada has surficial uranium concentrations above 2.0 ppm. Duval (1987) suggested that areas in Nevada with eU concentrations greater than 2 ppm might have more than 20 percent of the homes with indoor radon concentrations greater than 4 pCi/L. On a national basis, Peake and Schumann (1992) concluded that eU concentrations of 2 ppm or greater indicate areas that have the potential to produce a substantial number of elevated (greater than 4 pCi/L) indoor radon levels (in this report, eU values of 2.5 ppm or greater are considered to have high potential for generating elevated radon). Because of the dry climate, evaporative coolers are commonly used during summer months to cool homes. The use of such coolers blocks or greatly reduces the infiltration of soil-gas radon into homes by pressurizing the inside of the home. In southern Nevada, the use of evaporative coolers, less heating because of the warm climate, and the prevalent use of slab-on-grade construction, in which there is less contact area with the soil than in a basement home, may significantly reduce the number of homes with radon concentrations greater than 4 pCi/L despite the presence of ample source material in most Nevada soils.

The Paleozoic rocks, a mixture of carbonate and clastic rocks, found in a band in the southern corner of the State and scattered approximately through the eastern third of the State, have a relatively low eU signature (figs. 4 & 8). A band of rocks composed of Tertiary volcanics found along the border with California in the northwest corner of the State also have a low eU signature (figs. 4 & 8). Rocks with a lower eU signature should theoretically provide less of a radon risk because they contain less of the parent material for radon production.

The Precambrian gneiss and Tertiary volcanics in the southern tip of Nevada have elevated eU signatures (figs. 4 & 8). The Tertiary volcanic rocks (dominantly Miocene and Pliocene in age) so prevalent throughout the State have elevated eU signatures, as do the sediments derived from them (figs. 4 & 8). The Cretaceous granitic rocks found in the Sierra Nevada and adjacent ranges on the western side of the State also have an elevated eU signature. Elevated levels of radon have been found in ground water samples from the Carson Valley in west-central Nevada (samples ranged from <100 pCi/L to 16,000 pCi/L), particularly on the west side (Lico and others, 1989; Lico and others, 1992). The use of well water in west-central Nevada is likely contributing small amounts of radon to some homes.

The Nevada Bureau of Mines and Geology (1991) concluded that granitic rocks in west-central Nevada were producing elevated indoor radon and that granitic rocks around Austin and Lovelock may also be a source for elevated radon in these communities. They believe that metamorphic or granitic rocks may be a source of indoor radon for Carson City and Hawthorne. Silicic volcanic rocks, because they have relatively high uranium contents, have the potential to generate significant amounts of radon. Elevated radon in homes in Lincoln and Elko Counties and in the towns of Lovelock, Eureka, and Yerington may be attributed to the silicic volcanic rocks (Nevada Bureau of Mines and Geology, 1991).

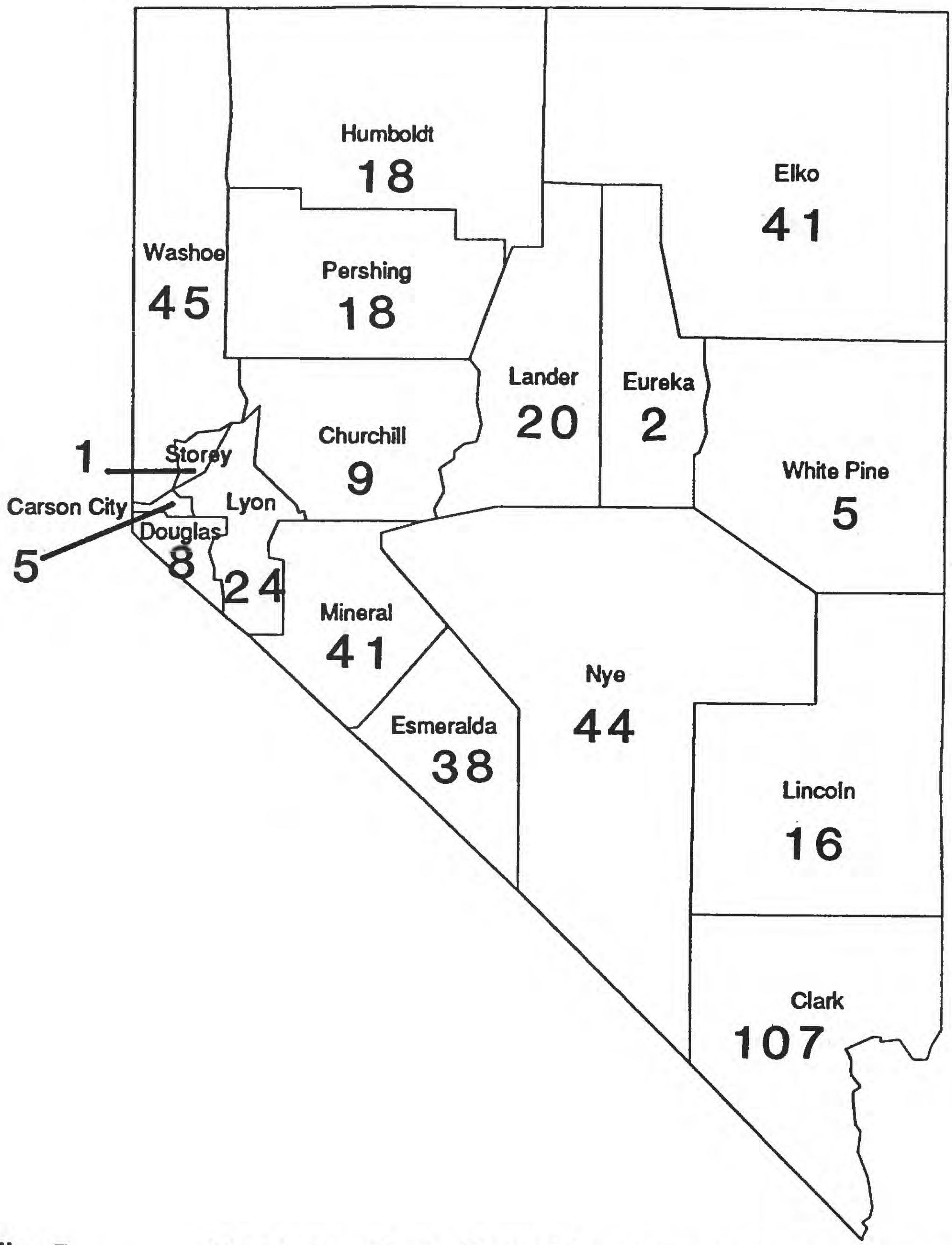


Fig. 7. Number of radioactive occurrences by county (statistics from Garside, 1973)

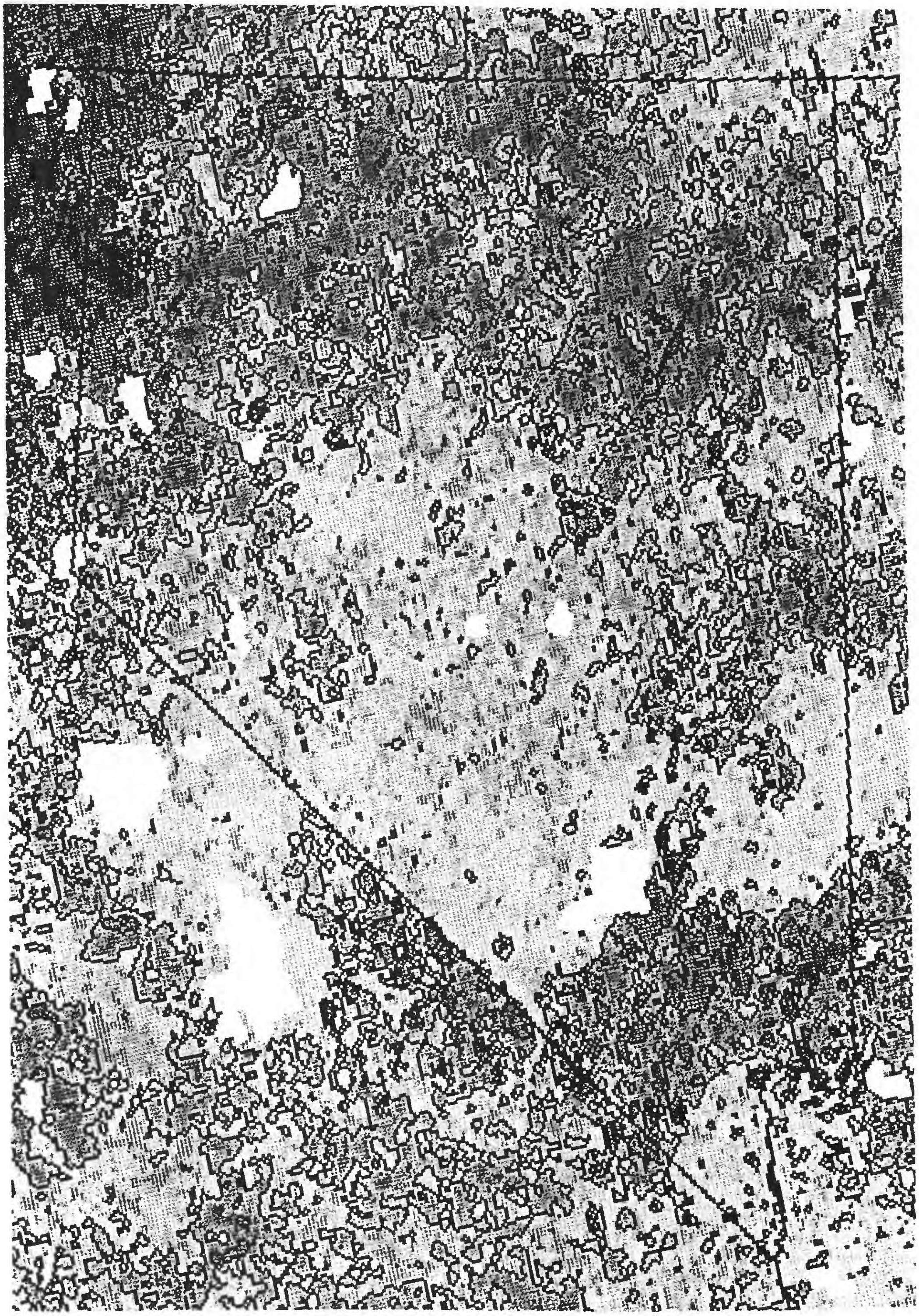


Fig. 8.

Aerial radiometric map of Nevada (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.

Most of Nevada has ample radon source material present in the near surface and suitable soil permeabilities for radon transport to give Nevada at least a moderate geologic radon potential. Nevada also has a number of uranium occurrences that represent locally high radon potentials. The common use of evaporative coolers and slab-on-grade construction within the State may have significantly lowered the total number of homes that have indoor radon concentrations above 4 pCi/L, especially in the southern half of the State, which also contains the largest percentage of the State's population.

SUMMARY

The RADON INDEX (RI) and the CONFIDENCE INDEX (CI) discussed in the introduction to this volume have been used to evaluate the geologic radon potential of the State. This evaluation is presented in Table 3, and the radon potential areas are shown on figure 9. Area 1, which includes the Sierra Nevada and adjacent ranges (fig. 3), is dominantly made up of intrusive and volcanic rocks with high eU. Area 1 falls in the high end of the moderate radon potential ranking. Area 2 contains many basaltic rocks that have very low eU. Area 2 falls in the low end of the moderate radon potential ranking. Area 3 is mixture of volcanic, intrusive, and sedimentary rocks with varying uranium contents. Area 3 has a moderate radon potential. Area 4 is dominated by volcanic rocks with high eU and falls in the high end of the moderate radon potential ranking. Area 5 contains dominantly a mixture of Paleozoic carbonate rocks that have low eU and volcanic and intrusive rocks with higher eU. Area 5 has a moderate radon potential. Area 6 is dominated by Paleozoic carbonate rocks with low eU and falls in the high end of the low radon potential ranking. Area 7 contains intrusive, volcanic, and metamorphic rocks with high eU and also contains numerous uranium occurrences. Area 7 falls in the high end of the moderate radon potential ranking.

This assessment of the State's radon potential is part of a nationwide assessment and is necessarily at a scale that may be too small for use in large counties of Nevada, because the geology of Nevada is quite complicated and variable. The assessments in this report are weighted by the available measurements of radon in homes. An area with geologically high potential for producing radon may not appear to be a problem area because of local building practices, such as few basements. Officials need to be aware that problems may arise if different building practices are used in the future. Larger scale mapping of radon potential is being conducted by various State agencies in Nevada (see list of State contacts in the Introduction chapter) and the reader is also encouraged to contact them for additional information.

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 3. Radon Index (RI) and Confidence Index (CI) scores for geologic radon potential areas of Nevada. See text for discussion of areas and figure 9 for location of areas.

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

	5		6		7	
FACTOR	RI	CI	RI	CI	RI	CI
INDOOR RADON	2	3	1	3	2	3
RADIOACTIVITY	3	3	2	3	3	3
GEOLOGY	2	2	2	2	3	2
SOIL PERM.	2	2	2	2	2	2
ARCHITECTURE	1	-	1	-	1	-
GFE POINTS	0	-	0	-	0	-
TOTAL	10	10	8	10	11	10
RANKING	MOD	HIGH	LOW	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

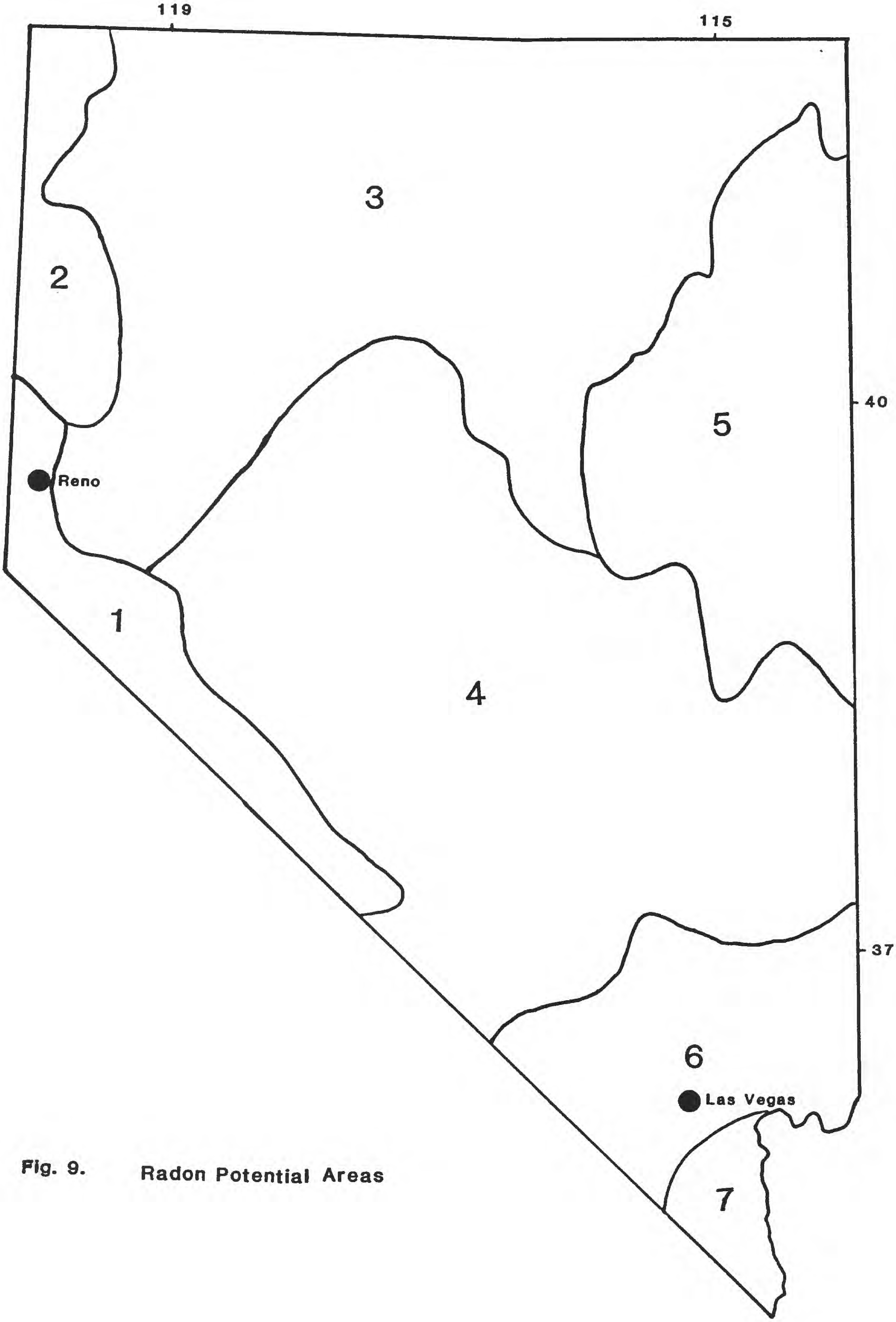


Fig. 9. Radon Potential Areas

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