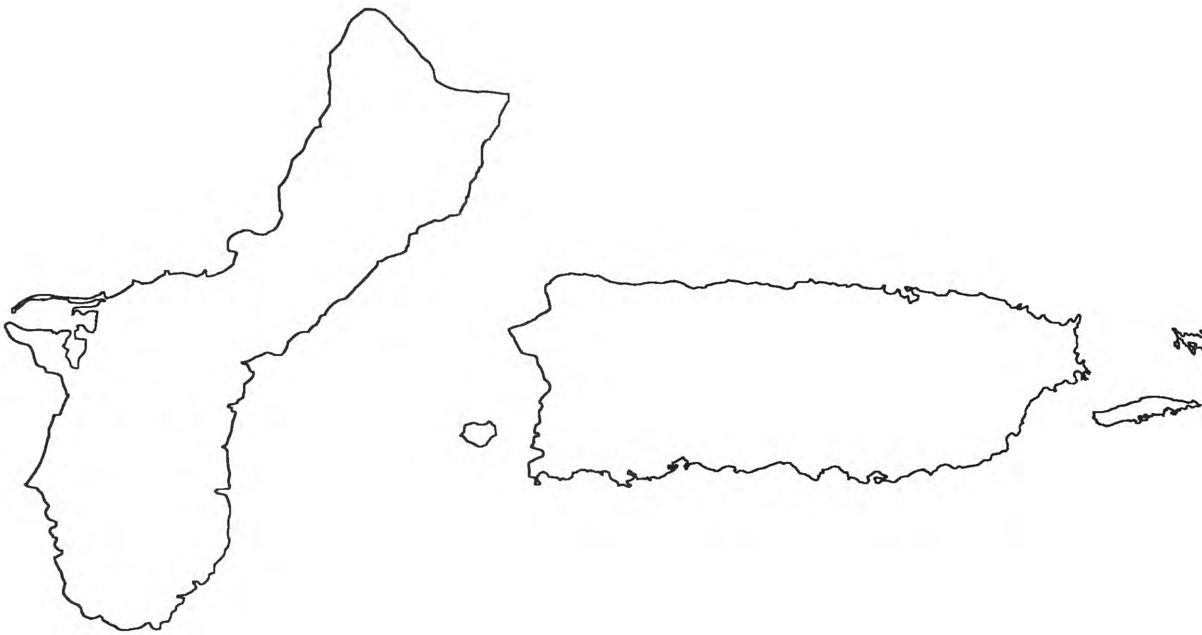
U.S. DEPARTMENT OF THE INTERIOR

U.S. GEOLOGICAL SURVEY

# GEOLOGIC RADON POTENTIAL OF GUAM AND PUERTO RICO



## OPEN-FILE REPORT 93-292-K

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

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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

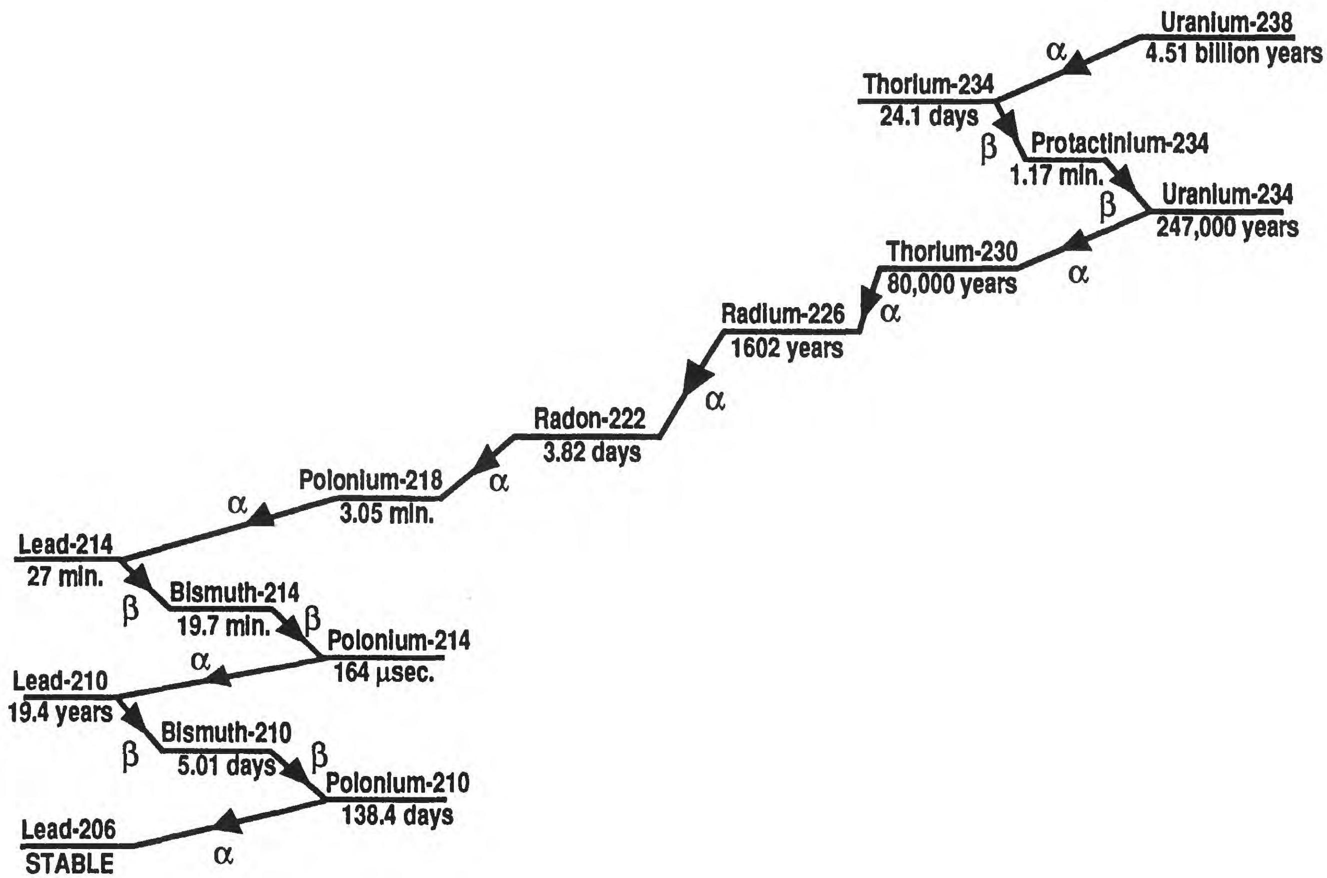


Figure 1. The uranium-238 decay series, showing the half-lives of elements and their modes of decay (after Wanty and Schoen, 1991). α denotes alpha decay, β denotes beta decay.

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 $2 \times 10^{-6}$ inches—this is known as alpha recoil (Tanner, 1980). Moisture in the soil lessens the chance of a recoiling radon atom becoming imbedded in an adjacent grain. Because water is more dense than air, a radon atom will travel a shorter distance in a water-filled pore than in an air-filled pore, thus increasing the likelihood that the radon atom will remain in the pore space. Intermediate moisture levels enhance radon emanation but do not significantly affect permeability. However, high moisture levels can significantly decrease the gas permeability of the soil and impede radon movement through the soil.

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

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

## RADON ENTRY INTO BUILDINGS

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

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

## METHODS AND SOURCES OF DATA

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

### GEOLOGIC DATA

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

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

## NURE AERIAL RADIOMETRIC DATA

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

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

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

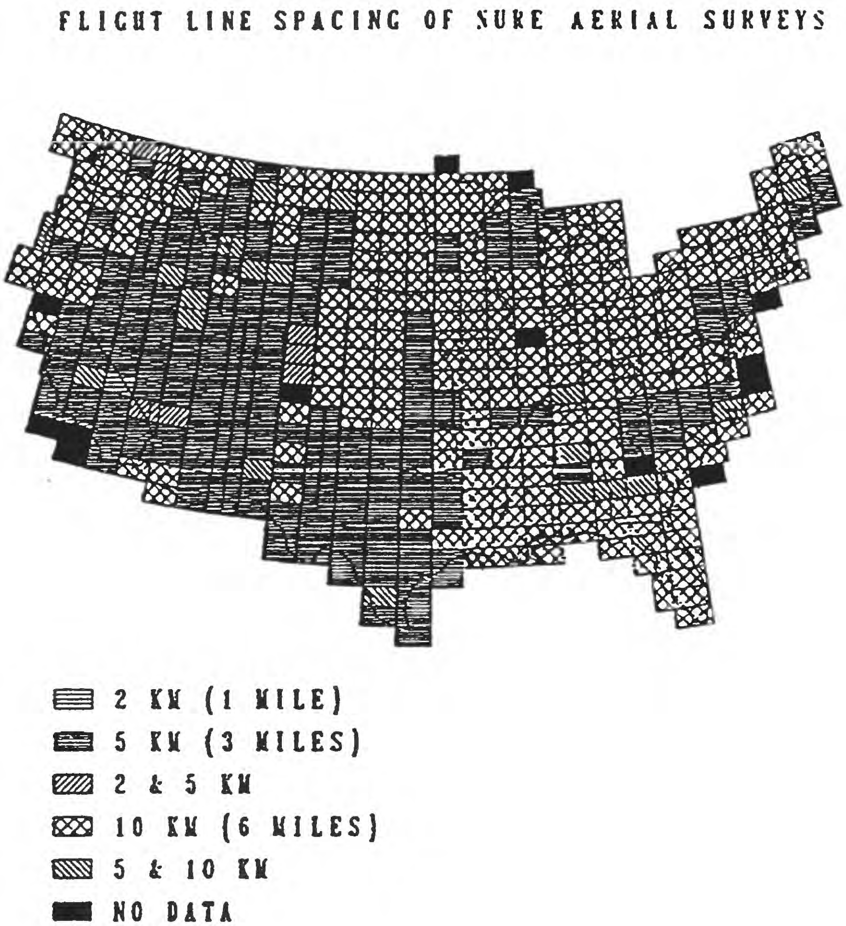


Figure 2. Nominal flightline spacings for NURE aerial gamma-ray surveys covering the contiguous United States (from Duval and others, 1990). Rectangles represent 1°x2° quadrangles.

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

## SOIL SURVEY DATA

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

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

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

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

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

## INDOOR RADON DATA

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

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

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

## RADON INDEX AND CONFIDENCE INDEX

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

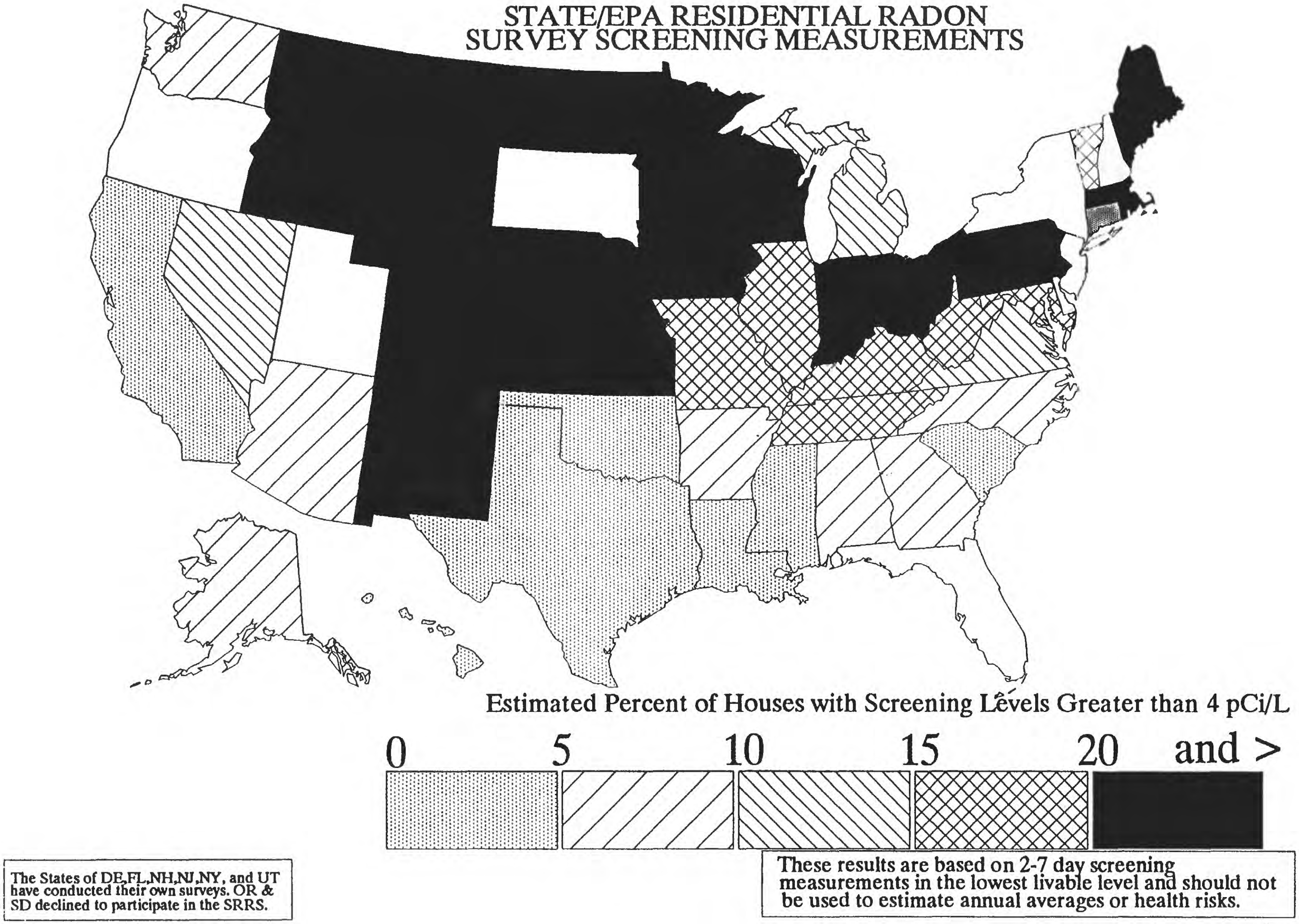


Figure 3. Percent of homes tested in the State/EPA Residential Radon Survey with screening indoor radon levels exceeding 4 pCi/L.

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

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

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

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

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

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

INCREASING RADON POTENTIAL →

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

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

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

**SCORING:**

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

POSSIBLE RANGE OF POINTS = 3 to 17

**TABLE 2. CONFIDENCE INDEX MATRIX**

INCREASING CONFIDENCE →

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

**SCORING:**

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

POSSIBLE RANGE OF POINTS = 4 to 12

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

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

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

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

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

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

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

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

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

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

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

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

## EPA COUNTY RADON POTENTIAL MAPS

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

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

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

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

Geologic terms and terms related to the study of radon

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

**eolian** Pertaining to sediments deposited by the wind.

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

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

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

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

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

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

**formation** A mappable body of rock having similar characteristics.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

**placer deposit** See heavy minerals

**residual** Formed by weathering of a material in place.

**residuum** Deposit of residual material.

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

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

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

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

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

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

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

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

**shrink-swell clay** See clay mineral.

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

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

**slope** An inclined part of the earth's surface.

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

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

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

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

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

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

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

**uraniferous** Containing uranium, usually more than 2 ppm.

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

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

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

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

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

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# PRELIMINARY GEOLOGIC RADON POTENTIAL ASSESSMENT OF GUAM

*by*
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## INTRODUCTION

This assessment of the radon potential of the Territory of Guam relies heavily on geologic information derived from publications of the U.S. Geological Survey and Guam scientists, from a soil survey by the Soil Conservation Service, and from an analysis of indoor radon data from the Territory/U.S. EPA Indoor Radon Survey of Guam and a radon survey of Andersen Air Force Base by the U.S. Air Force.

This is a generalized assessment of geologic radon potential of rocks, soils, and surficial deposits of Guam. The scale of this assessment is such that it is inappropriate for use in identifying the radon potential of small areas such as individual building sites or housing tracts. 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 values, 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 territory, and the U.S. EPA recommends that all homes be tested. For more information, the reader is urged to consult the offices of the Guam EPA (Guam Environmental Protection Agency, Harmon Plaza Complex, Unit D-107, 130 Rojas St., Harmon, Guam 96911, Phone: (671) 646-8863).

## GEOGRAPHIC SETTING

The island of Guam lies at the southern end of the Mariana Islands chain in the western Pacific. The island is about 48 km long and ranges from 6.5 to 18.5 km wide. The land area is about 540 $km^2$. The island may be divided physiographically into two major provinces; a northern limestone plateau, characterized by flat to gently rolling uplands about 60-200 m above sea level bordered by steep cliffs, and a southerly province, composed of a dissected volcanic upland 30-400 m above sea level with a high ridge on the western side, an interior valley, and narrow fringing limestone plateaus and coastal lowlands (fig. 1) (Tracey and others, 1964).

The mean annual air temperature is about 27°C with only slight seasonal variation and the air is humid most of the year. Rainfall typically ranges from 2300-2800 mm and about two-thirds of it falls in a wet season from mid-July to mid-November. Intense rainfalls can occur during the wet season. Strong trade winds blow during the dry season. Because of high evapotranspiration, soils are quite dry in the dry season. In spite of high rainfall, few surface streams are found in the northern physiographic province (fig. 2) because of the high permeability of the soils and rock (Tracey and others, 1964).

The Territory of Guam is divided into 19 municipalities, each consisting of one or more villages (fig. 3). The population of the island is about 133,000 (1990 census). Most villages are located on the upland areas of the northern province and the fringing uplands and lowlands of the southern province. Although prior to 1970 much of Guam was used for agricultural purposes, the Territory is now rapidly being developed for housing and tourism. Tourism is the largest private industry on the island. The U.S. Navy and Air Force have several installations on Guam and control about one-third of the Territory. The government is the principal employer in the Territory (Siegrist and Randall, 1992).

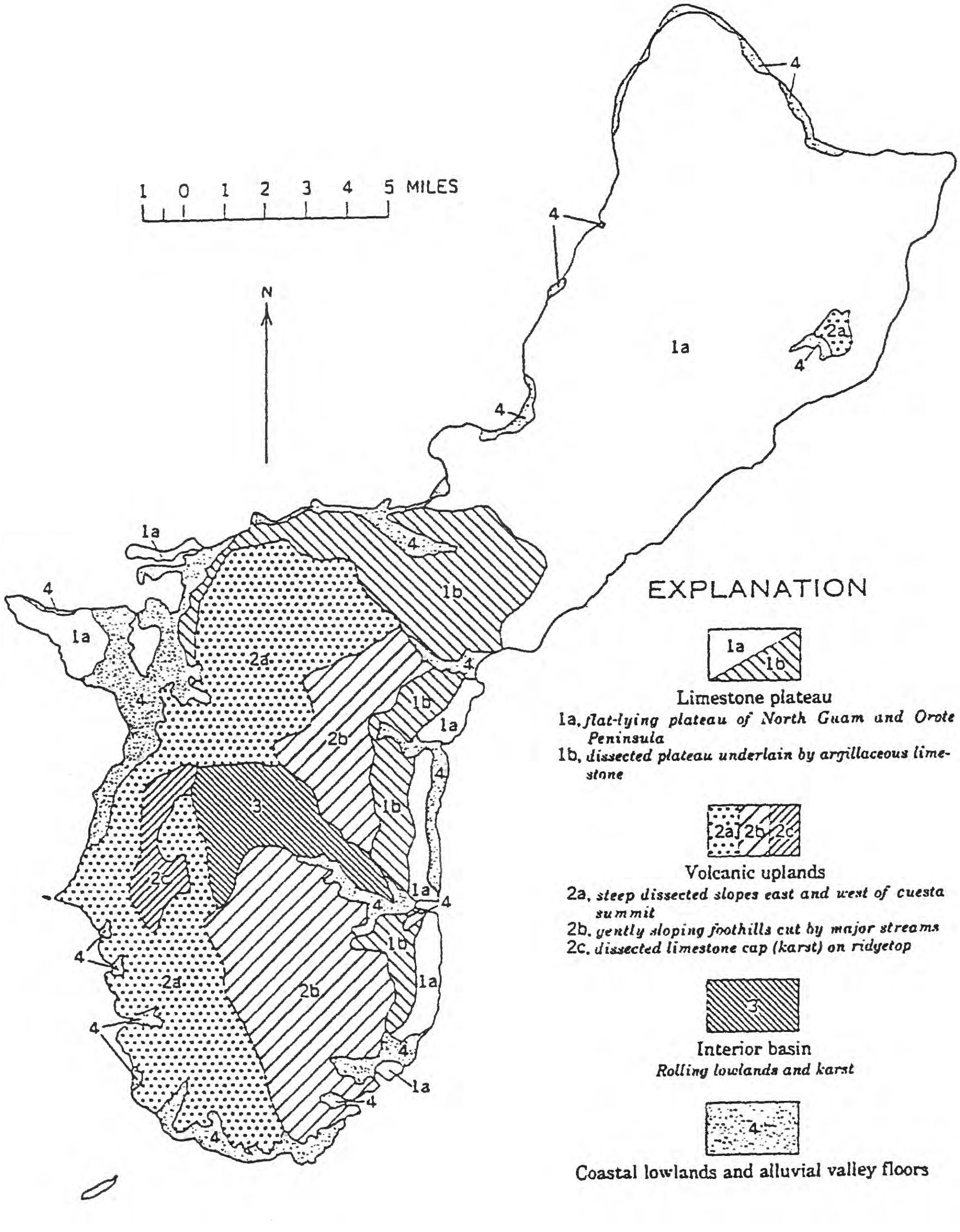


Fig. 1- Physiographic provinces of the Territory of Guam (from Tracey and others, 1964).

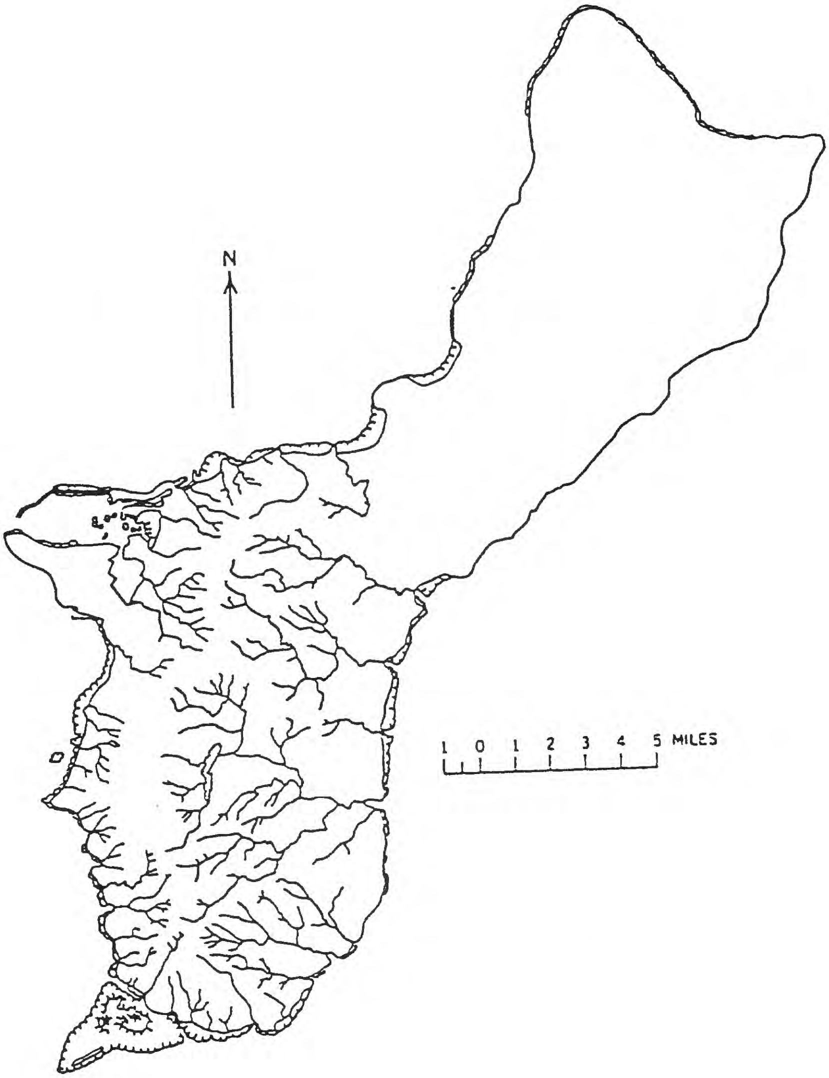


Fig. 2- Stream drainage pattern of the Territory of Guam (from Tracey and others, 1964).

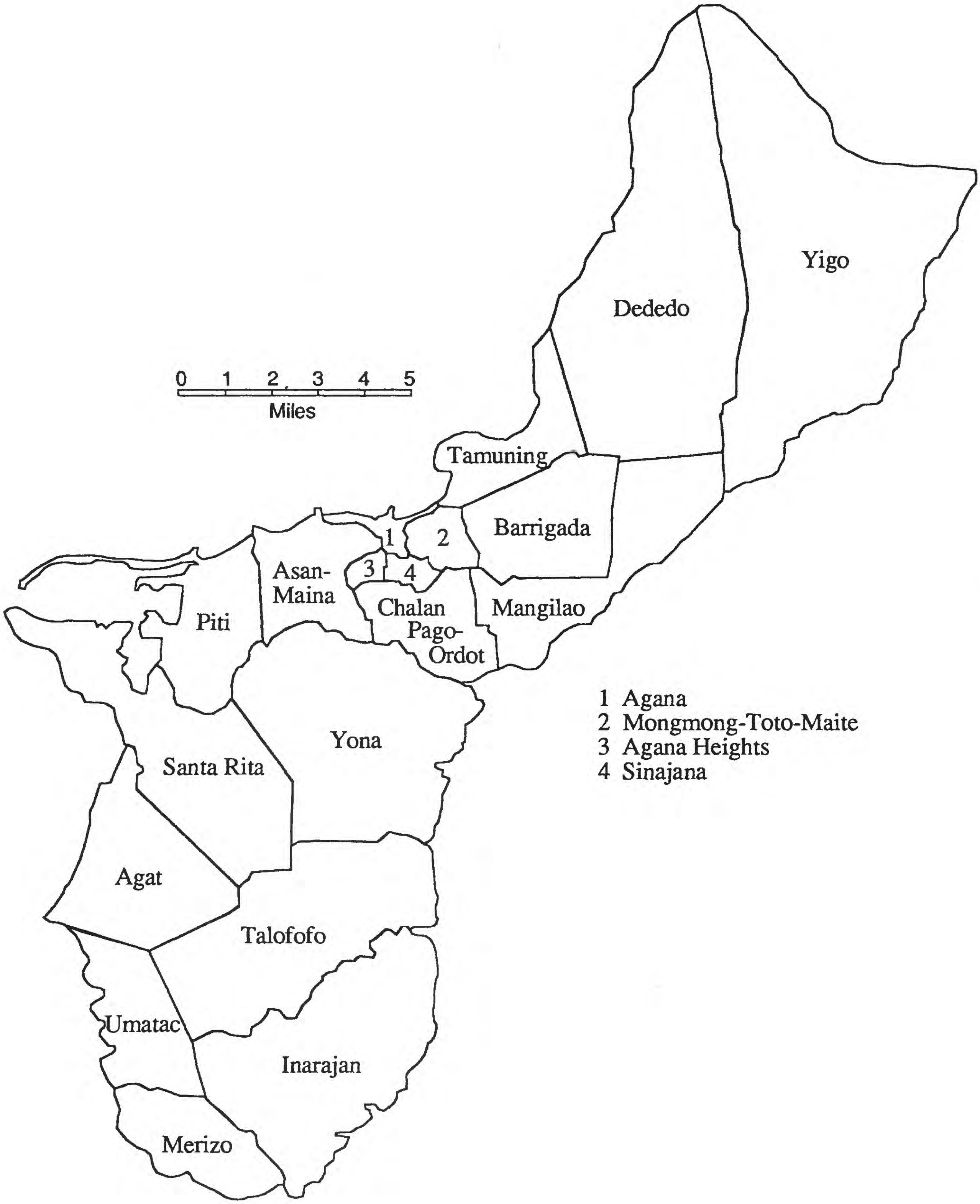


Figure 3. Municipalities of the Territory of Guam.

## GEOLOGIC SETTING

The two physiographic provinces are geologically distinct. The northern province is underlain by Pliocene and Pleistocene limestones that rest on a core of older, little-exposed volcanic rocks, whereas the southerly province is underlain by Eocene to Miocene basaltic to andesitic volcanic rocks, clastic sedimentary rocks derived from them, Miocene limestones, and fringing areas of younger limestones and coastal plain sediments (fig. 4). A northwest-trending normal fault effectively marks the boundary between the two geologic provinces (Tracey and others, 1964).

The Pliocene and Pleistocene Barrigada and Mariana limestones, which are exposed in the northern part of the northern province, are formed largely from reefs or detritus derived from reefs, tend to contain little insoluble residue, and contain few detrital components derived from the volcanic rocks. These limestones formed in shallow waters around the margins of an emergent volcanic high, remnants of which are exposed in two hills in the northern province. Limestones from the southern part of the northern province and from the area fringing the volcanic terrane in the southern province are clayey and contain abundant clastic detritus derived from the volcanic rock terrane.

Topographic depressions caused by sinkhole development are common in areas underlain by both types of limestone in the northern province, but they tend to be more prominent where the argillaceous limestone is mapped. These depressions tend to follow fractures zones in the limestone. In south-central Guam, the main area underlain by limestone forms a topographic basin with interior drainage marked by mogotes, sharp knobs of limestone that rise tens of meters above the landscape (Tracey and others, 1964, Siegrist and Randall, 1992).

Beach deposits occur between many of the headlands around the island. Alluvium underlies the lower parts of most stream valleys and many coastal areas. Most of the island is rimmed with modern coral and algal reefs. Fossil reefs of various ages and altitudes above sea level rim much of the northern province and occur along the eastern edge of the southern province. Artificial fill has been used to create land in the Agana and Apra Harbor areas (Tracey and others, 1964).

Aeroradiometric data for rocks and soils on Guam are not available and radiochemical data are relatively limited. Natural gamma-ray logs of two of eleven boreholes around a landfill complex on the Air Force base on the northern part of Guam show radioactivity in the soil horizons many times that of clayey horizons in the limestone (S. Terracciano, oral commun., 1993). In the other nine boreholes, the soil horizons were too thin for the borehole gamma device to record a signature. The extremely low potassium content (< 0.2 percent) of these soils (Carroll and others, 1963) suggests that most of this gamma activity comes from uranium, thorium, or their decay products, rather than from potassium-40. Radiochemical analyses of limestone samples from a vertical profile exposed in a roadcut show 6-7 pCi/g radium-226 near the top of the cut just below the natural soil and about 1 pCi/g near the base of the roadcut (James Burkhart, oral commun., 1993). The radium is likely associated with iron oxyhydroxides that coat the clays and limestone.

Otton and Asher-Bolinder (1993) suggest that high concentrations of radium have accumulated in soils developed on the limestones in the northern part of the island by intensive weathering of aerosol dust from local and distant sources and of the limestone itself. High concentrations of radium (as much as 15 pCi/g) have accumulated in soils developed on marine limestone terraces as old as 1 million years on several islands in the Caribbean and western Atlantic

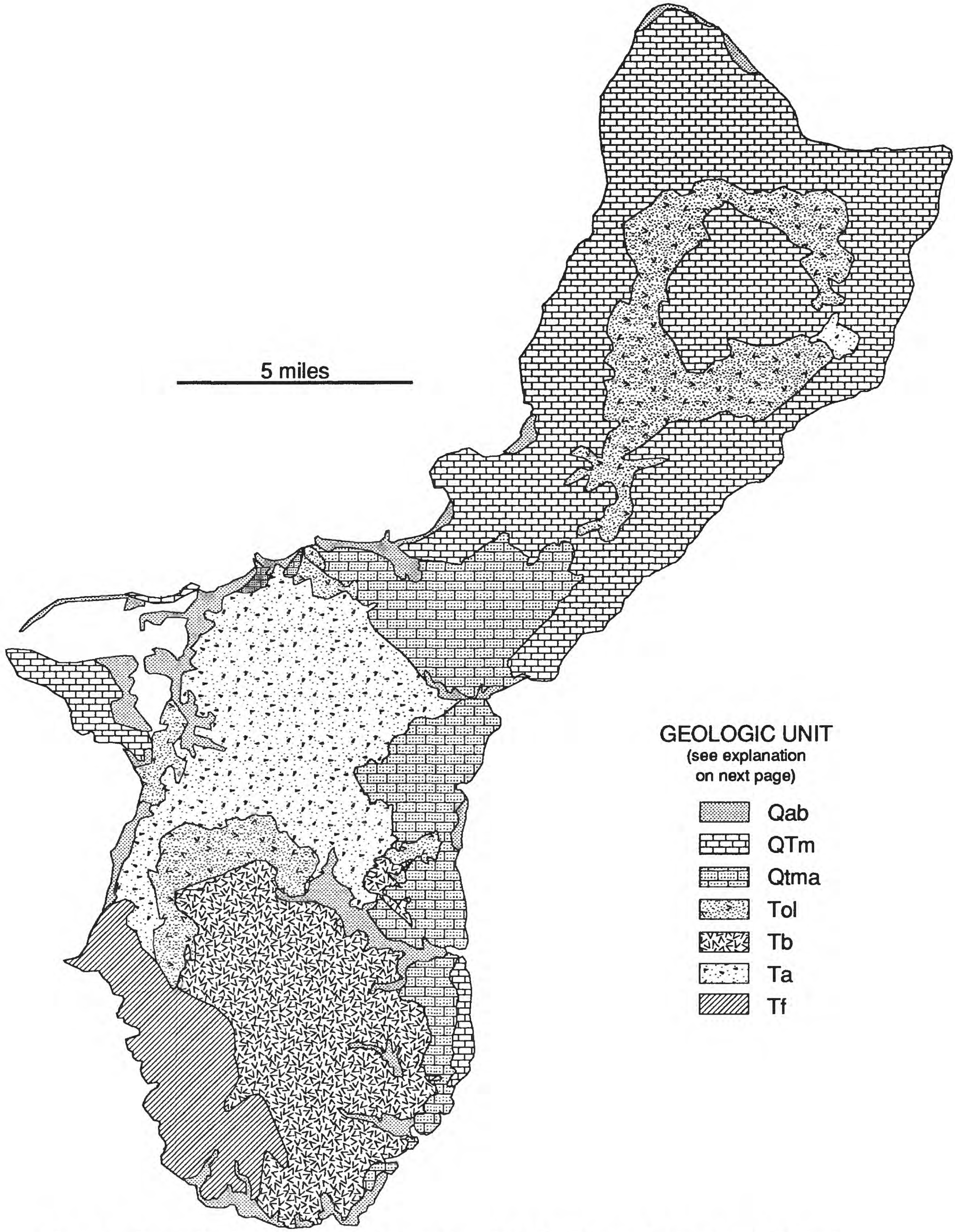


Figure 4. Generalized geologic map of Guam (modified from Tracey and others, 1964, and Siegrist and Randall, 1992). See next page for map explanation.

## GENERALIZED GEOLOGIC MAP OF GUAM

## EXPLANATION

| Age | Map symbol | Description |
|---|---|---|
| Recent | Qab | Alluvium, beach deposits, modern reefal limestone (Merizo Limestone) and artificial fill |
| Pliocene and Pleistocene | QTm<br>QTma | Mariana Limestone<br>QTm- Reef, forereef, detrital, and molluscan limestone. Very low clay content.<br>QTma- Detrital limestone with 2-5 percent disseminated clay and as much as 20 percent clay in pockets. Some smaller areas of QTm included. |
| Miocene and Pliocene | Tol | Older limestones and related rocks<br>Fossiliferous, locally argillaceous, limestone, conglomerate, lignite, clay, and marl. Includes Alifan Limestone, Janum Formation, Barrigada Limestone (northern province), Talisay Clay, and Bonya Limestone. |
| Miocene | Tb | Bolanos Formation<br>Pillow basalt, tuffaceous shale and sandstone, limestone, tuff breccia, and volcanic conglomerate. |
| Eocene and Oligocene | Ta | Alutom Formation<br>Tuffaceous shale and sandstone, volcanic breccia, conglomerate and minor interbedded lava flows.<br>Some outcrops of the lower Miocene Maemong Limestone mapped with this unit. |
| Eocene | Tf | Facpi Volcanics<br>Submarine boninite pillow flows and breccias, tholeitic basalt dikes, minor pelagic carbonate sediment.<br>Some outcrops of lower Miocene Maemong Limestone mapped with this unit. |

(D. R. Muhs, written commun., 1993). Geochemical studies of these soils suggest that dust derived from the Sahara is the parent material for these soils (Muhs and others, 1990). These Saharan dusts have been shown to have substantial concentrations of uranium (average 3.6 ppm uranium or 1.2 pCi/g radium, assuming equilibrium; Rydell and Prospero, 1972). Aerosol dusts from continental sources form a substantial component of Pacific pelagic sediment (Olivarez and others, 1991) and are thus a likely parent material for at least part of the soils formed during weathering of the detritus-poor limestones on Guam. Detrital clays within the argillaceous limestones may also be, in part, derived from aerosol dusts.

## SOILS

Soils on Guam (fig. 5) are typically red in color and vary in composition and thickness as the slope and substrate varies. Soils developed on the relatively pure limestones of the northern uplands are 10 to 25 cm thick except where deep karst pockets have formed (Guam, Yigo, and Ritidian soils; Young, 1988). For example, in the drillholes discussed above, 2 drillholes encountered karst depressions filled with 3 m and 4.5 m of red clayey soil. They are composed almost exclusively of alumina clay (gibbsite) and iron oxyhydroxides, have very low silica ($SiO_2$) content (1 to 2 percent; Carroll and others, 1963), and a modest phosphate content (0.68 to 2.5 percent $P_2O_5$). Radium is sometimes associated with phosphate, but the presence of radium associated with the phosphate has not been confirmed in these soils. The soils are typically cobbly clay loams with abundant rock outcrop in some areas. Permeabilities are moderate (1.5-5 cm/hr) to moderately rapid (5-15 cm/hr). In contrast, the soils formed on the argillaceous limestones are 25 to 50 cm thick (Pulantat, Kagman, and Chacha soils; Young, 1988), are kaolinitic to montmorillonitic, and have $SiO_2$ contents of 20 to 35 percent and iron ($Fe_2O_3$) contents of about 20 percent (Carroll and others, 1963). The soils are very clayey with slow (0.02-0.5 cm/hr) to moderately slow (0.5-1.5 cm/hr) permeability. The higher silica content likely reflects the more abundant silicate detritus in the original limestone.

In all of the limestone terranes, the limestone immediately underlying the soils is often deeply weathered and highly permeable. Some facies of the limestones have high primary porosity which contributes to the intrinsic permeability and susceptibility to dissolution. Fracturing and jointing of the limestone also locally contributes to dissolution. Clays and iron oxyhydroxides have often infiltrated downward from the soil profile along solution pathways. Clays and iron oxyhydroxides readily absorb and concentrate radium. This radium usually occurs on the surface of the clay grains where radon formed during decay can easily escape to the soil pores. Where radium is carried downward with the clay and iron oxyhydroxides, the weathered limestone can be a significant source of radon.

Deeper residual soils (50 to 100 cm) have formed on the volcanic rocks and sediments derived from volcanic rocks (Akina, Agfayan, Togcha, Ylig, and Atate soils; Young 1988). These are kaolinitic to montmorillonitic and have even higher $SiO_2$ contents of 25 to 50 percent and somewhat lower iron contents (10 to 20 percent). These soils are typically clays and silty clays of moderately slow (0.5-1.5 cm/hr) to moderate (1.5-5 cm/hr) permeability. Soils formed on alluvium in valley floors or in narrow coastal plain areas (Inarajan; Young 1988) are derived from mixed sources but are typically greater than 150 cm in thickness and clayey. Permeabilities vary from slow (0.02-0.5 cm/hr) to moderate (1.5-5 cm/hr).

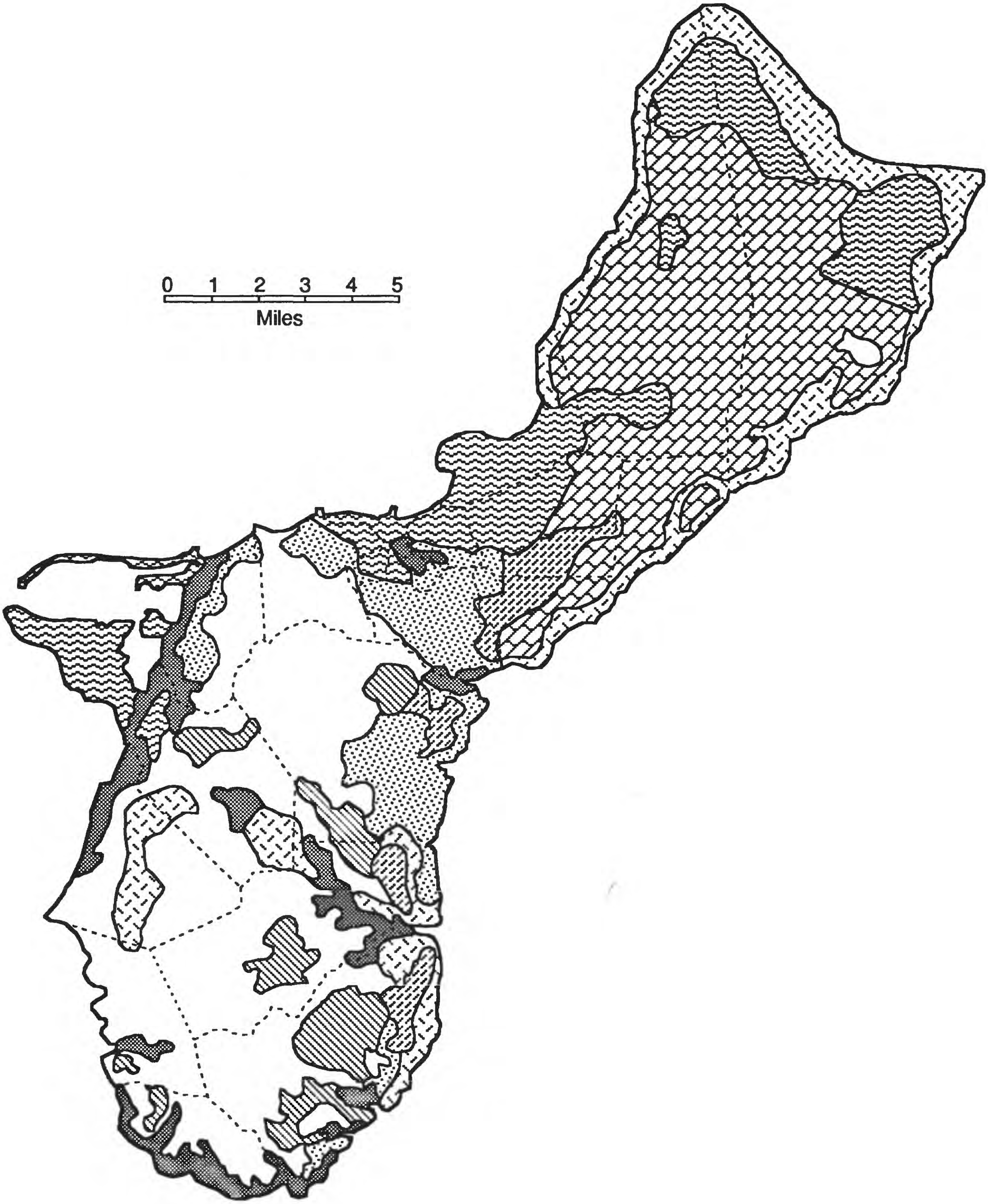


Figure 5. General soil map for the Territory of Guam (after Young, 1988). See next page for map explanation.

## GENERALIZED SOIL MAP OF GUAM

# EXPLANATION

(after Young, 1988)

### SOILS ON BOTTOMLANDS

Inajaran-Inajaran Variant: Deep and very deep, somewhat poorly drained and poorly drained, level and nearly level soils; on valley bottoms and coastal plains

### SOILS ON VOLCANIC UPLANDS

Akina-Agfayan: Very shallow to very deep, well-drained, moderately steep to extremely steep soils; on strongly dissected mountains and plateaus

Akina-Togcha-Ylig: Very deep, somewhat poorly drained and well drained, gently sloping to strongly sloping soils; on plateaus and in basins

### SOILS ON LIMESTONE UPLANDS

Guam: Very shallow, well drained, nearly level to moderately sloping soils; on plateaus

Guam-Urban land-Pulantat: Very shallow and shallow, well drained, level to gently sloping soils, and Urban land; on plateaus

Ritidian-Rock outcrop-Guam: Very shallow, well drained, gently sloping to extremely steep soils, and Rock outcrop; on plateaus, mountains, and escarpments

Pulantat: Shallow, well drained, gently sloping to steep soils; on dissected plateaus and hills

Pulantat-Kagman-Chacha: Shallow, deep, and very deep, somewhat poorly drained and well drained, nearly level to strongly sloping soils; on plateaus and hills

As noted above, the soils developed on the purer limestones of northern Guam are typically moderately to moderately rapidly permeable, and, with the high permeability of the shallow limestone bedrock for most of these soils, this makes for a highly permeable substrate for structures built on these soils. Soils developed on the argillaceous limestone are slowly permeable to moderately slowly permeable and the depth to limestone bedrock is variable. These soils commonly have high shrink-swell potential and thus may damage foundations and create entryways for radon-bearing soil-gas. Soils developed on the volcanic rocks and related sedimentary rocks are mostly moderately to moderately slowly permeable and some have high shrink-swell potential. These soils are generally very thick and thick saprolite (weathered bedrock) commonly underlies them.

During the wet season alluvial soils and some of the soils developed on volcanic rocks may experience flooding or have high water tables. The depth to the water table in most of the limestone terrane is very deep, except where perched water tables form over clayey beds during the wet season.

## INDOOR RADON DATA

A screening survey of indoor radon levels in housing and a complete survey of indoor radon levels in all schools on Guam was completed in 1991 by the Guam Environmental Protection Agency (Guam EPA) for areas throughout the island (Kladder and others, 1991). In 1989, the U.S. Air Force tested all residences and other buildings on Andersen Air Force base at the north end of the island (J.H. Lohaus, Jr., USAF, written commun., 1993). Location information is available only for the measured schools.

Thirteen percent of the classrooms (47 schools, 1242 classrooms, fig. 6) had indoor radon levels exceeding 4 picocuries per liter (pCi/L) and 57 percent of all schools had at least one classroom with radon levels greater than 4 pCi/L. Two of sixteen schools sited on the limestone averaged less than 2 pCi/L whereas twelve of eighteen schools sited on argillaceous limestone averaged less than 2 pCi/L. However, the argillaceous limestone yielded the highest indoor radon level for an individual classroom (117 pCi/L) and the highest school average (31 pCi/L). Eleven schools sited on the volcanic rocks yielded no classroom readings over 1 pCi/L. Two schools sited on beach deposits and alluvium also yielded no classroom readings over 1 pCi/L.

In private residences (208 measurements, Table 1, fig. 7A, B), 27 percent of indoor radon measurements exceeded 4 pCi/L and the highest reading was 143 pCi/L. Residences in municipalities along the western side of the southern province, whose housing is sited largely on volcanic rock or alluvium derived from volcanic rock, averaged less than 2 pCi/L. Municipalities whose residences are largely on argillaceous limestones on the east side of the southern province average between 1 and 4 pCi/L. Municipalities sited mostly on argillaceous limestones in the northern province have variable averages, but all are greater than 2 pCi/L. The highest individual residence reading (143 pCi/L) is in one of these municipalities. If that single high reading is taken out of the data set the municipality average drops from 10.5 to 2.6 pCi/L. Municipalities sited mostly on the pure limestones of the northern province average greater than 4 pCi/L. The village of Agana, with most houses on beach deposits, averages 0.9 pCi/L.

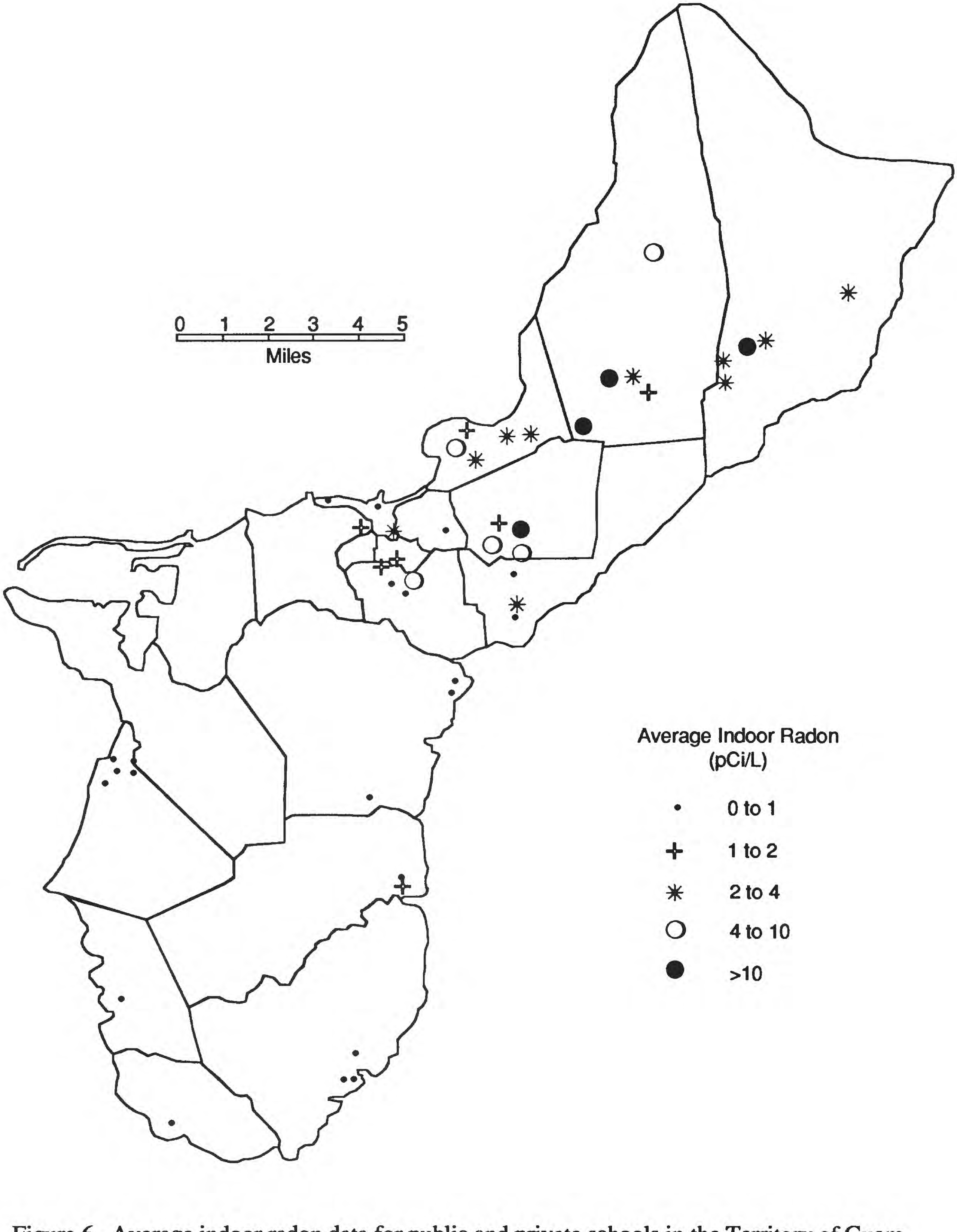


Figure 6. Average indoor radon data for public and private schools in the Territory of Guam from the Territory/EPA Indoor Radon Survey. Each symbol represents one school.

TABLE 1. Screening indoor radon data from the Territory/EPA Indoor Radon Survey of Guam conducted during 1991. Data represent 2-7 day charcoal canister measurements from the lowest level of each home tested.

| MUNICIPALITY | NO. OF MEAS. | MEAN | GEOM. MEAN | MEDIAN | STD. DEV. | MAXIMUM | %>4 pCi/L | %>20 pCi/L |
|---|---|---|---|---|---|---|---|---|
| Agana | 3 | 0.9 | 0.8 | 1.0 | 0.4 | 1.2 | 0 | 0 |
| Agana Heights | 6 | 4.9 | 2.4 | 5.1 | 4.1 | 10.3 | 50 | 0 |
| Agat | 2 | 0.3 | 0.6 | 0.3 | 0.4 | 0.6 | 0 | 0 |
| Asan Maina | 1 | 0.2 | 0.2 | 0.2 | | 0.2 | 0 | 0 |
| Barrigada | 10 | 7.2 | 4.8 | 4.0 | 7.5 | 24.1 | 50 | 10 |
| Chalan Pago Ordot | 6 | 2.1 | 1.6 | 1.6 | 1.6 | 4.9 | 17 | 0 |
| Dededo | 36 | 8.2 | 3.0 | 2.2 | 17.3 | 75.6 | 31 | 11 |
| Inarajan | 2 | 2.1 | 1.1 | 2.1 | 2.6 | 4.0 | 0 | 0 |
| Mangilao | 17 | 11.4 | 3.3 | 2.1 | 19.5 | 72.1 | 29 | 24 |
| Merizo | 3 | 0.3 | 0.3 | 0.4 | 0.2 | 0.6 | 0 | 0 |
| Mongmong-Toto-Maite | 18 | 9.5 | 1.6 | 1.1 | 33.5 | 143.5 | 22 | 6 |
| Piti | 5 | 1.1 | 0.6 | 1.0 | 1.0 | 2.6 | 0 | 0 |
| Santa Rita | 8 | 1.3 | 0.8 | 1.3 | 1.3 | 3.9 | 0 | 0 |
| Sinajana | 3 | 2.9 | 2.1 | 2.6 | 2.4 | 5.4 | 33 | 0 |
| Talafofo | 10 | 1.9 | 0.6 | 0.7 | 2.6 | 7.2 | 20 | 0 |
| Tamuning | 48 | 6.2 | 3.0 | 2.9 | 8.5 | 35.9 | 38 | 8 |
| Umatac | 2 | 0.1 | 0.3 | 0.1 | 0.2 | 0.3 | 0 | 0 |
| Yigo | 18 | 7.5 | 4.0 | 3.9 | 13.4 | 59.0 | 39 | 6 |
| Yona | 10 | 2.9 | 2.3 | 2.9 | 2.2 | 8.5 | 10 | 0 |

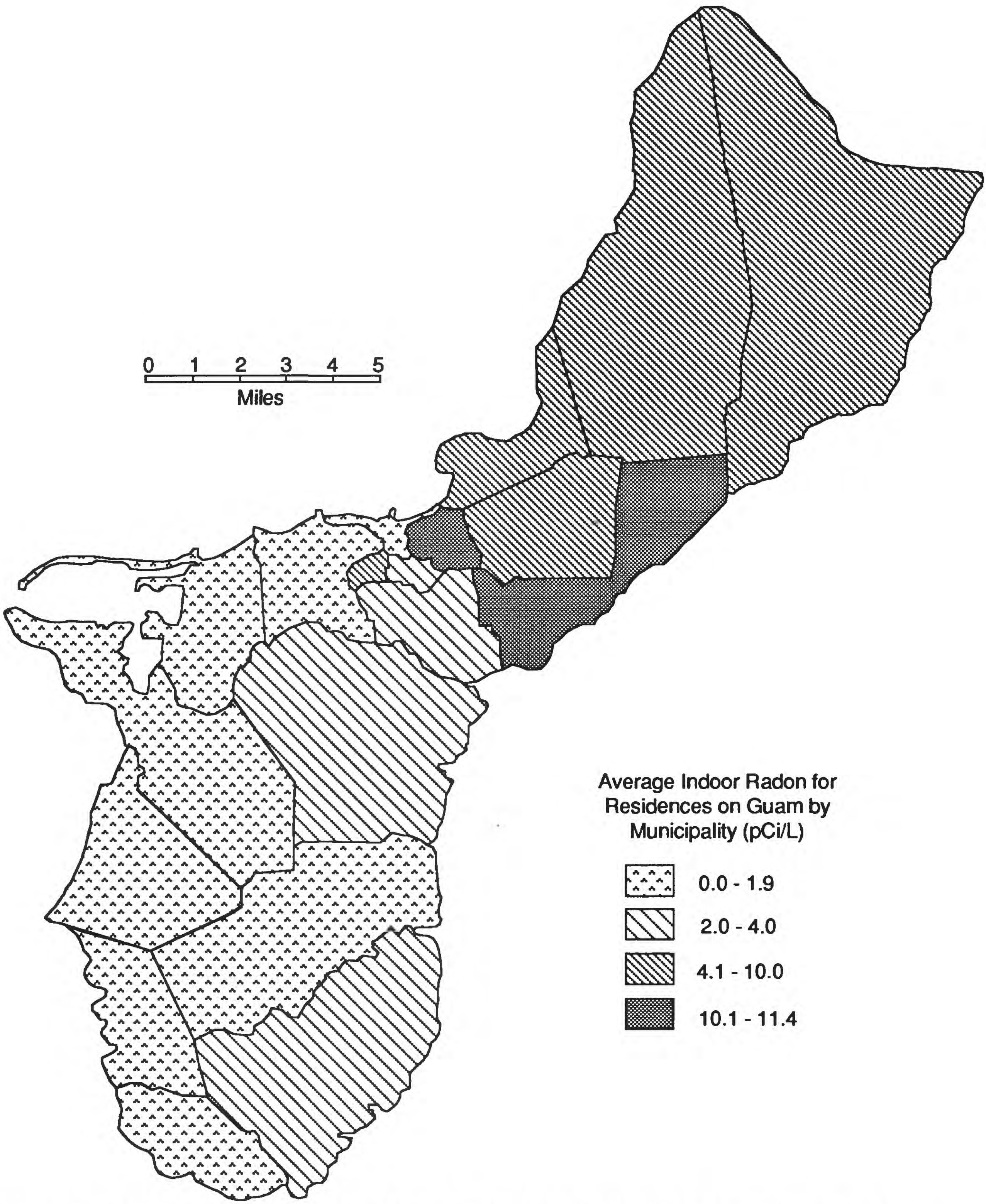


Figure 7A. Screening indoor radon data from the Territory/EPA Indoor Radon Survey of Guam, 1991. Data are from 2 day charcoal canister tests with closed house conditions. The number of samples in each municipality (see Table 1) may not be sufficient to statistically characterize the radon levels of the villages, but they do suggest general trends. Unequal category intervals were chosen to provide reference to decision and action levels.

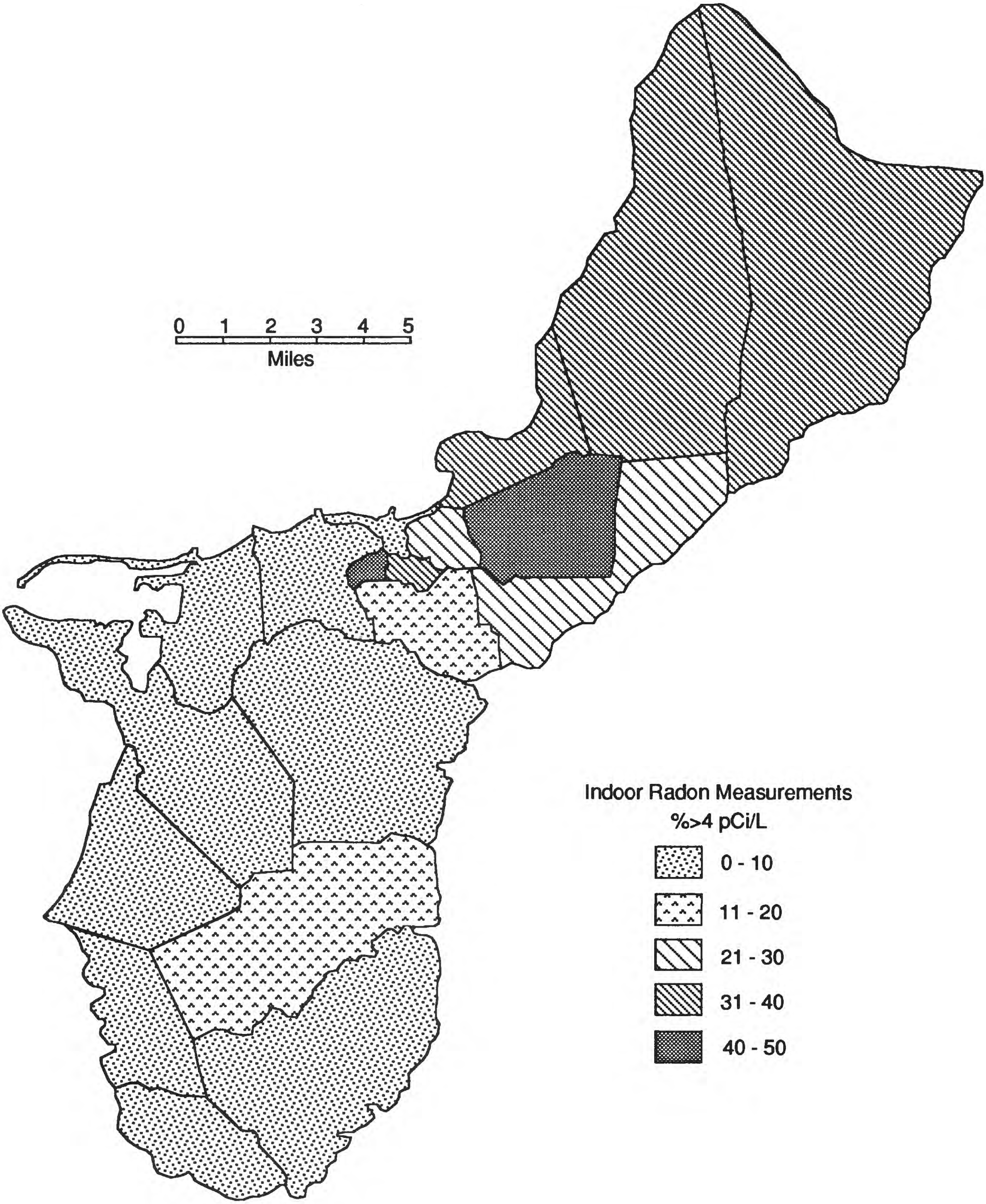


Figure 7B. Percent of homes tested in each municipality of Guam with screening indoor radon levels greater than 4 pCi/L, from the Territory/EPA Indoor Radon Survey.

The Air Force base is sited mostly on the pure limestones on which Guam soils have formed. The indoor radon levels on the Air Force Base (2 month alpha-track wintertime readings) average 7.9 pCi/L, with 56.7 percent of the 1406 readings exceeding 4 pCi/L. The maximum reading was 221 pCi/L. This average value is identical to an average of 7.9 pCi/L for the villages of Dededo and Yigo combined (54 residences) which surround the base.

## GEOLOGIC RADON POTENTIAL

The limestone areas of the northern province are assigned a high geologic radon potential. Evidence suggests that radium has accumulated in the soils and underlying weathered limestones to moderately high levels. The generally gentle slopes of most of the area and the lack of surface drainage have permitted soils to form and remain in place. The soils are thin and have moderately high intrinsic permeability, and the underlying bedrock has high permeability. These conditions create a strong source for indoor radon. Local, small areas of volcanic rocks and beach deposits within this province have low radon potential.

The argillaceous limestones of the northern province have a moderate radon potential overall, but the radon potential appears to vary from low to high. The origins of this variability are probably related to differences in soil thickness and the radium content and permeability of the underlying limestone. Construction conditions may locally contribute to increased radon potential. In many areas, soils apparently have accumulated elevated levels of radium, but the permeability is too low to transmit much radon. Thus where the soils are very thick and the bedrock is too deeply buried to influence the overall permeability of the substrate, the radon potential is low. Where soils are locally thin or have been removed during building site preparation, and the radium content and permeability of the underlying weathered limestone is high, the radon potential is high.

During construction in Guam, residential sites are generally cleared and then graded using crushed limestone (S. Terracciano, written commun., 1994). Poured concrete footers and a concrete slab are placed on the graded surface. A vapor barrier is usually placed between the slab and the crushed limestone to keep moisture from the slab. Where grading of the site removes soil, exposes highly permeable weathered limestone bedrock, and creates pathways for radon migration into the crushed limestone base, the indoor radon potential may be increased, especially if the vapor barrier or the concrete slab integrity is compromised. Where the soils are thick, of low permeability, or the bedrock is of low permeability the grading and construction practices probably do not enhance radon potential significantly.

Earth movements related to earthquakes or progressive collapse of karst features may also contribute to foundation damage and development of entry pathways for radon.

The limestones of the southern province have a moderate radon potential overall, but it varies from low to moderate. Soils are thicker and generally less permeable. Modest amounts of radium have accumulated in some soils, but the fairly steep slopes and surface stream flow have apparently carried away soil material in most areas before significant accumulations of radium can form. In other areas alluvium derived from volcanic rocks may partly cover the limestones.

The volcanic and sedimentary rocks of the southern province have low radon potential. The steep slopes and surface stream flow have apparently carried away soil material in most areas before significant accumulations of radium can form. The low permeability of the soils slows soil gas movement towards the foundation of structures. The alluvium in valley and coastal plain areas and the sands in beach areas apparently have little radium associated with them and some alluvial areas are water saturated. All these areas have low radon potential.

## SUMMARY

The radon potential of the Territory of Guam is summarized in Table 2. Figure 8 is a map of radon potential areas based on the geology, soils, and indoor radon data summarized herein. Estimates of the radioactivity factor are based on reports of radium accumulation in soils formed on the limestones and accepted norms for the radiochemistry of mafic to intermediate volcanic rocks and sediments derived from them. These data and observations suggest that soils formed on the pure limestones of the northern province have high radon potential; soils formed on the argillaceous limestones of the northern province have moderate radon potential overall, but it is highly variable; soils formed on the mostly argillaceous limestones within and around the margins of the southern province have low to moderate radon potential; and soils formed on the volcanic rocks and related sedimentary rocks of the southern province and alluvium, coastal plain sediments, and beach deposits throughout Guam have low radon potential.

This is a generalized assessment of Guam'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 the Guam EPA or the U.S. EPA regional office listed in chapter 1 of this booklet.

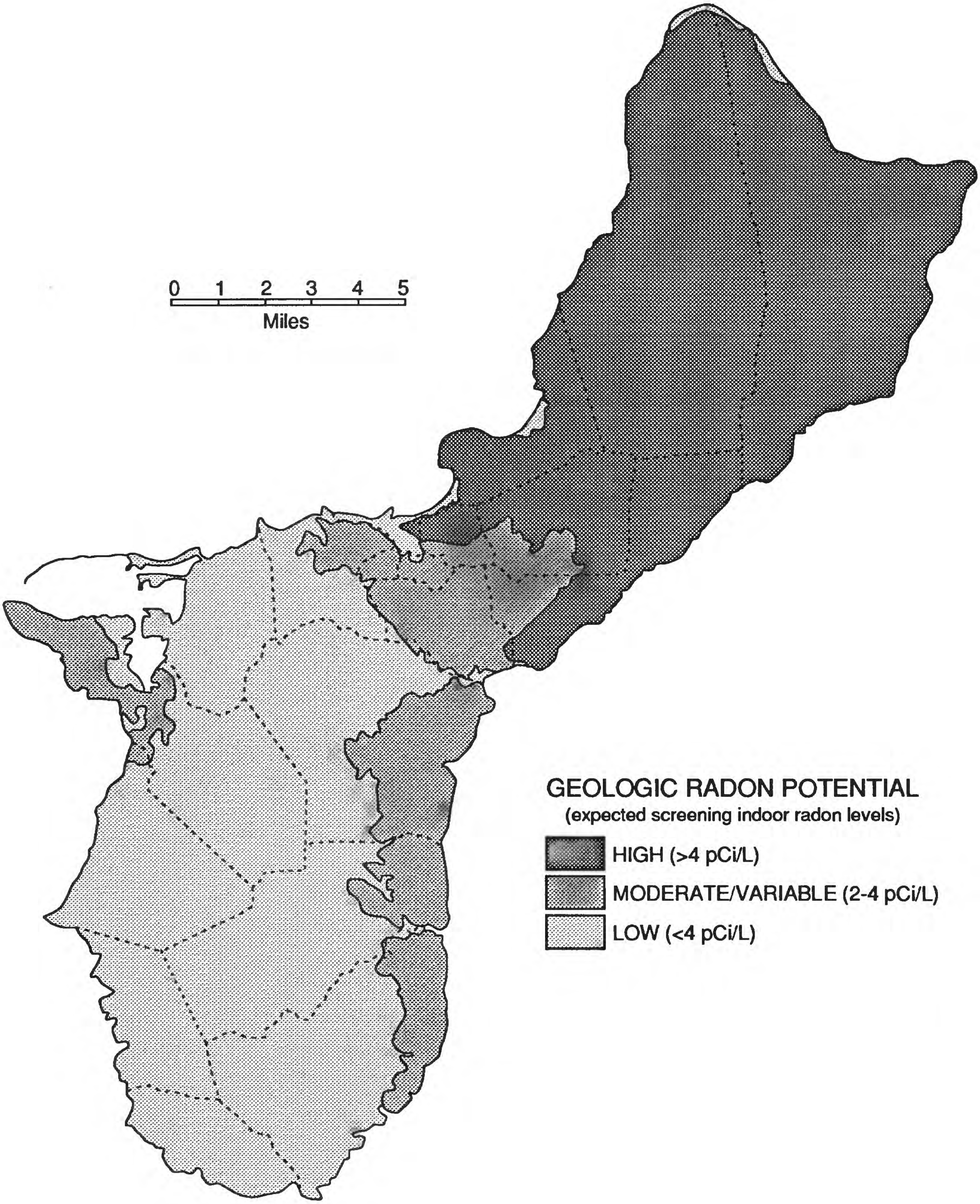


Figure 8. Geologic radon potential map for the Territory of Guam. Numbers in parentheses indicate predicted average screening indoor radon levels for each category of geologic radon potential. See Table 2 for Radon Index and Confidence Index scores of areas.

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

| | Northern Province limestone | | Northern Province argillaceous limestone | | Southern Province limestone | | Southern Province volcanic rocks | |
|---|---|---|---|---|---|---|---|---|
| FACTOR | RI | CI | RI | CI | RI | CI | RI | CI |
| Indoor radon | 3 | 3 | 2 | 3 | 2 | 3 | 1 | 3 |
| Radioactivity | 3? | 1 | 2? | 1 | 2? | 1 | 1? | 1 |
| Geology | 3 | 3 | 2 | 3 | 2 | 3 | 1 | 3 |
| Soil permeability | 3 | 3 | 2 | 3 | 2 | 3 | 1 | 3 |
| Architecture | 1 | - | 1 | - | 1 | - | 1 | - |
| GFE points | 0 | - | 0 | - | 0 | - | 0 | - |
| Total | 13 | 10 | 9 | 10 | 9 | 10 | 5 | 10 |
| Ranking | High | High | Mod | High | Mod | High | Low | High |

- Not used in CI.

RADON INDEX SCORING:

| Radon potential category | point range | probable indoor Rn average |
|---|---|---|
| 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 PUERTO RICO

*by*
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## INTRODUCTION

Puerto Rico is the easternmost island of the Greater Antilles, in the northeastern part of the Caribbean Sea. Its diverse geology and topography ranges from rugged mountains composed of plutonic and volcanic rocks to sandy coastal plains. At the scale of this evaluation, most areas in Puerto Rico have geologic radon potential ranging from low to moderate. Several areas in Puerto Rico have the geologic potential to generate locally high indoor radon levels if housing conditions are favorable for the entry and accumulation of radon.

This is a generalized assessment of geologic radon potential of rocks, soils, and surficial deposits of Puerto Rico. 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 Puerto Rico Department of Health or EPA Region 2 office. More detailed information on local geology may be obtained from the Puerto Rico Geological Survey Division. Addresses and phone numbers for these agencies are listed in chapter 1 of this booklet.

## PHYSIOGRAPHIC AND GEOGRAPHIC SETTING

The Commonwealth of Puerto Rico is located in the northeastern part of the Caribbean sea, southeast of the continental United States (fig. 1). It consists of a main island, measuring approximately 175 km in an east-west direction and 60 km north-south, and several smaller islands, including Isla de Vieques and Isla de Culebra to the east, Isla de Desecheo and Isla de Mona to the west, and Isla Caja de Muertos to the south. The main island of Puerto Rico occupies approximately 8850 km$^2$, slightly less area than Connecticut. The main island can be subdivided into three major physiographic regions that are distinct in their relief and landforms (Monroe, 1980a): A large Uplands area that covers more than half the island's area; a northern Karst Province underlain primarily by limestone; and Coastal Plains (fig. 2). Each of the provinces can be subdivided into smaller areas of local significance. The following discussion of physiographic regions is condensed from Monroe (1980a) and Picó (1974) unless noted otherwise. Information on population of the municipios (fig. 3) is compiled from 1990 U.S. Census data. A map showing the names of the municipios is provided for reference (fig. 4).

The Upland province includes mountains, foothills, and several lowland areas surrounded by mountains. Elevations in this province range from sea level at the eastern and western ends of the island to 1338 m (4390 ft) at Cerro de Punta, north of Ponce. The Cordillera Central is the highest ridge on the island and forms the "backbone" of Puerto Rico, dividing the drainages that flow northward into the Atlantic Ocean from those that flow southward into the Caribbean Sea. Most of the Cordillera Central is composed of volcanic sediments and lava flows, but near Maricao

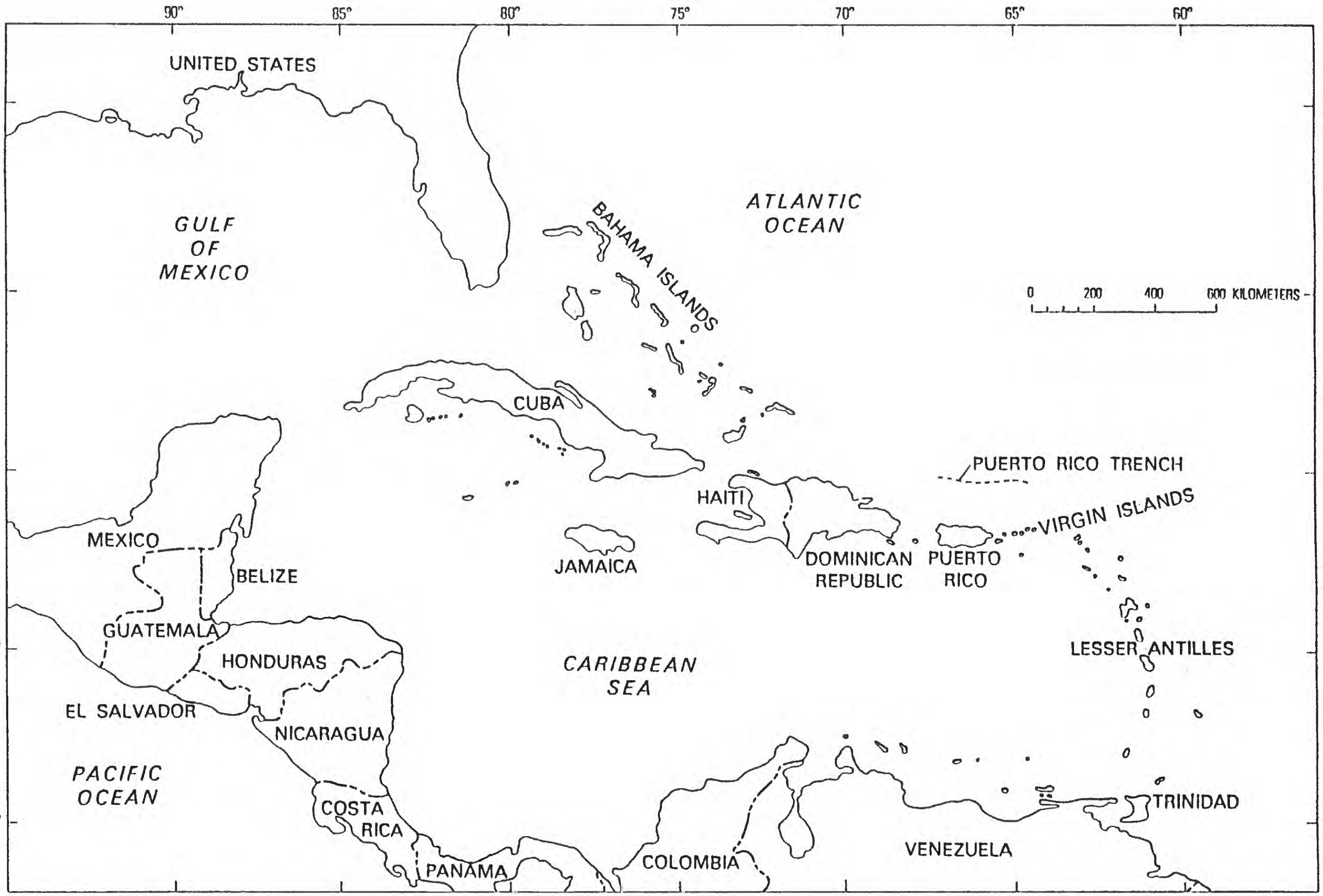



Figure 1. Location of Puerto Rico (from Monroe, 1980a).

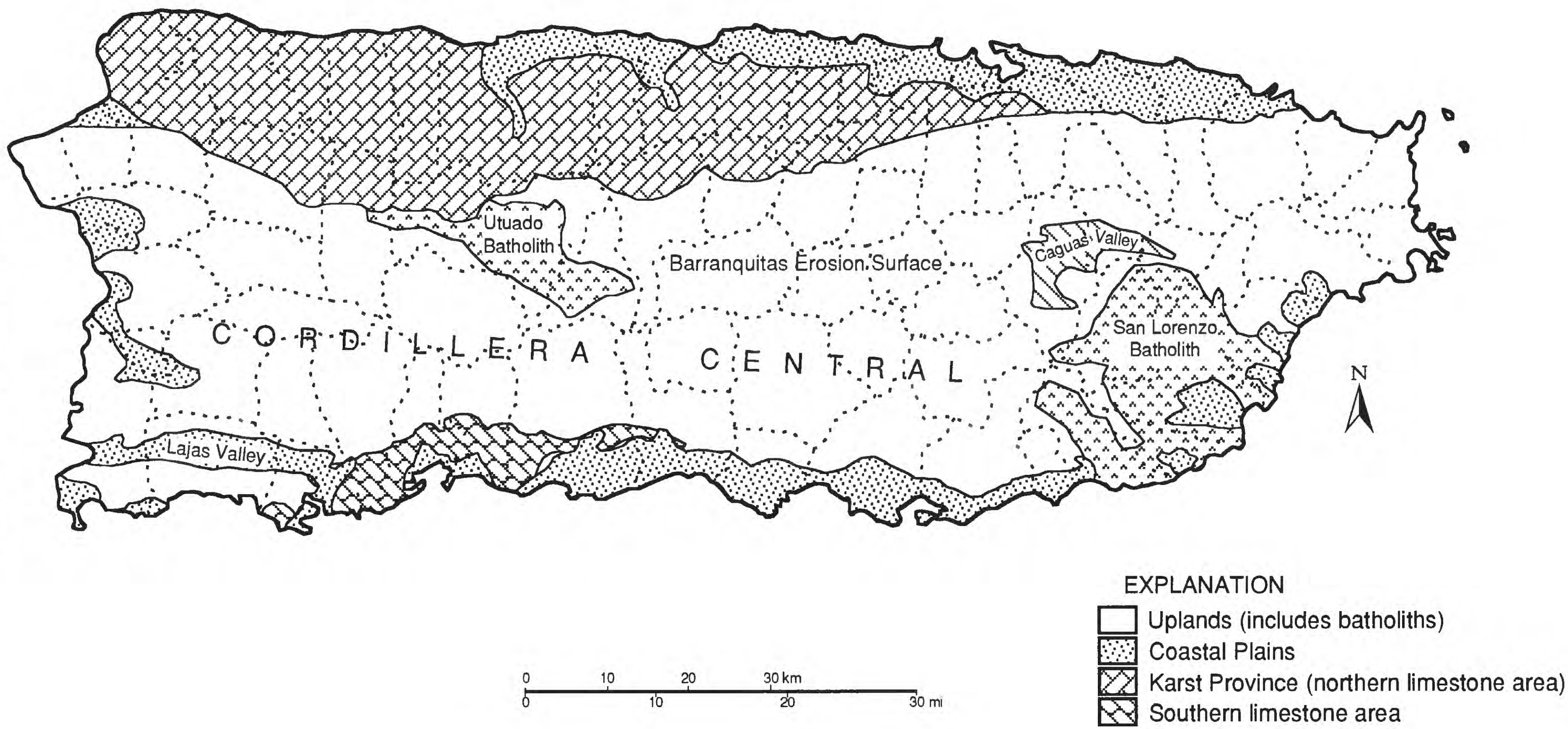



Figure 2. Physiographic regions of the main island of Puerto Rico (after Monroe, 1980).

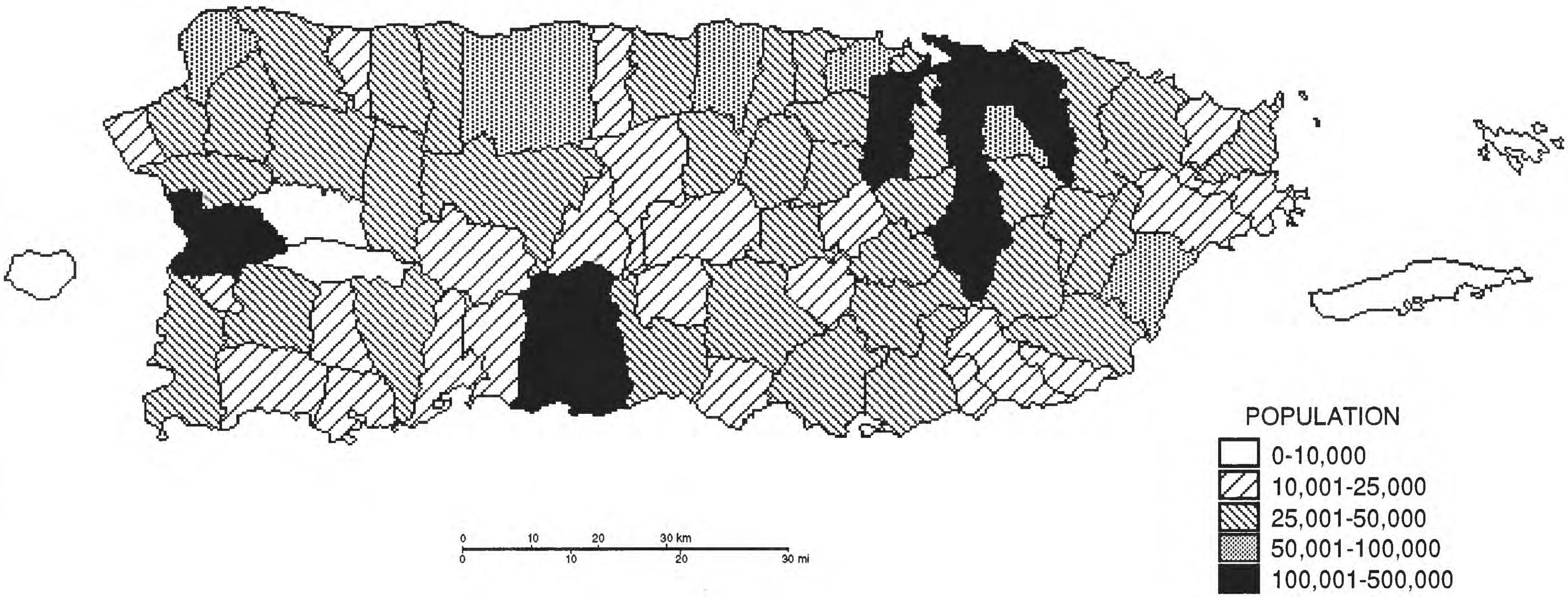



Figure 3. Population of municipios in Puerto Rico. Data from 1990 U.S. Census.

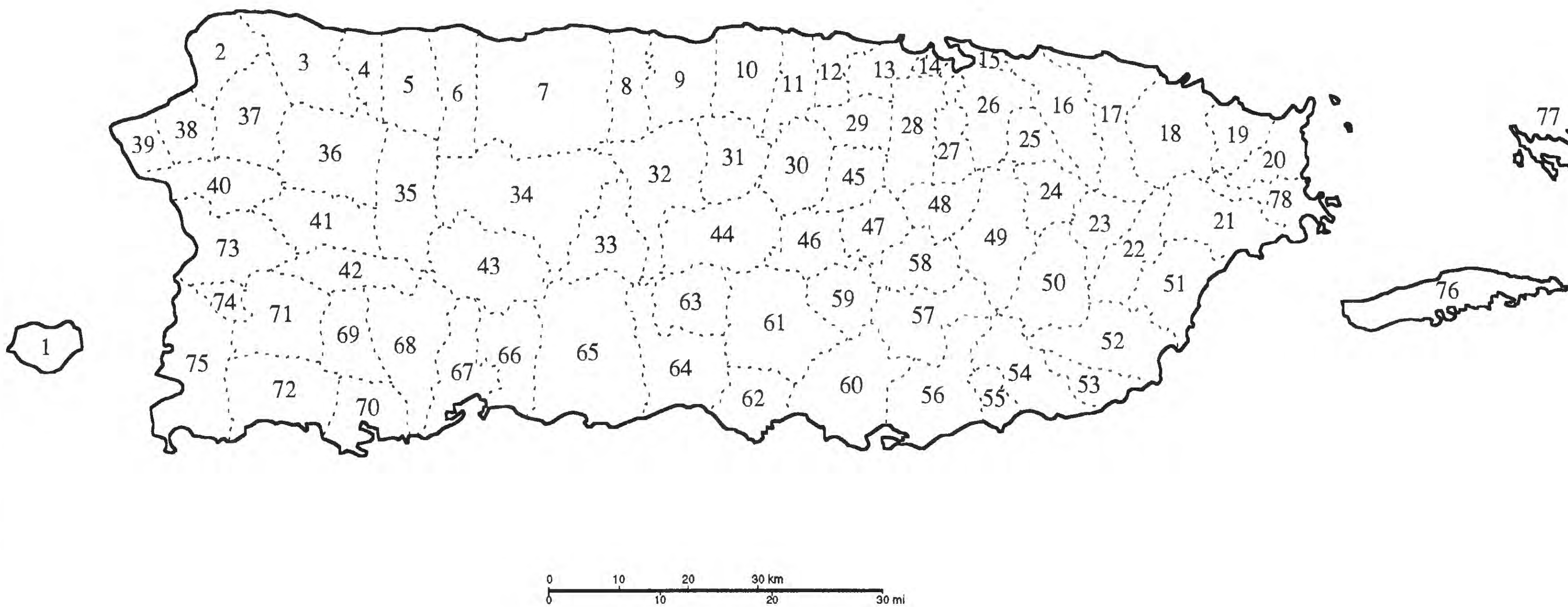



Figure 4. Names of municipios and major islands in Puerto Rico.

Figure 4 (continued). Names of municipios in Puerto Rico.

SORTED BY MAP NUMBER

| Map Number | Name | Map Number | Name | Map Number | Name |
|---|---|---|---|---|---|
| 1 | Isla de Mona* | 27 | Guaynabo | 53 | Maunabo |
| 2 | Aguadilla | 28 | Bayamón | 54 | Patillas |
| 3 | Isabela | 29 | Toa Alta | 55 | Arroyo |
| 4 | Quebradillas | 30 | Corozal | 56 | Guayama |
| 5 | Camuy | 31 | Morovis | 57 | Cayey |
| 6 | Hatillo | 32 | Ciales | 58 | Cidra |
| 7 | Arecibo | 33 | Jayuya | 59 | Aibonito |
| 8 | Barceloneta | 34 | Utuado | 60 | Salinas |
| 9 | Manatí | 35 | Lares | 61 | Coamo |
| 10 | Vega Baja | 36 | San Sebastián | 62 | Santa Isabel |
| 11 | Vega Alta | 37 | Moca | 63 | Villalba |
| 12 | Dorado | 38 | Aguada | 64 | Juana Díaz |
| 13 | Toa Baja | 39 | Rincón | 65 | Ponce |
| 14 | Cataño | 40 | Añasco | 66 | Peñuelas |
| 15 | San Juan | 41 | Las Marías | 67 | Guayanilla |
| 16 | Carolina | 42 | Maricao | 68 | Yauco |
| 17 | Loíza | 43 | Adjuntas | 69 | Sabana Grande |
| 18 | Río Grande | 44 | Orocovis | 70 | Guánica |
| 19 | Luquillo | 45 | Naranjito | 71 | San Germán |
| 20 | Fajardo | 46 | Barranquitas | 72 | Lajas |
| 21 | Naguabo | 47 | Comerío | 73 | Mayagüez |
| 22 | Las Piedras | 48 | Aguas Buenas | 74 | Hormigueros |
| 23 | Juncos | 49 | Caguas | 75 | Cabo Rojo |
| 24 | Gurabo | 50 | San Lorenzo | 76 | Isla de Vieques |
| 25 | Trujillo Alto | 51 | Humacao | 77 | Isla de Culebra |
| 26 | Río Piedras | 52 | Yabucoa | 78 | Ceiba |

SORTED BY NAME

| Map Number | Name | Map Number | Name | Map Number | Name |
|---|---|---|---|---|---|
| 43 | Adjuntas | 56 | Guayama | 21 | Naguabo |
| 38 | Aguada | 67 | Guayanilla | 45 | Naranjito |
| 2 | Aguadilla | 27 | Guaynabo | 44 | Orocovis |
| 48 | Aguas Buenas | 24 | Gurabo | 54 | Patillas |
| 59 | Aibonito | 6 | Hatillo | 66 | Peñuelas |
| 40 | Añasco | 74 | Hormigueros | 65 | Ponce |
| 7 | Arecibo | 51 | Humacao | 4 | Quebradillas |
| 55 | Arroyo | 3 | Isabela | 39 | Rincón |
| 8 | Barceloneta | 77 | Isla de Culebra | 18 | Río Grande |
| 46 | Barranquitas | 1 | Isla de Mona* | 26 | Río Piedras |
| 28 | Bayamón | 76 | Isla de Vieques | 69 | Sabana Grande |
| 75 | Cabo Rojo | 33 | Jayuya | 60 | Salinas |
| 49 | Caguas | 64 | Juana Díaz | 71 | San Germán |
| 5 | Camuy | 23 | Juncos | 15 | San Juan |
| 16 | Carolina | 72 | Lajas | 50 | San Lorenzo |
| 14 | Cataño | 35 | Lares | 36 | San Sebastián |
| 57 | Cayey | 41 | Las Marías | 62 | Santa Isabel |
| 78 | Ceiba | 22 | Las Piedras | 29 | Toa Alta |
| 32 | Ciales | 17 | Loíza | 13 | Toa Baja |
| 58 | Cidra | 19 | Luquillo | 25 | Trujillo Alto |
| 61 | Coamo | 9 | Manatí | 34 | Utuado |
| 47 | Comerío | 42 | Maricao | 11 | Vega Alta |
| 30 | Corozal | 53 | Maunabo | 10 | Vega Baja |
| 12 | Dorado | 73 | Mayagüez | 63 | Villalba |
| 20 | Fajardo | 37 | Moca | 52 | Yabucoa |
| 70 | Guánica | 31 | Morovis | 68 | Yauco |

*included for location information only.

the ridge is composed of serpentinite. In the Utuado area, the mountains are composed of granitic intrusive rocks of the Utuado Batholith (fig. 2). In much of this area, the granodiorite and quartz diorite have weathered more rapidly and intensely than the surrounding volcanic rocks, forming deeply gullied lowlands. The west central mountains extend roughly from the center of the island to the west coast. These mountains are generally higher than those in the east, and the terrain is rugged, with narrow valleys. Rainfall is abundant, with an annual average of 2400 mm (fig. 5). The area is sparsely populated and the urban centers are relatively small.

The east-central mountains occupy most of the eastern half of the Uplands province. The area's southern border is marked by the Sierra de Cayey, a series of peaks underlain primarily by volcanic rocks in the western part and plutonic rocks in the east, with elevations ranging from 450 to 900 m. To the southeast the Sierra de Cayey splits to form the Sierra de Guardarraya and the Cuchilla de Panduras, both of which are underlain by granodiorite and quartz diorite of the San Lorenzo Batholith (fig. 2). Much of the area underlain by the San Lorenzo Batholith is lowlands with gullied, clayey-sandy residual soils. Average annual rainfall in the east-central mountains is about 1980 mm and this area is more densely populated than the west-central mountains. The northeastern corner of Puerto Rico is occupied by the Sierra de Luquillo, which extends between Gurabo and Fajardo. Most of the Sierra consists of relatively low foothills, but in its central part it contains several high peaks including El Yunque at 1065 m, and El Toro at 1074 m. Most of the Sierra is underlain by volcanic rocks but an area south of El Yunque is underlain by quartz diorite and metamorphosed volcanic rocks. The asymmetric shape of the sierra suggests that it is a fault block (Monroe, 1980a). To the north of the Cordillera Central, near the center of Puerto Rico, lies the Barranquitas erosion surface, a dissected upland with generally concordant summit elevations, indicating that it is the remnant of a low flat plain that was later uplifted and dissected by streams. The erosion surface is underlain primarily by volcanic and sedimentary rocks. Altitudes of the broad, gently rolling upland surfaces range from 600 to 1000 m. Entrenched river meanders are a striking and common feature of this area. The Caguas Valley is another lowland area related to the weathering of granitic rocks but modified by the deposition of alluvial fans along the sides of the valley. It is the largest of Puerto Rico's interior valleys, with a humid tropical climate and annual average rainfall of about 1750 mm.

Foothills flank the uplands to the north and south of the Cordillera Central. The northeastern Cretaceous section extends from Ciales to Cabezas de San Juan and includes mountains with elevations as high as 600 m. The climate of the area is humid, with annual rainfall averaging 1900-2500 mm. The northwestern part of the Uplands is a group of foothills underlain by Cretaceous sedimentary rocks called the Atalaya Hills, which extend from just south of San Sebastián to just south of Aguadilla. The climate of the Atalaya Hills is generally humid, with an average annual rainfall of 2100-2300 mm (fig. 5). Winters are generally dry, as is typical for the west coast (Picó, 1974). The southern foothills area a series of low ridges of clastic sediments and limestones that lie between the central mountains and the southern coastal plains. Their climate is generally arid, with annual rainfall averaging 1000-1500 mm. The Sierra Bermeja is the mountain range that lies south of the Lajas Valley. It is composed of a faulted mass of volcanic and metamorphic rocks.

The Karst Province covers a 135-km long belt to the north of the Upland Province extending from Loíza Aldea on the east to Aguadilla on the west. It is underlain by limestone that has been intensely modified by dissolution of the rock by flowing water, forming sinkholes (locally called sumideros), caves, cone-shaped hills called mogotes, subsurface drainages, linear ridges and trenches called zanjones, and several other distinctive features collectively called karst

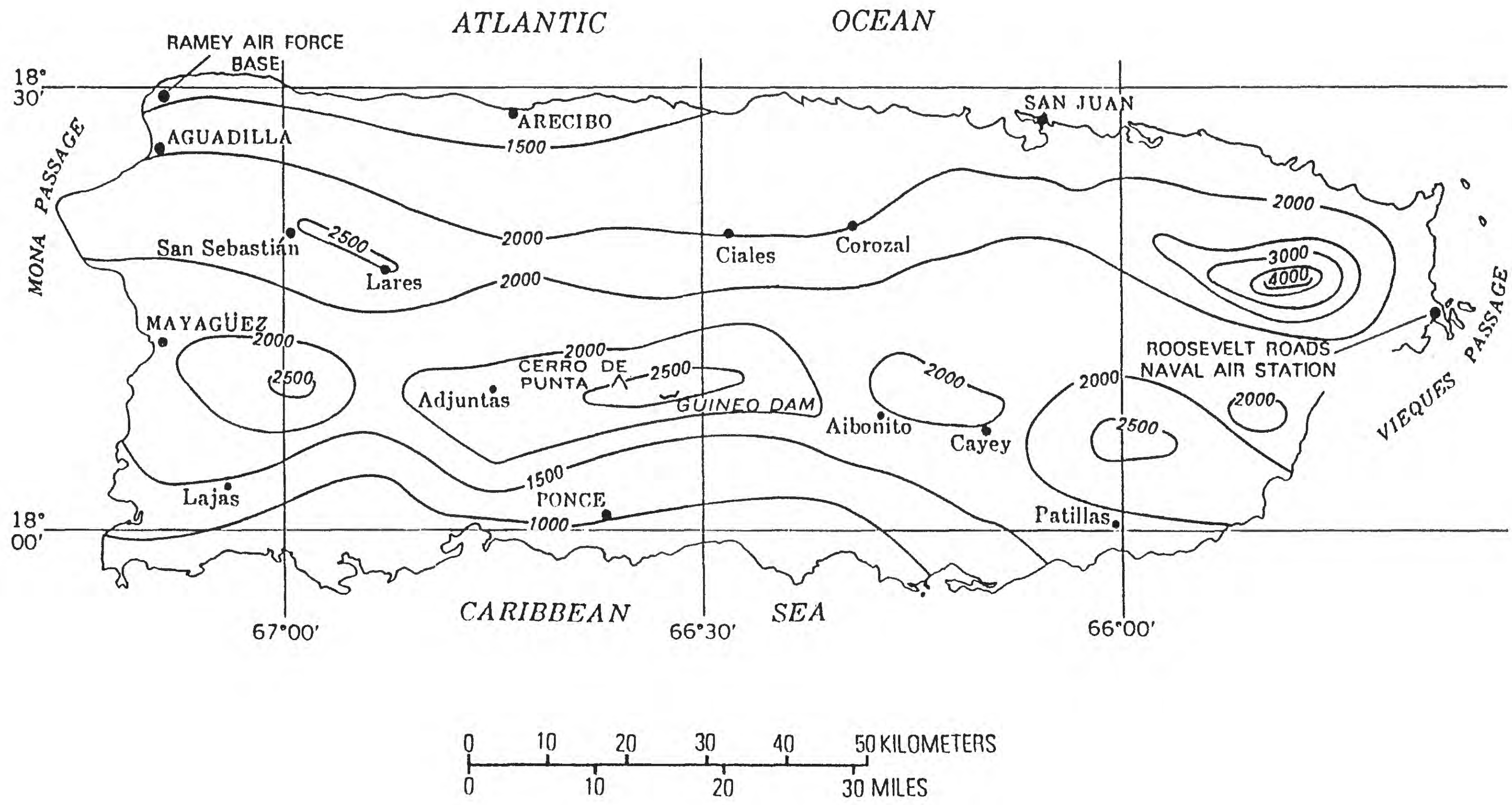



Figure 5. Average annual precipitation in Puerto Rico (from Monroe, 1980a). Data from U.S. National Weather Service.

topography. In many areas, the limestones are buried beneath alluvial deposits from several rivers. Except for the through-flowing rivers that supplied the aforementioned alluvium, all of the drainage of the karst belt is underground. In some areas, differential erosion of the gently-dipping limestone beds has formed a series of low ridges, called cuestas, that are characterized by steep south-facing scarps and long, gentle, north-facing slopes that are interrupted by karst features. The largest of these features is the Lares cuesta scarp, which extends continuously from San Sebastián to Corozal, interrupted only by alluvial valleys of the major rivers that cross the belt.

On all sides of Puerto Rico, coastal plains have been formed on alluvial deposits that have been in many places reworked by the ocean and by wind. In northern Puerto Rico, the Coastal Plain consists of alluvial plains at the mouths of present and past rivers that drain into the Atlantic Ocean from the uplands. Between the alluvial plains are lagoons, such as Laguna Tortugero near Manatí and Laguna San José near San Juan, or former lagoons that have since filled with sediment, such as Ciénaga or Caño Tiburones, east of Arecibo, and large swamps such as those at Sabana Seca between Dorado and Bayamón. Much of the coast is covered by beach deposits consisting of quartz sand mixed with shell fragments and in some cases with volcanic sand, which in some areas is cemented to form beachrock. Sand dunes commonly border the beaches. The climate of the northern coastal plains ranges from subhumid to humid, with annual rainfall ranging from less than 1500 mm in the west to almost 2000 mm at Río Piedras in the east. The northern coastal plains are the most densely populated region of Puerto Rico, with more than 60 percent of the island's urban population (Picó, 1974; also see figure 3).

The eastern coast of Puerto Rico consists of irregular rocky headlands that separate coastal lowlands composed of quartz-rich alluvial sand and gravel deposits. Annual precipitation generally averages more than 1900 mm (fig. 5), and the climate of this region is classified as humid tropical. Maunabo, on the southeastern coast of Puerto Rico, has the highest annual average temperature in the Commonwealth, 26.4°C (79.6°F; Picó, 1974). The west coast is much like the east, with rocky headlands separating wide coastal valley mouths with sandy beaches. Mangrove swamps are common inland of the beaches. Rainfall in the coastal valleys is abundant from May to November but nearly absent from December to March, causing floods during the rainy season and drought in winter. The average annual rainfall is about 1900 mm at Mayagüez.

The southern Coastal Plains, particularly between Ponce and Guayama, are composed primarily by a series of large alluvial fans consisting of poorly sorted sediments derived from the mountains to the north. Gravel and cobble beaches are common and large lagoons are less common than in the north. West of Ponce the coastline is dominated by seacliffs and rocky headlands that are interrupted by several bays. The southern coastal areas have a semiarid climate, with average annual rainfall generally less than 1300 mm (fig. 5); Ponce receives about 950 mm of rainfall annually, and although it is one of the drier regions of Puerto Rico, it is considered the richest agricultural region. Sugar cane, tomatoes, and peppers are grown in irrigated fields. Plantains, bananas, corn, and beans, and dairy and beef cattle are other agricultural products of the region. The Lajas Valley, in the southwestern corner of Puerto Rico, lies inland from the coast. Until the Pleistocene Epoch the valley was a strait that separated southwestern Puerto Rico from the remainder of the island. The valley is nearly flat and formerly contained a number of lakes and lagoons, most of which have been drained. Sugar cane is grown in the rich alluvial soils, which, as in the Ponce region, require irrigation in the semiarid climate.

Several islands off the coast of Puerto Rico were formed when parts of the main island were separated from it by structural movements or by drowning when sea level rose during the melting of late Pleistocene ice sheets of North America and Europe. Isla de Culebra is part of the

Uplands province that was drowned in the recent geologic past. It is underlain mostly by volcanic rocks but contains an outcrop of granitic intrusive rock on its northern shore. The climate of the island is characterized by rainy spring and fall seasons and cool, drier winters. Isla de Vieques, to the south of Isla de Culebra, is the largest of the offshore islands. Most of the western half of the island is underlain by granitic rocks related to the San Lorenzo batholith. The eastern part of the island is underlain primarily by volcanic rocks and some limestone. The average annual rainfall is approximately 1200 mm. White sand beaches and modern hotels make Isla de Vieques a major tourist attraction. Isla de Mona, located about 80 km west of the main island of Puerto Rico, is a wave-eroded limestone plateau rising 70-90 m above sea level. Its climate is arid and vegetation is relatively sparse.

## GEOLOGY

Puerto Rico lies within the seismically active boundary zone between the Caribbean and North American plates. Puerto Rico and the Virgin Islands appear to be a separate tectonic block within the plate boundary zone (Schellekens and others, 1991). Relative motion between the two plates is expressed in a series of lateral faults and underthrusts in the Puerto Rico Trench, offshore to the north of the island. Some plate motion and underthrusting also occurs in the Muertos Trench south of the island. A number of faults with dominantly east-west or northwest-southeast trends exist on the island as well (fig. 6A) and attest to the tectonically active character of Puerto Rico.

Puerto Rico can be conveniently divided into three main geologic provinces. The central part of the island is occupied by the mountainous volcanic-plutonic complex, underlain primarily by volcanic and plutonic rocks ranging from Cretaceous to Eocene in age. On the flanks of the island's crystalline core lie the northern and southern limestone provinces, composed of marine sedimentary rocks, primarily limestone, ranging from Oligocene to Miocene in age. Surficial deposits of alluvium, beach deposits, and marine deposits are found in valleys and plains along the coast and in a few large interior valleys (Cox and Briggs, 1973); these coastal plain deposits comprise the third geologic province. The following discussion of the geology of Puerto Rico is condensed from Briggs (1964), Cox and Briggs (1973), and Schellekens and others (1991). The reader is urged to consult these and other publications for more information.

The volcanic-plutonic province is characterized by broad folds and extensive fault systems along which significant lateral movement has occurred, both oriented in a dominantly west to northwest direction, although some major faults that are oriented in other directions also occur. The volcanic-plutonic province has been subdivided into three subprovinces along two major fault zones, called the northeastern, central, and southwestern igneous provinces (fig. 6B; Schellekens and others, 1991), or the northeastern, central, and southwestern volcanic-plutonic subprovinces (Cox and Briggs, 1973).

The southwestern volcanic-plutonic subprovince is characterized by large bodies of serpentinite and extensive thick limestone deposits. Plutonic bodies are rare. The oldest rocks of the southwestern province are the Bermeja Complex, consisting of serpentinite (Ks in figure 6A) with gneissic amphibolite, chert, and metabasalt. The Bermeja Complex is considered to be Early Cretaceous in age. Post-Bermeja rocks consist of lava, volcaniclastic rocks (agglomerate), marine limestone, mudstone, and tuff, primarily of Late Cretaceous age, and lava, volcanic breccias, tuff, and reworked volcanic rocks of Paleocene and Eocene age. East-west trending faults and ridges occur in the western part of the province, whereas northwest-trending faults and ridges occur in the eastern part.

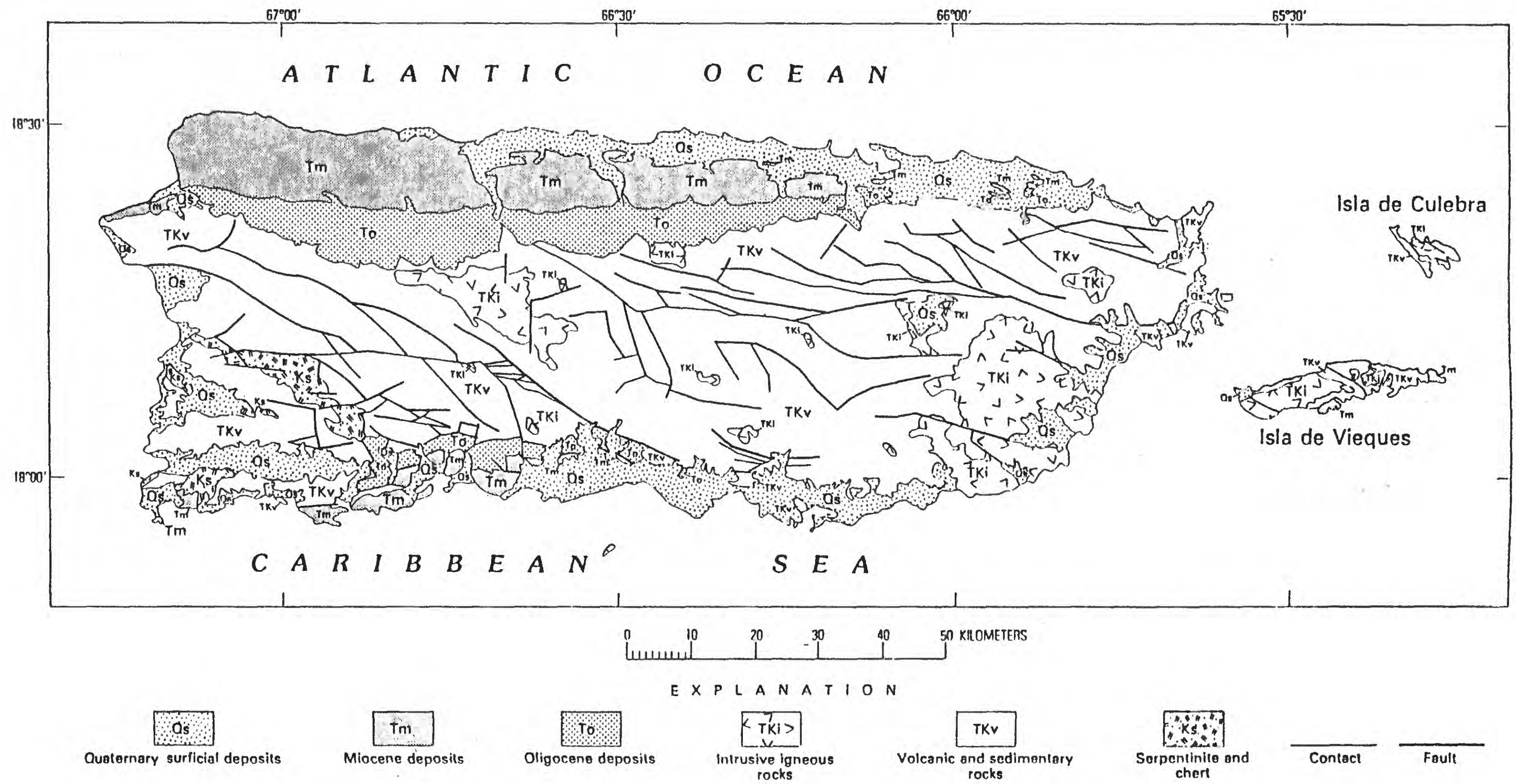



Figure 6A. Generalized map of the geology of Puerto Rico (from Monroe, 1980a). Description of geologic units (next page) condensed from Briggs (1964).

Qs

**QUATERNARY SURFICIAL DEPOSITS**
**Alluvial deposits**–Sand, silt, clay, and gravel floodplain and terrace deposits, and piedmont fan deposits; also includes colluvium at margains of alluvial deposits.
**Landslide deposits**–Commonly composed of blocks and residual boulders 10 feet or more across in a matrix of clay, sand, and gravel.
**Beach and dune deposits**–Largely calcite, quartz, and(or) volcanic-rock-fragment sand with locally conspicuous magnetite; includes pebble and cobble deposits and organic reef rubble; locally includes cemented sand (beach-rock) in bands parallel to the shore.
**Compound dunes**–Friable eolianite and marine sandstone largely composed of calcite and quartz; some hard calcarenite beds 10 feet or less in thickness.
**Blanket deposits**–Quartz sand, clayey sand, sandy clay, and clay; principally in the north coastal plain and in areas of karst topography developed on strata of Oligocene and Miocene age.
Swamp and marsh deposits–Largely organic swamp muck, locally sandy or silty, and peat.

Tm

**MIOCENE DEPOSITS– NORTHERN PUERTO RICO**
**Camuy Formation**–Punky fragmental limestone and marl containing some sandstone and hard limestone beds; some discontinuous dolomite beds.
**Aymamón Limestone**–Thick-bedded and massive dense limestone and calcarenite; some dolomite beds. Rocks in natural outcrops are commonly hard as a result of surficial recrystallization, but rocks are commonly soft and chalky in excavations.
**Aguada Limestone**–Hard, thick-bedded to massive calcarenite and dense limestone interbedded with chalky limestone and marl; commonly contains quartz grains; locally thin bedded near top.

Tm

**MIOCENE DEPOSITS– SOUTHERN PUERTO RICO** – Ponce Limestone (upper member) – Hard, thick-bedded and finely crystalline limestone and calcarenite; locally contains beds of shale.

To

**OLIGOCENE DEPOSITS– NORTHERN PUERTO RICO**
**Cibao Formation** –Interbedded marl, chalk and limestone; some thin sand and clay beds; occasional conglomerate lenses.
**Lares Limestone**–Thick-bedded to massive dense limestone and calcarenite.
**San Sebastián Formation**–Largely composed of clay and sand beds with conglomerate near the base; some limestone lenses; does not crop out in the central part of northern Puerto Rico.

To

**OLIGOCENE DEPOSITS– SOUTHERN PUERTO RICO**
**Ponce Limestone** (lower member) (Oligocene-Miocene)–Chalky, thin- to medium-bedded limestone; some massive limestone; locally contains beds of shale and sand.
**Juana Díaz Formation** – Shale, sandy limestone, and sandy conglomerate; does not crop out in the area just west of Peñuelas.

TKi

**INTRUSIVE IGENEOUS (PLUTONIC) ROCKS** – Largely granodiorite and quartz diorite; some diorite; minor quartz porphyry, gabbro, and amphibolite; believed to have been emplaced during the Late Cretaceous, Paleocene, and Eocene. Includes some hydrothermally altered rock and some areas of complexly and intimately associated plutonic and volcanic rock.

TKv

**VOLCANIC AND SEDIMENTARY ROCKS** – Siltstone, sandstone, conglomerate, lava, tuff, tuffaceous sandstone, breccia, and tuffaceous breccia, largely deposited in a marine environment. Includes algal limestone beds; some pure and impure limestone lenses; some hydrothermally altered rocks; some plutonic rocks; some amphibolite. Locally deeply weathered.

Ks

**SERPENTINITE AND CHERT** – Serpentinized peridotite(?); probably emplaced during the Early or early Late Cretaceous. Includes small areas of volcanic rocks of Early Cretaceous(?) age. Extensive deep weathering.

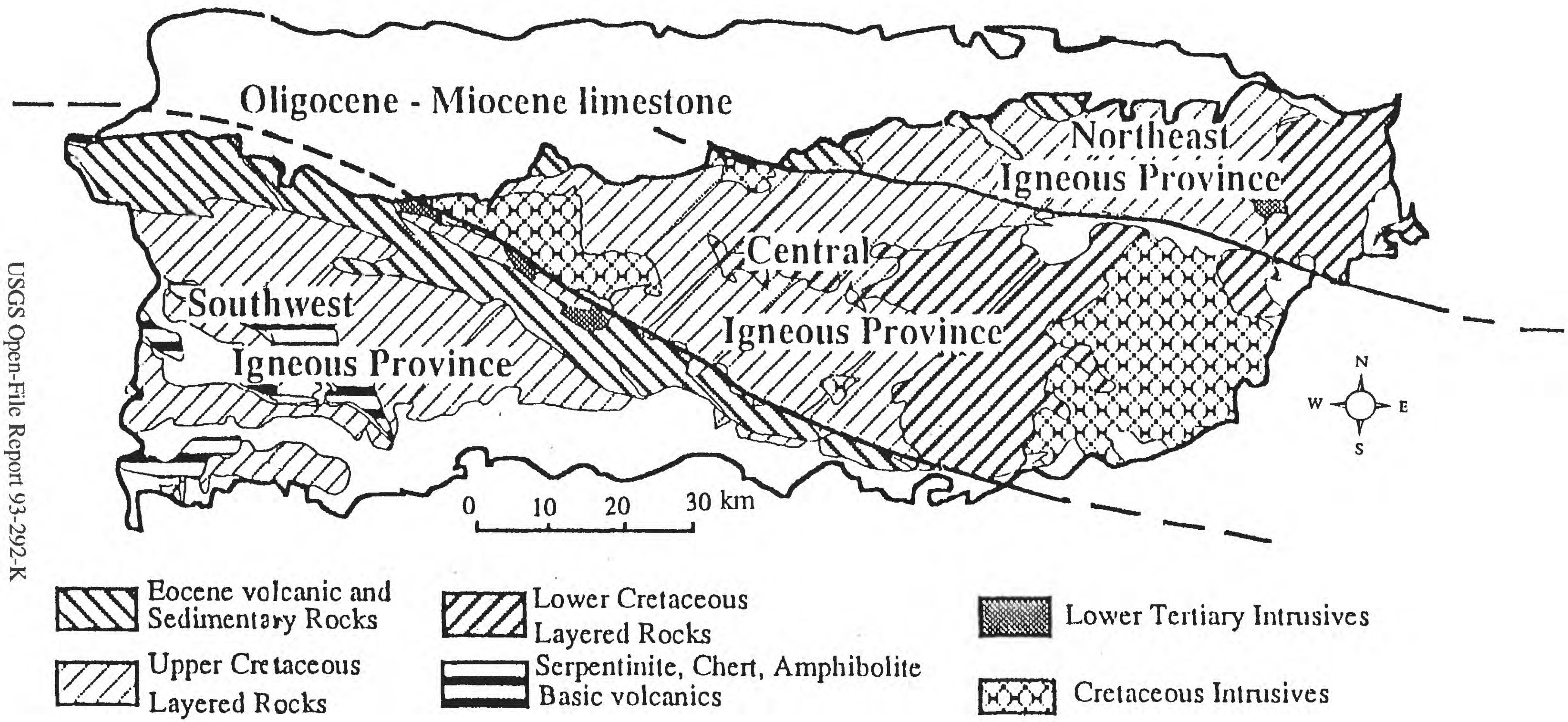



Figure 6B. Generalized map showing subdivisions of the volcanic-plutonic geologic province of central Puerto Rico (modified from Schellekens and others, 1991).

The central volcanic-plutonic subprovince is characterized by several large Late Cretaceous plutons that have intruded older volcanic flows and breccias with occasional limestone lenses, tuffaceous sandstone and siltstone intercalated with basalt and andesite, and nonmarine tuffaceous limestone, conglomerate, and volcanic breccia. Some of the volcanic and volcaniclastic rocks have undergone zeolite- to greenschist-facies metamorphism. The San Lorenzo and Utuado batholiths and numerous smaller plutons occupy approximately 20 percent of the outcrop area of the central subprovince. The plutonic rocks are composed mainly of granodiorite but also include diorite, quartz diorite, gabbro, and quartz monzonite. Tuffaceous rocks and limestone of Paleocene to Eocene age overlie the Cretaceous rocks in this subprovince.

The northeastern volcanic-plutonic subprovince consists of a complex sequence of stratified volcanic and sedimentary rocks ranging from Early Cretaceous to early Tertiary in age. This sequence was intruded by a number of small plutons in the Late Cretaceous and Eocene. In the western part of the subprovince, Late Cretaceous lava and volcaniclastic rocks rest on a thick sequence of stratified tuff, volcanic breccia, and lava. In the eastern part, Late Cretaceous (Cenomanian) breccias and tuffs overlie a thick sequence of Early Cretaceous stratified tuff and breccia, which in turn overlies and older lava. Late Cretaceous stratified tuff, breccia, limestone, and lava overlie the Cenomanian rocks and are in turn overlain disconformably by early Tertiary volcanic breccia, tuff, limestone, and siltstone. Although the rocks of the northeastern subprovince have experienced widespread hydrothermal alteration, only one large intrusion, the Rio Blanco Stock, crops out in the area.

After middle Eocene time, extensive uplift and erosion occurred, followed by deposition of marine clastic rocks of the northern and southern limestone provinces. The larger of the two areas, the northern limestone province, is composed of Oligocene and Miocene limestone, marl, claystone, and lesser amounts of dolomite that dip gently northward. The northern limestone province exhibits extensive karst topography, characterized by sinkholes (locally called sumideros), caves, cone karst, haystack hills (locally called mogotes), subsurface drainages, linear ridges and trenches called zanjones, and several other distinctive features (Monroe, 1980a). Blanket sands of Miocene to Holocene age are common in the northern karst area. The southern limestone province is lithologically similar but is highly faulted and exhibits only minor karst.

On all sides of Puerto Rico, coastal plains have formed on alluvial deposits that have been in many places reworked by the ocean and by wind. Pleistocene eolianite (cemented windblown sand deposits) and marine calcarenite (calcium-carbonate cemented beach sands) are present along the north and west coasts. Holocene alluvial, swamp, delta, piedmont, beach, and dune deposits are common to many coastal areas of the island. The southern coastal plains, particularly between Ponce and Guayama, are composed primarily of a series of large alluvial fans consisting of poorly sorted sediments derived from the mountains to the north.

## SOILS

With the exception of Aridisols, soils of every classification are found in Puerto Rico (Beinroth, 1982). A generalized soils map of Puerto Rico (fig. 7) and the following discussion are based on Acevedo (1982), Beinroth (1971), Boccheciamp (1977, 1978), Carter (1965), Gierbolini (1975, 1979), and U.S. Soil Conservation Service (1992). Definitions of major soil orders are from Soil Survey Staff (1975) and U.S. Soil Conservation Service (1985). The reader is urged to consult these and other references for further information.


Figure 7. General soil map of Puerto Rico (after U.S. Soil Conservation Service, 1992).

# GENERAL SOIL MAP OF PUERTO RICO
# EXPLANATION

## HUMID COASTAL PLAINS

A: ULTISOLS, SPODOSOLS, AND ENTISOLS – Deep, moderately to highly permeable, gently sloping to sloping, sandy soils formed in coarse textured quartz sediments; on coastal plains and close to the limestone hills. Some soils have clayey subsurface horizons.

B: ULTISOLS AND OXISOLS – Deep, moderately permeable, undulating to sloping, clayey soils formed in fine textured sediments over hard limestone; on coastal plains and upper valleys.

C: MOLLISOLS, ALFISOLS, AND LIMESTONE OUTCROPS – Shallow to deep, moderately permeable, undulating to very steep, clayey and loamy soils formed in fine textured residuum derived from hard limestone; on uplands and coastal plains.

D: ENTISOLS AND HISTOSOLS – Deep, slowly to moderately permeable, nearly level, organic and clayey soils formed in organic materials; in low depressions and lagoons of the coastal plains.

E: MOLLISOLS, ENTISOLS, AND INCEPTISOLS – Deep, slowly to moderately permeable, nearly level, loamy to clayey soils formed in alluvium that consists of recent deposits of silt and clay and sediments washed from the volcanic and limestone hills; on flood plains of rivers.

F: ULTISOLS – Deep, slowly to moderately permeable, undulating to very steep, clayey, sandy and gravelly soils formed in residual material weathered from conglomerate that consists of cobblestones, gravel, and sand.

## SEMIARID COASTAL PLAINS

G: VERTISOLS – Deep, very slowly to slowly permeable, flat to moderately sloping, clays derived from volcanic and limestone residuum; on alluvial fans, valley floors, and coastal lowlands.

H: MOLLISOLS AND INCEPTISOLS – Deep, moderately to highly permeable, nearly level to strongly sloping sands and gravels formed in sediment derived from volcanic and limestone rock; on terraces and alluvial fans.

J: MOLLISOLS – Shallow to deep, slowly to moderately permeable, nearly level, clayey, sandy, and gravelly soils formed in recent fine-textured sediment of mixed origin that washed from volcanic and limestone hill; on river flood plains.

K: ULTISOLS – Moderately deep to deep, highly permeable, level to gently sloping, sands and sandy loams, some overlying a slowly permeable subsurface clay layer, formed on sandy Coastal Plain sediments.

L: MOLLISOLS – Moderately deep, very slowly to moderately permeable, steep and very steeply sloping, loamy and clayey soils formed in moderately fine textured residuum of soft limestone; on foot slopes, side slopes, and hilltops on the limestone uplands.

## HUMID UPLANDS

M: INCEPTISOLS – Shallow to moderately deep, moderately permeable, undulating to very steep, silty, loamy, and clayey soils formed in residual material weathered from volcanic rock; on volcanic uplands, side slopes and ridges.

N: ULTISOLS – Deep to moderately deep, moderately permeable, moderately steep to very steep, silty, loamy, and clayey soils formed in residual material weathered from volcanic rock and tuffaceous mudstone; in the humid mountainous areas on side slopes, narrow ridgetops of the uplands, strongly dissected uplands and volcanic uplands of the tropical rain forest.

O: ULTISOLS AND INCEPTISOLS – Shallow to deep, moderately to highly permeable, sloping to very steep, sandy, silty, and clayey soils formed in residuum derived from partly weathered plutonic rocks, mainly quartz diorite and granodiorite; on plutonic uplands.

P: OXISOLS – Deep to moderately deep, moderately to highly permeable, undulating to very steep, clayey soils formed in material weathered from serpentine rock; on mesa like ridgetops.

## SEMIARID UPLANDS

R: INCEPTISOLS AND ALFISOLS – Shallow to deep, moderately permeable, nearly level to very steep, clayey, silty, and some gravelly soils formed in sediment derived from volcanic and limestone rocks; on long and short side slopes, hilltops, ridgetops, terraces, and alluvial fans.

## HUMID UPLAND VALLEYS

S: INCEPTISOLS AND ALFISOLS – Deep, slowly to moderately slowly permeable, nearly level to sloping, clayey and sandy soils formed in sediment derived from volcanic rocks; on terraces, foot slopes, and alluvial fans of inner valleys.

T: ULTISOLS AND INCEPTISOLS – Deep, slowly permeable, gently sloping to steep, clay soils formed in fine textured material over plastic clay, gravel, and cobblestones; on uplands and coastal plains.

U: MOLLISOLS AND ALFISOLS – Deep to moderately deep, moderately permeable, rolling to very steep, clayey to loamy soils formed in moderately fine residuum weathered from soft limestone; on uplands.

Soils of the mountains are primarily Ultisols, generally moist, acidic soils with subsurface horizons of clay accumulation, and Inceptisols, generally moist soils that exhibit weakly developed horizons, and in which mineral matter has been altered or removed but not accumulated (fig. 7). These moderately permeable, silty and clayey soils are formed from weathered volcanic rocks and mudstones, generally on valley side slopes and ridges. Sandy soils with moderate to moderately high permeability have formed on the plutonic rocks underlying upland areas such as the Utuado and San Lorenzo batholiths, and other smaller plutonic bodies scattered throughout the mountainous part of the island (figs. 6A, 7). The Caguas and Cayey valleys are underlain by slowly to moderately slowly permeable, clayey and sandy alluvial and colluvial soils derived primarily from volcanic and plutonic rocks. These soils are classified as Inceptisols and Alfisols. Alfisols are generally moist soils that are medium to high in bases, have gray to brown surface horizons, and contain subsurface horizons of accumulated clay. The semiarid to subhumid southern foothills are covered by Inceptisols and Alfisols (fig. 7). These soils are moderately permeable, clayey, silty, and locally gravelly soils derived from weathered volcanic rocks and limestone. Oxisols consisting of moderately to highly permeable clayey soils formed in material weathered from serpentinite rock have developed on some ridgetops to the south and southeast of Mayagüez in western Puerto Rico (fig. 7).

Soils of the northern limestone region comprise Ultisols, Oxisols, Mollisols, and Alfisols. Oxisols are soils composed of mixtures of kaolin, hydrated oxides, and quartz, that are low in weatherable minerals, organic matter, and bases. The Mollisols in this area are soils with subsurface accumulations of calcium carbonate but no clay accumulations. In general the soils formed on limestone residuum are shallow to deep, moderately permeable, clays and clay loams. Soils of upland valleys in the northern limestone province consist of Ultisols, Alfisols, Mollisols, and Inceptisols with slow to moderate permeability and clayey to loamy textures, developed on alluvium, colluvium, and limestone. Soils of the southern limestone region are very slowly to moderately permeable loamy and clayey Mollisols with calcium carbonate horizons in the subsurface, formed in fine-textured residuum of soft limestone. Some of these soils are gravelly at the surface.

Soils of the humid coastal plains on the northern, eastern, and western coasts of the island consist of Entisols, Mollisols, Histosols, Ultisols, Spodosols, and Inceptisols (fig. 7). Entisols are poorly-developed soils containing no pedogenic horizons; the Entisols in this area are described as wet soils of floodplains and deltas. Spodosols are soils containing a subsurface horizon in which mixtures of organic matter, clay, and commonly, iron, have formed. Histosols are wet, organic rich soils (peats and mucks) formed in marsh and swamp environments. The texture of the northern coastal plain soils ranges from clayey to sandy and gravelly and they have permeability ranging from low to high. Soils with finer textures and lower permeability generally occur in alluvial valleys and in deltaic, tidal flat, lagoonal, and coastal marsh environments, whereas sandy or gravelly, permeable soils occur in coastal plain and beach environments. Soils of the semiarid to subhumid southern coastal plain consist of Mollisols, Inceptisols, and Ultisols (fig. 7). These soils are generally sandy and gravelly soils with moderate to high permeability developed on coastal plains and alluvial terraces, fans, and floodplains. Some of these soils, particularly the Ultisols, contain a clayey subsurface horizon that may impede gas and water flow through the soil column. Inland valleys such as the Lajas Valley and the northern Ponce area are underlain by Vertisols, deep, slowly permeable clay soils that develop distinct desiccation cracks when dry.

A generalized soil permeability map of Puerto Rico, based on the map units (fig. 7) and soil unit characteristics described above, indicates that most soils derived from volcanic rocks and limestone are moderately permeable (fig. 8). Soils derived from plutonic (granitic) rocks have moderate to high permeabilities, and coastal plain soils developed from sediments and sedimentary rocks have permeabilities ranging from low to high (fig. 8). Clayey alluvial valley bottom soils (fig. 7) generally have low permeability (fig. 8).

## RADIOACTIVITY

Puerto Rico was not included in the National Uranium Resource Evaluation (NURE) program so uranium occurrence and spectral aeroradiometric data are not available from this source. However, a total gamma-ray aeroradioactivity survey covering the entire main island of Puerto Rico (fig. 9) was conducted in 1961 as part of the Aerial Radiological Measurement Surveys (ARMS-I) program of the U.S. Atomic Energy Commission (MacKallor, 1965, 1966). Because the majority of naturally-produced gamma radiation comes from a combination of uranium, thorium, and potassium, data from such a survey is not as definitive as a spectral gamma-ray survey, in which the gamma rays from these three elements are differentiated, it is nonetheless extremely useful in identifying areas of unquestionably low radioactivity as well as indicating those areas of higher radioactivity that, if the source of the radioactivity is primarily uranium-series elements, may pose a potential radon hazard. In these areas, definitive identification of the contributing radioactive isotopes would require additional field or aerial spectral gamma-ray surveys and(or) sample collection and laboratory analysis.

The aerial radioactivity survey was conducted using a fixed-wing aircraft that flew across the island in east-west traverses spaced one mile (0.62 km) apart (MacKallor, 1966). Background radiation from cosmic sources was measured over water at the eastern and western ends of flightlines, averaged, and subtracted from the data collected over land areas. This background gamma radiation averaged approximately 400 counts per second (cps). The compensated terrestrial radioactivity data were then averaged along short flightline segments and contoured to produce the aeroradioactivity map (fig. 9).

The radioactivity of Puerto Rico is generally low. It ranges from approximately 50 to 800 cps (MacKallor, 1965, 1966). More than 75 percent of the island has radioactivity of 300 cps or less. The central part of the island generally has higher radioactivity than the coastal margins. Two areas of moderately high radioactivity (> 400 cps) appear to be associated with the Utuado batholith and with Oligocene limestones (Lares Limestone and Cibao Formation) in northwestern Puerto Rico (figs. 6A, 9). The Utuado pluton exhibits radioactivity between 300 and 600 cps in the central granodioritic part, and 200-300 cps in the marginal dioritic and gabbroic part. The higher radioactivity is most likely due to the higher percentage of potassium feldspar in the granodiorite (MacKallor, 1966) but may also indicate a slight increase in uranium and(or) thorium content as well. The northern and eastern parts of the San Lorenzo batholith have radioactivity in the 200-400 cps range (fig. 9). The southwestern part of the batholith has radioactivity in the 100-200 cps range, which is indistinguishable from the radioactivity of the Cretaceous volcanic rocks adjacent to the batholith. Other plutons appear to have radioactivity signatures that are indistinguishable from those of the surrounding rocks with the exception of a small pluton south of Bayamón, southwest of San Juan, which exhibits radioactivity in the 200-300 cps range (fig. 9). One small area of 650 cps near the center of Puerto Rico lies along a major fault (MacKallor, 1966). Several other areas of elevated radioactivity (>400 cps) in the central Part of Puerto Rico also appear to be associated with faults or faulted geologic contacts.

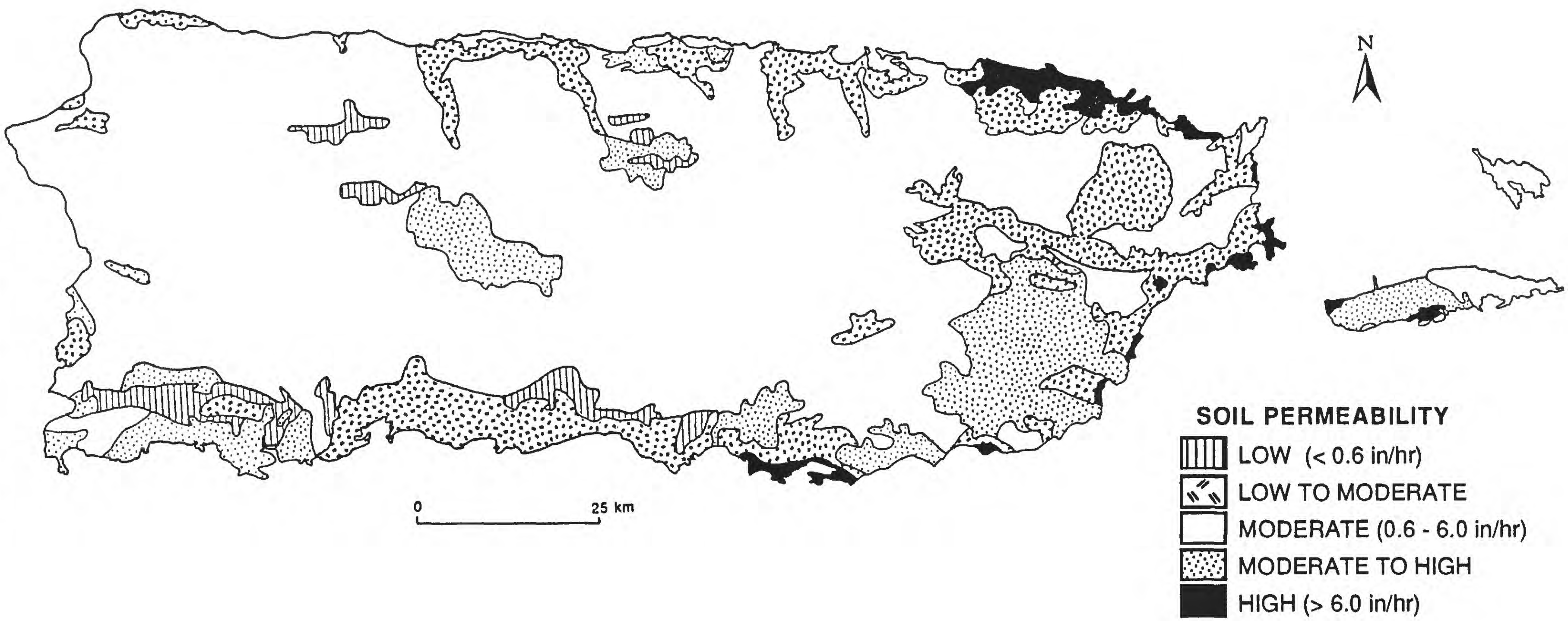



Figure 8. Generalized map of soil permeability in Puerto Rico. "Low to moderate" and "moderate to high" indicate that the map unit contains soils with permeabilities in both ranges. Map units from U.S. Soil Conservation Service (1992); data from Acevedo (1982), Beinroth (1971), Boccheciamp (1977, 1978), Carter (1965), and Gierbolini (1975, 1979).

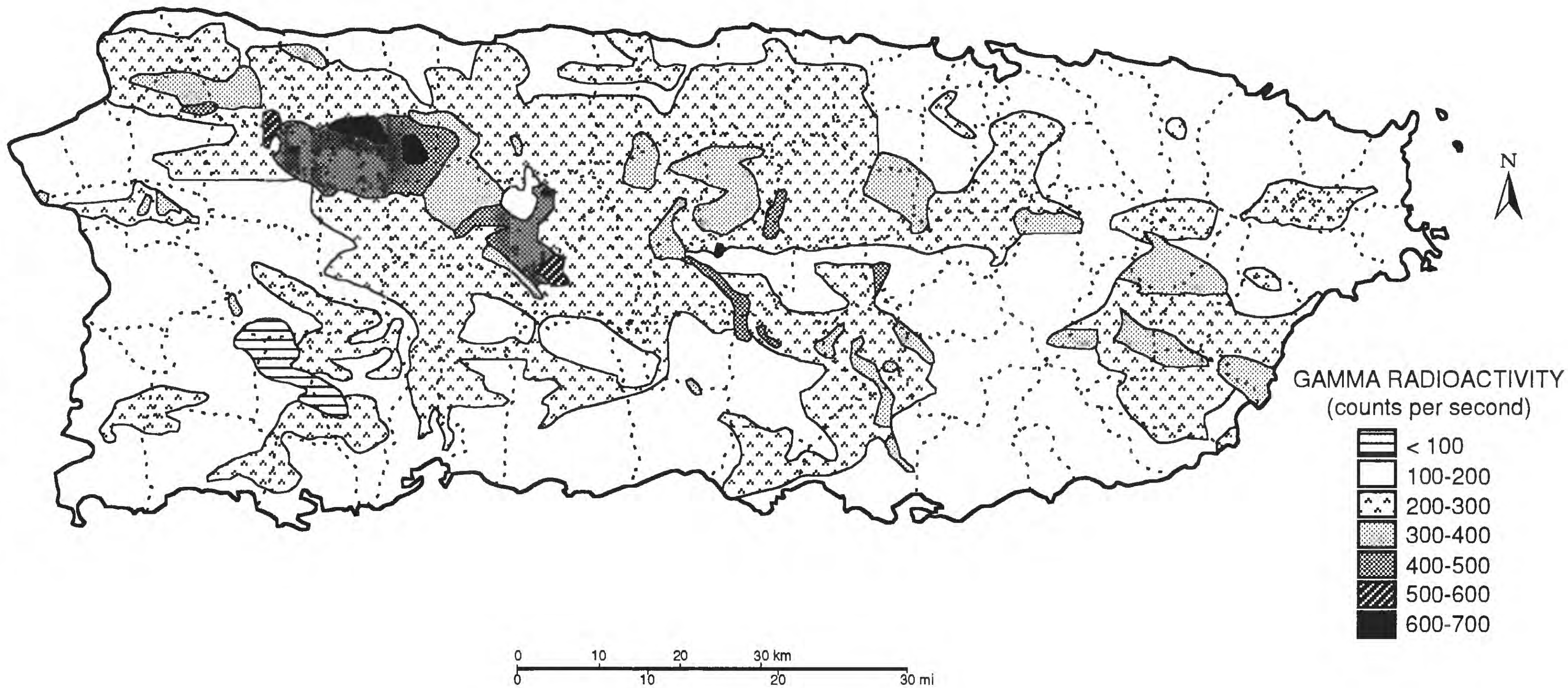



Figure 9. Generalized total-count aerial radioactivity map of Puerto Rico (after MacKallor, 1965).

Some limestone areas in northwestern Puerto Rico exhibit moderately elevated radioactivity signatures (fig. 9). As previously noted, an area underlain by the Lares Limestone and Cibao Formation exhibit radioactivity in the 200 to 700 cps range. A small area of Cibao Formation approximately 5 km northeast of San Sebastián exhibits radioactivity as high as 800 cps. Miocene-age limestones of the Aguada Limestone, Camuy Formation, and Aymamón Limestone in northern Puerto Rico generally exhibit radioactivity in the 100-300 cps range, increasing to 200-400 cps in the northwestern part of the island. Limestones in southwestern Puerto Rico generally have radioactivity of 100-200 cps. MacKallor (1966) notes that most limestones surveyed in other ARMS surveys in the United States have radioactivity less than 500 cps.

Seventeen samples of soils formed on limestones and coastal plain deposits were collected as part of a background radioactivity study prior to construction of a nuclear power generation plant in Barrio Islote, Arecibo (Block and others, 1980). The soil samples were collected from the surface 15 cm of the soil layer and analyzed in a gamma spectrometer. Radium-226 analyses of the soil samples yielded concentrations ranging from 0.023 to 0.112 pCi/g, with an average of $0.069 \pm 0.024$ pCi/g (Block and others, 1980). For comparison, the average Ra-226 concentration of 327 surface soil samples from locations across the United States was $1.1 \pm 0.48$ pCi/g (Myrick and others, 1983). An average radium concentration in limestones is approximately 0.3-0.4 pCi/g (Eisenbud, 1987).

One area of exceptionally low radioactivity is located in the central southwestern part of the island (fig. 9). This area generally corresponds to part of the outcrop area of Cretaceous serpentinite (fig. 6A). A narrower outcrop band of the serpentinite extends northwestward almost to Mayagüez, but this part of the outcrop appears to have radioactivity in the 100-200 cps range, similar to that of the surrounding volcanic and sedimentary rocks (fig. 9). MacKallor (1966) suggests that alluvium derived from surrounding rocks may be covering or partially covering the serpentinite in this area, causing the higher radioactivity signature.

## INDOOR RADON DATA

The Puerto Rico Department of Health, in cooperation with the U.S. Environmental Protection Agency, conducted screening indoor radon testing of buildings in Puerto Rico during 1993-1995. Data from 610 of these measurements, grouped by city, are presented in Table 1. Assuming that the data from each city is representative of the municipio in which it is located, these same data are presented by county in figure 10.

Overall, the Commonwealth of Puerto Rico exhibits generally low indoor radon levels. Of the 610 indoor radon measurements available at the time of this writing, the arithmetic mean screening indoor radon concentration was 0.5 pCi/L, with 1.8 percent of the measurements exceeding 4.0 pCi/L. The highest value recorded in the data set was 38.3 pCi/L in Morovis. Higher than average indoor radon levels occur primarily in the areas of northern and northwestern Puerto Rico that are underlain by residual limestone soils.

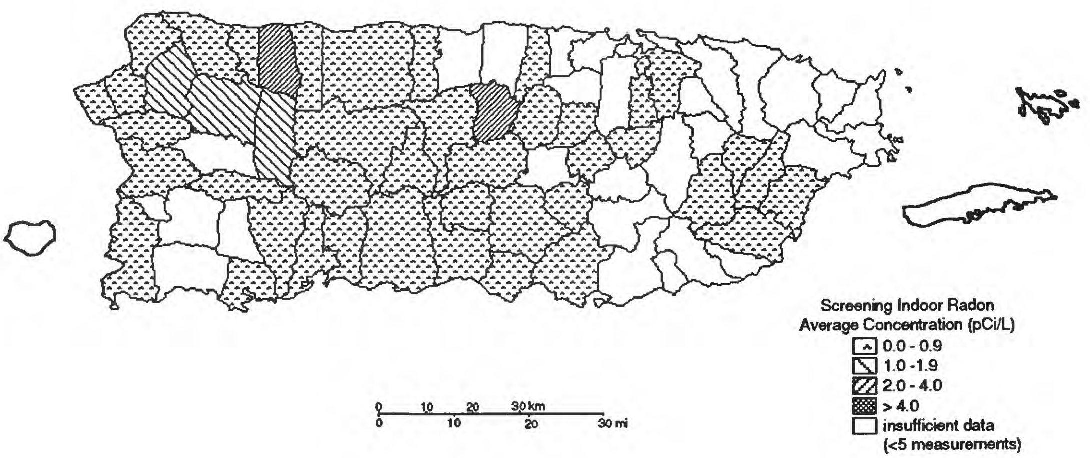
A survey of radon concentrations of offices, housing units, schools, and other buildings on federal military reservations in Puerto Rico was conducted by the U.S. Department of Defense. A total of 681 readings were reported from one-year alpha-track detector measurements made between 1989 and 1992. Indoor radon levels ranged from 0.0 to 1.9 pCi/L, with an average of $0.2 \pm 0.2$ pCi/L. The majority of these reservations and associated buildings are situated on coastal plains, so these low indoor radon levels are not unexpected.

**TABLE 1.** Screening indoor radon data from the State/EPA Residential Radon Survey of Puerto Rico conducted during 1993-1995. Data represent 2-7 day charcoal canister measurements.

| CITY | NO. OF MEAS. | MEAN | GEOM MEAN | MEDIAN | STD. DEV. | MAXIMUM | %>4 pCi/L | %>20 pCi/L |
|---|---|---|---|---|---|---|---|---|
| Adjuntas | 12 | 0.3 | 0.3 | 0.2 | 0.1 | 0.4 | 0 | 0 |
| Aguada | 19 | 0.3 | 0.1 | 0.1 | 0.8 | 3.6 | 0 | 0 |
| Aguadilla | 19 | 0.4 | 0.5 | 0.2 | 0.5 | 2.0 | 0 | 0 |
| Aguas Buenas | 14 | 0.2 | 0.3 | 0.0 | 0.4 | 1.1 | 0 | 0 |
| Aibonito | 6 | 0.2 | 0.1 | 0.1 | 0.3 | 0.7 | 0 | 0 |
| Anasco | 25 | 0.1 | 0.1 | 0.1 | 0.1 | 0.3 | 0 | 0 |
| Arecibo | 13 | 0.3 | 0.3 | 0.3 | 0.2 | 0.9 | 0 | 0 |
| Barceloneta | 21 | 0.5 | 0.3 | 0.3 | 0.5 | 1.6 | 0 | 0 |
| Bayamon | 1 | 0.6 | 0.6 | 0.6 |  | 0.6 | 0 | 0 |
| Cabo Rojo | 8 | 0.1 | 0.2 | 0.0 | 0.1 | 0.2 | 0 | 0 |
| Caguas | 3 | 0.2 | 0.2 | 0.1 | 0.2 | 0.4 | 0 | 0 |
| Camuy | 26 | 2.1 | 0.7 | 0.7 | 3.5 | 15.4 | 8 | 0 |
| Carolina | 2 | 0.1 | 0.1 | 0.1 | 0.0 | 0.1 | 0 | 0 |
| Ciales | 10 | 0.6 | 0.2 | 0.1 | 1.7 | 5.4 | 10 | 0 |
| Coamo | 12 | 0.1 | 0.1 | 0.0 | 0.3 | 1.0 | 0 | 0 |
| Comerio | 12 | 0.3 | 0.3 | 0.2 | 0.2 | 0.6 | 0 | 0 |
| Corozal | 13 | 0.3 | 0.4 | 0.2 | 0.4 | 1.3 | 0 | 0 |
| Guanica | 12 | 0.1 | 0.2 | 0.0 | 0.1 | 0.4 | 0 | 0 |
| Guayanilla | 8 | 0.3 | 0.3 | 0.3 | 0.1 | 0.4 | 0 | 0 |
| Guaynabo | 7 | 0.0 | 0.1 | 0.0 | 0.1 | 0.1 | 0 | 0 |
| Hatillo | 17 | 0.9 | 0.5 | 0.5 | 1.3 | 5.0 | 6 | 0 |
| Humacao | 14 | 0.0 | 0.1 | 0.0 | 0.0 | 0.1 | 0 | 0 |
| Isabela | 20 | 0.3 | 0.2 | 0.1 | 0.3 | 1.1 | 0 | 0 |
| Jayuya | 8 | 0.1 | 0.1 | 0.1 | 0.1 | 0.2 | 0 | 0 |
| Juana Diaz | 13 | 0.4 | 0.4 | 0.4 | 0.1 | 0.8 | 0 | 0 |
| Juncos | 5 | 0.0 | 0.2 | 0.0 | 0.1 | 0.2 | 0 | 0 |
| Lajas | 3 | 0.2 | 0.2 | 0.1 | 0.2 | 0.5 | 0 | 0 |
| Lares | 17 | 1.8 | 0.7 | 0.4 | 2.9 | 9.2 | 18 | 0 |
| Las Piedras | 7 | 0.1 | 0.1 | 0.0 | 0.1 | 0.2 | 0 | 0 |
| Maricao | 8 | 0.3 | 0.3 | 0.3 | 0.1 | 0.5 | 0 | 0 |
| Maunabo | 1 | 0.3 | 0.3 | 0.3 |  | 0.3 | 0 | 0 |
| Mayaguez | 9 | 0.3 | 0.2 | 0.2 | 0.4 | 1.4 | 0 | 0 |
| Moca | 23 | 1.1 | 0.9 | 1.0 | 0.8 | 3.7 | 0 | 0 |
| Morovis | 21 | 2.5 | 0.6 | 0.6 | 8.2 | 38.3 | 5 | 5 |
| Naranjito | 9 | 0.1 | 0.2 | 0.0 | 0.3 | 0.8 | 0 | 0 |
| Orocovis | 22 | 0.2 | 0.1 | 0.1 | 0.3 | 1.3 | 0 | 0 |
| Penuelas | 8 | 0.0 | 0.1 | 0.0 | 0.1 | 0.2 | 0 | 0 |
| Ponce | 11 | 0.1 | 0.1 | 0.1 | 0.1 | 0.3 | 0 | 0 |
| Puerta de Tierra | 2 | 0.6 | 0.5 | 0.6 | 0.1 | 0.6 | 0 | 0 |
| Quebradillas | 16 | 0.5 | 0.3 | 0.4 | 0.5 | 2.1 | 0 | 0 |

TABLE 1 (continued). Screening indoor radon data for Puerto Rico.

| CITY | NO. OF MEAS. | MEAN | GEOM MEAN | MEDIAN | STD. DEV. | MAXIMUM | %>4 pCi/L | %>20 pCi/L |
|---|---|---|---|---|---|---|---|---|
| Rincon | 11 | 0.1 | 0.1 | 0.1 | 0.2 | 0.7 | 0 | 0 |
| Rio Piedras | 9 | 0.6 | 0.4 | 0.2 | 0.8 | 2.3 | 0 | 0 |
| Salinas | 10 | 0.4 | 0.3 | 0.1 | 0.6 | 1.7 | 0 | 0 |
| San German | 2 | 0.2 | 0.4 | 0.2 | 0.3 | 0.4 | 0 | 0 |
| San Lorenzo | 21 | 0.2 | 0.3 | 0.2 | 0.1 | 0.5 | 0 | 0 |
| San Sebastian | 20 | 1.5 | 0.7 | 0.8 | 2.0 | 6.9 | 15 | 0 |
| Santa Isabel | 9 | 0.0 | 0.0 | 0.1 | 0.0 | 0.1 | 0 | 0 |
| Santurce | 1 | 0.2 | 0.2 | 0.2 | | 0.2 | 0 | 0 |
| Utuado | 11 | 0.5 | 0.4 | 0.3 | 0.5 | 1.7 | 0 | 0 |
| Vega Alta | 6 | 0.4 | 0.4 | 0.4 | 0.3 | 0.7 | 0 | 0 |
| Vieques | 2 | 1.1 | 1.0 | 1.1 | 0.6 | 1.5 | 0 | 0 |
| Villalba | 12 | 0.2 | 0.1 | 0.1 | 0.1 | 0.4 | 0 | 0 |
| Yabucoa | 5 | 0.1 | 0.2 | 0.1 | 0.1 | 0.2 | 0 | 0 |
| Yauco | 14 | 0.1 | 0.1 | 0.1 | 0.1 | 0.4 | 0 | 0 |



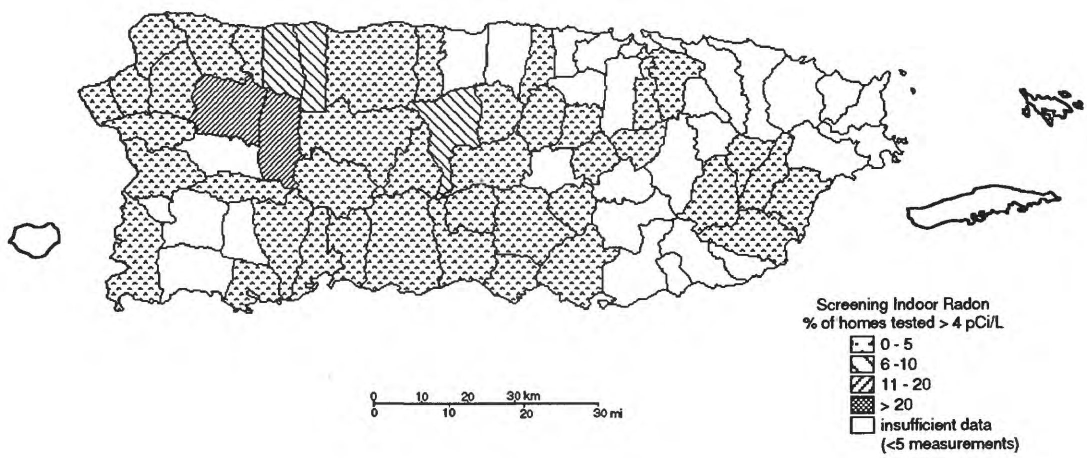




Figure 10. Screening indoor radon data from the State/EPA Residential Radon Survey of Puerto Rico, 1993-95, for counties with 5 or more measurements. Data are from 2-7 day charcoal canister tests. The number of samples in each county (see Table 1) may not be sufficient to statistically characterize the radon levels of the counties, but they do suggest general trends. Unequal category intervals were chosen to provide reference to decision and action levels.

GEOLOGIC RADON POTENTIAL

Several areas of Puerto Rico have the geologic potential to generate indoor radon levels exceeding 4 pCi/L, perhaps locally reaching very high levels (>50 pCi/L?), if house construction and ventilation allow the soil-gas radon to enter and concentrate within structures. In some areas, rocks and soils with sufficient radium content and permeability to generate and transport substantial amounts of radon may not cause indoor radon problems, or may cause seasonal indoor radon problems due to high soil moisture conditions that inhibit radon transport, or to the tendency for homeowners to use natural ventilation (i.e., open windows) for cooling.

Some rocks in the Upland province of granitic composition are likely to have elevated uranium and(or) radium concentrations (greater than 2.5 ppm uranium or approximately 1 pCi/g radium) and thus may provide a source for elevated indoor radon concentrations (>4 pCi/L). Those rocks with more felsic compositions (i.e., granodiorite or quartz monzonite) are more likely to contain elevated uranium contents than rocks of more mafic composition (such as diorite or gabbro). The Utuado batholith and a smaller pluton south of Bayamón exhibit significantly elevated gamma radioactivity signatures and are likely to generate at least scattered elevated indoor radon occurrences, but may possibly cause consistently moderately elevated to rarely extremely elevated indoor radon levels. Other plutonic rocks, including parts of the San Lorenzo batholith and other small plutons that may not be mapped separately on figures 6A and 6B, may also provide a local source for elevated indoor radon levels if they are of granodiorite to quartz monzonite composition and have sufficient permeability to allow soil-gas transport. Areas underlain by these rocks are considered to have generally moderate to locally high geologic radon potential.

Valley-fill sediments composed of residuum, alluvium, or colluvium eroded from granitic rocks may also be a source of locally elevated indoor radon levels. One example of this situation is the area including and surrounding the town of Utuado. Enhanced permeability and localized mineralization along fractures, faults, and shears may also cause locally elevated indoor radon levels. Several areas of elevated gamma radioactivity were correlated with fault and shear zones by MacKallor (1966), particularly in central Puerto Rico. Most of the volcanic rocks, and the plutonic rocks of dominantly mafic composition in the Uplands province are not likely to generate significant radon concentrations in soils or buildings, and are considered to have generally low geologic radon potential, although some locally elevated indoor radon levels may be found in these areas if the soil permeability is sufficient and the building construction characteristics favor radon entry and accumulation. The area of serpentinite in southwestern Puerto Rico (fig. 6A, 6B) has extremely low radioactivity and probably has very low geologic radon potential.

Some areas underlain by limestone are likely to be sources of locally elevated indoor radon levels. In particular, those areas with extensive karst, which provides increased permeability and pathways for soil gas flow, and limestone areas on which residual clay soils have developed, are likely to cause locally elevated indoor radon levels. Areas underlain by the Lares Limestone and Cibao Formation exhibit radioactivity in the 200 to 700 cps range in northwestern Puerto Rico, and the Aguada Limestone, Camuy Formation, and Aymamón Limestone generally exhibit radioactivity in the 100-300 cps range in northern Puerto Rico, increasing to 200-400 cps in the northwestern part of the island. The increased radioactivity of the limestones is most likely due to concentration of radionuclides in the iron- and clay-rich residuum that remains when the calcium carbonate matrix of the limestone has been dissolved away (Schultz and others, 1992), a process common to many limestone areas. Monroe (1980b) notes that parts of the Cibao Formation contain glauconite, an iron silicate that commonly contains elevated uranium concentrations (Gundersen and Schumann, 1989). Areas underlain by karst limestone, residual soils developed on limestone, and glauconitic sediments are considered to have generally moderate to locally high geologic radon potential.

The blanket sands that cover some limestone areas in northwestern Puerto Rico may serve to reduce radon potential if their thickness is such that it would prevent radon from migrating upward from the underlying limestones before decaying. Blanket sand deposits thicker than about 15 m are likely to prevent radon generated in underlying layers from reaching the surface. However, thinner sand deposits would likely have little effect on radon potential because radon generated in the underlying limestones would likely be able to migrate to the surface during its 3.8-day half life. Blanket deposits containing significant amounts of clay generally have lower permeability than deposits composed dominantly of quartz sand, and would thus further retard radon gas transport. However, such clays may also constitute a near-surface radon source in themselves, which may negate any reduced gas transport effects. Limestone areas in southern Puerto Rico generally exhibit lower radioactivity and are not as extensively karstified as in the northern part of the island. These southern limestone areas are not as likely to generate elevated indoor radon levels, although local occurrences of homes with indoor radon levels exceeding 4 pCi/L are possible in these areas, especially if residual soils have developed on the limestone deposits.

The coastal plains and Lajas Valley are underlain by clastic sedimentary rocks of marine and terrestrial origin. In general, these deposits do not contain notable amounts of uranium or radium and therefore do not constitute significant radon sources. A rare exception to this may be found in coastal valleys underlain by alluvium derived from granitic rocks of the uplands. The generally low permeability and(or) high water tables of most coastal deposits serves to retard the migration of whatever radon may be generated in the soils and surficial deposits. These areas have generally low geologic radon potential.

## SUMMARY

For purposes of assessing radon potential, Puerto Rico was divided into eight major areas (fig. 11) and scored with a Radon Index (RI), a measure of radon potential based on geologic, soil, radioactivity, and housing construction factors, 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 predictions (Table 2). For further details on the ranking schemes and the factors used in the predictions, refer to the introduction chapter of this report. Because the radioactivity data are from total-count gamma radioactivity data rather than from equivalent uranium data, as were used in the continental United States, a different scheme was used to assign points for the radioactivity factor, as follows: if the average radioactivity in the area is less than 300 cps, 1 point was awarded; 300-500 cps, 2 points; greater than 500 cps, 3 points. The quality and availability of data for the factors used in evaluating radon potential was considered to be relatively uniform at the scale of this investigation, so all areas have the same Confidence Index score of 9 (moderate confidence; see table 2).

The Northwestern Limestone area (fig. 11) is delineated as the area underlain primarily by Lares Limestone and Cibao Formation with an elevated gamma radioactivity signature. Gamma radioactivity measured in this area averages 200 to 500 cps but locally is as high as 800 cps (MacKallor, 1966). Residual clay soils and limestone solution (karst) features may generate and(or) transport locally high concentrations of radon in soils and surficial deposits. This area is ranked moderate/variable in geologic radon potential, with an RI score of 10. Locally very high indoor radon levels may be possible in this area if building construction and ventilation conditions are favorable for radon entry and accumulation.

The Northern Limestone area consists of those areas in northern Puerto Rico that are underlain primarily by Oligocene- and Miocene-age limestone and which are not included in the Northwestern Limestone area. The characteristics of this area are similar to those of the Northwestern Limestone area except that the gamma radioactivity is lower, averaging 200-300 cps. This area is ranked moderate/variable in geologic radon potential, with an RI score of 9.

The Utuado Pluton, located in west-central Puerto Rico, is composed of granodiorite and other plutonic igneous rocks that weather to form sandy, permeable soils. The Utuado pluton has a moderately high radioactivity signature. Areas underlain by rocks with more felsic compositions (such as granodiorite and quartz monzonite) are more likely to generate elevated indoor radon levels than areas underlain by rocks with more mafic compositions (such as diorite and gabbro). Overall, this area is ranked moderate/variable (RI=10). Locally very high indoor radon levels may be possible in this area if building construction and ventilation conditions are favorable for radon entry and accumulation.

The San Lorenzo Pluton and other plutonic rocks scattered across central Puerto Rico and on Isla de Vieques and Isla de Culebra have generally lower radioactivity than the Utuado pluton (fig. 9) and vary in composition from granodiorite to amphibolite and gabbro. As a group, these plutons are ranked moderate/variable in geologic radon potential (RI=9). Again, areas underlain by rocks with more felsic compositions are more likely to generate elevated indoor radon levels than areas underlain by rocks with more mafic compositions.

The Southern Limestone area consists of those areas underlain by the Ponce Limestone. Because of the drier climate in this area compared to northern Puerto Rico, development of residual soils and solution features is not as intense as in the north. The Southern Limestone area has a low gamma radioactivity signature and generally low soil permeability. The Southern Limestone area is ranked low in geologic radon potential (RI=6). Areas with notable development of residual soils and(or) karst may generate locally elevated indoor radon levels if building construction and ventilation conditions are favorable for radon entry and accumulation.

The part of the Uplands area underlain by volcanic and sedimentary rocks covers most of central Puerto Rico. The geology, topography, soils, and to some degree, climate, are variable across this area. In general, however, the composition of the bedrock is such that few radon precursors are present, as indicated by the generally low radioactivity, and the soils have generally moderate permeability. Overall, this area is ranked low in geologic radon potential, with an RI score of 7. Special note must be made of fault, fracture, and shear zones in this area, which may contain zones of radionuclide mineralization and are areas of enhanced permeability. MacKallor (1966) noted correlations between elevated radioactivity and some fault or fracture zones, particularly in central Puerto Rico. Fault, fracture, and shear zones should be considered to have locally moderate to high geologic radon potential.

The area underlain by serpentinite in southwestern Puerto Rico (fig. 11) has extremely low radioactivity. Serpentinite does not generally contain significant amounts of uranium-series nuclides and thus is not expected to generate elevated radon. Thus this area is ranked low in geologic radon potential (RI=6) but fault and shear zones, particularly along the margins of the serpentinite body, could possibly be localized sources of elevated radon.

Coastal plains and valleys along the perimeter of the island and on outlying islands are composed of continental and marine sediments that are generally poor sources for radon. In many areas, low permeability, poor drainage, or high water tables impede soil-gas transport so that any radon that may be generated is not available for transport and entry into buildings. The coastal areas have low gamma radioactivity. Although there may be rare instances in which Coastal Plain alluvium derived from Upland plutonic rocks may generate locally elevated radon concentrations, the majority of coastal areas may be considered to have very low (RI=5) geologic radon potential.

This is a generalized assessment of the geologic radon potential of Puerto Rico 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 than 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 radon program office or EPA regional office. More detailed information on local geology may be obtained from the Puerto Rico Geological Survey. Addresses and phone numbers for these agencies are listed in chapter 1 of this booklet.

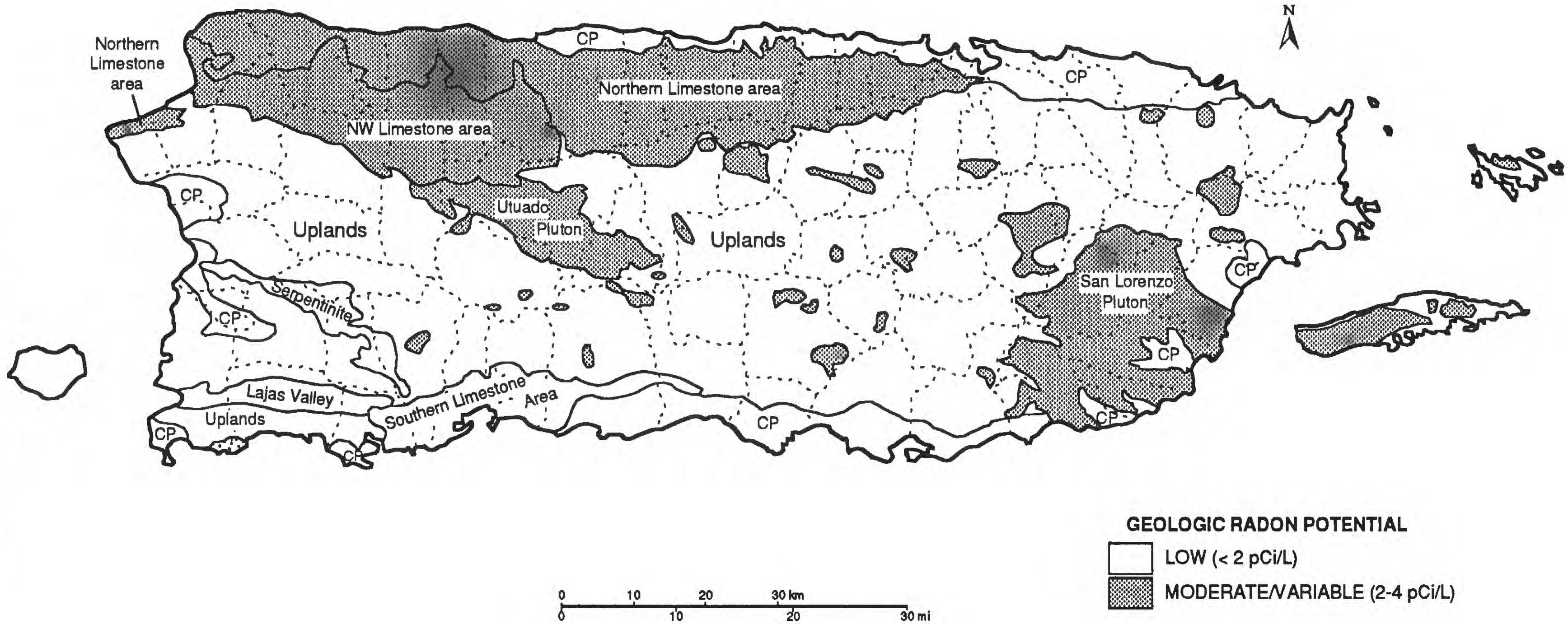



Figure 11. Geologic radon potential areas of Puerto Rico. All unlabeled gray-shaded areas are areas of plutonic rocks. "CP" denotes coastal plain areas. Distances between the main island and outlying islands have been shortened for ease of presentation. Refer to Table 2 for geologic radon potential scores of areas.

**TABLE 2.** Radon Index (RI) and Confidence Index (CI) scores for geologic radon potential areas of Puerto Rico. Refer to figure 11 for locations of areas.

| | Northwestern Limestone area | | Northern Limestone area | | Utuado Pluton | | San Lorenzo and other plutons | |
|---|---|---|---|---|---|---|---|---|
| FACTOR | RI | CI | RI | CI | RI | CI | RI | CI |
| INDOOR RADON | 2 | 2 | 2 | 2 | 1 | 2 | 1 | 2 |
| RADIOACTIVITY | 2 | 1 | 1 | 1 | 2 | 1 | 2 | 1 |
| GEOLOGY | 3 | 3 | 3 | 3 | 3 | 3 | 2 | 3 |
| SOIL PERM. | 2 | 3 | 2 | 3 | 3 | 3 | 3 | 3 |
| ARCHITECTURE | 1 | -- | 1 | -- | 1 | -- | 1 | -- |
| GFE POINTS | 0 | -- | 0 | -- | 0 | -- | 0 | -- |
| TOTAL | 10 | 9 | 9 | 9 | 10 | 10 | 9 | 9 |
| RANKING | MOD | MOD | MOD | MOD | MOD | HIGH | MOD | MOD |

| | Southern Limestone area | | Uplands volcanic & sedimentary rocks | | Serpentinite | | Coastal plains/valleys | |
|---|---|---|---|---|---|---|---|---|
| FACTOR | RI | CI | RI | CI | RI | CI | RI | CI |
| INDOOR RADON | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 2 |
| RADIOACTIVITY | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| GEOLOGY | 2 | 3 | 2 | 3 | 1 | 3 | 1 | 3 |
| SOIL PERM. | 1 | 3 | 2 | 3 | 2 | 3 | 1 | 3 |
| ARCHITECTURE | 1 | -- | 1 | -- | 1 | -- | 1 | -- |
| GFE POINTS | 0 | -- | 0 | -- | 0 | -- | 0 | -- |
| TOTAL | 6 | 9 | 7 | 9 | 6 | 9 | 5 | 9 |
| RANKING | LOW | MOD | LOW | MOD | LOW | MOD | LOW | MOD |

RADON INDEX SCORING:

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

CONFIDENCE INDEX SCORING:

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

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