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

GEOLOGIC RADON POTENTIAL OF EPA REGION 1

Connecticut Maine Massachusetts
New Hampshire Rhode Island Vermont

OPEN-FILE REPORT 93-292-A

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

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BACKGROUND

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

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

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

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

RADON GENERATION AND TRANSPORT IN SOILS

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

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

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

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

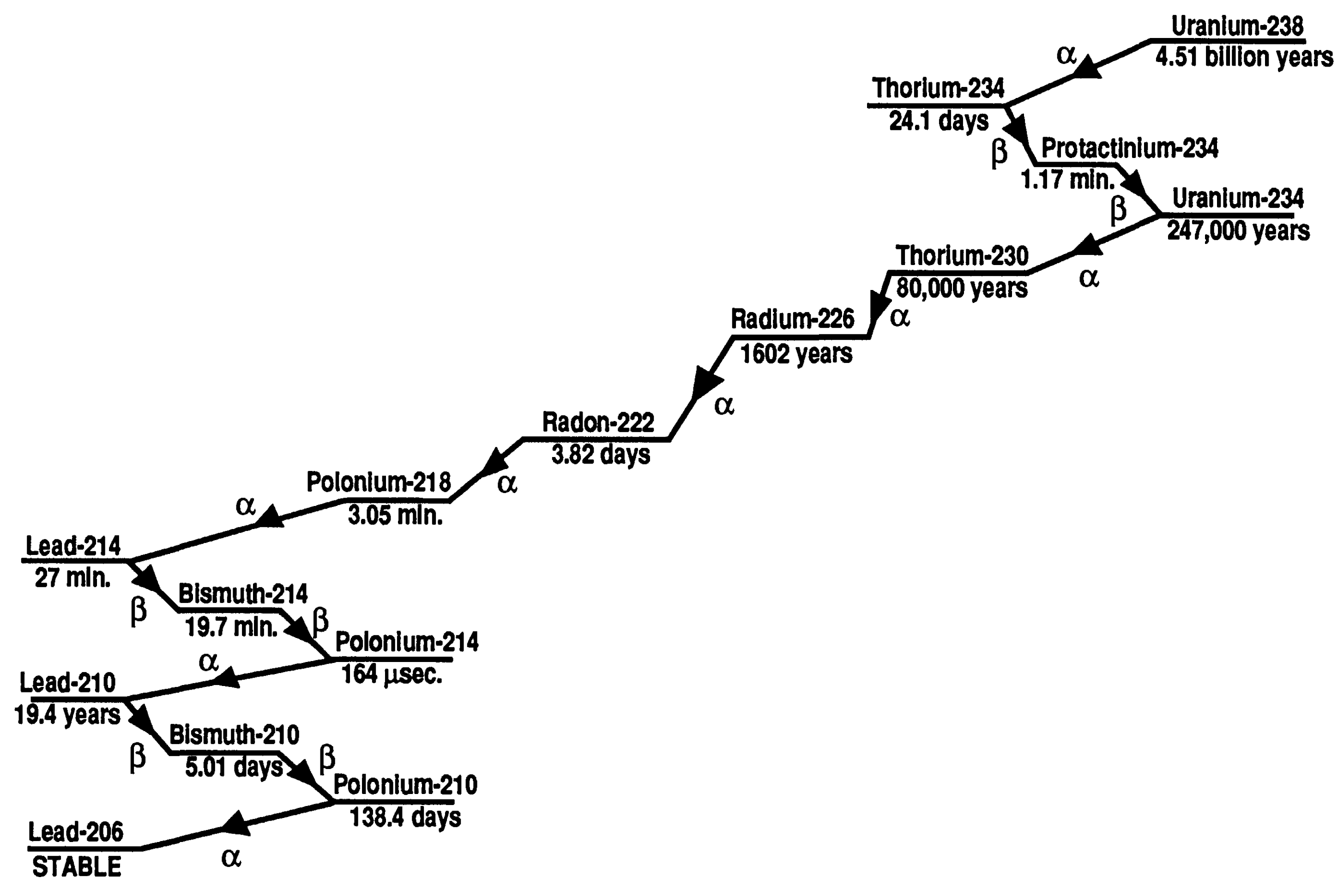

Figure 1. The uranium-238 decay series, showing the half-lives of elements and their modes of decay (after Wanty and Schoen, 1991). α denotes alpha decay, β denotes beta decay.

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

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

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

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

RADON ENTRY INTO BUILDINGS

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

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

METHODS AND SOURCES OF DATA

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

GEOLOGIC DATA

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

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

NURE AERIAL RADIOMETRIC DATA

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

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

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

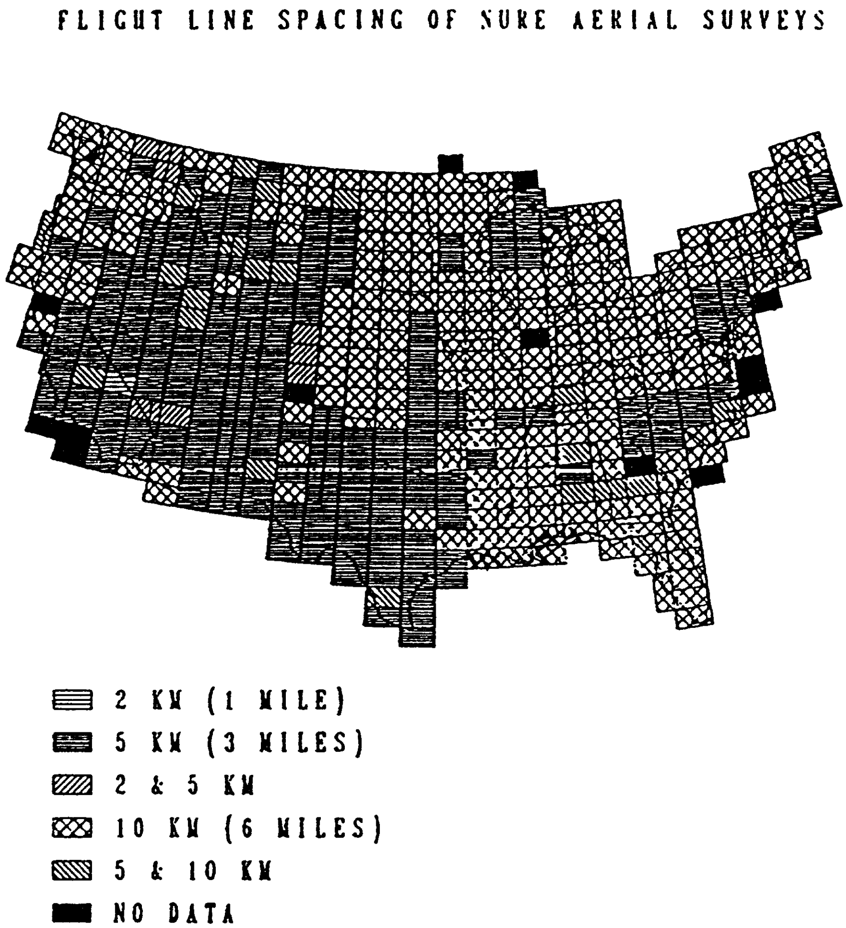

Figure 2. Nominal flightline spacings for NURE aerial gamma-ray surveys covering the contiguous United States (from Duval and others, 1990). Rectangles represent 1°x2° quadrangles.

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

SOIL SURVEY DATA

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

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

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

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

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

INDOOR RADON DATA

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

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

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

RADON INDEX AND CONFIDENCE INDEX

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

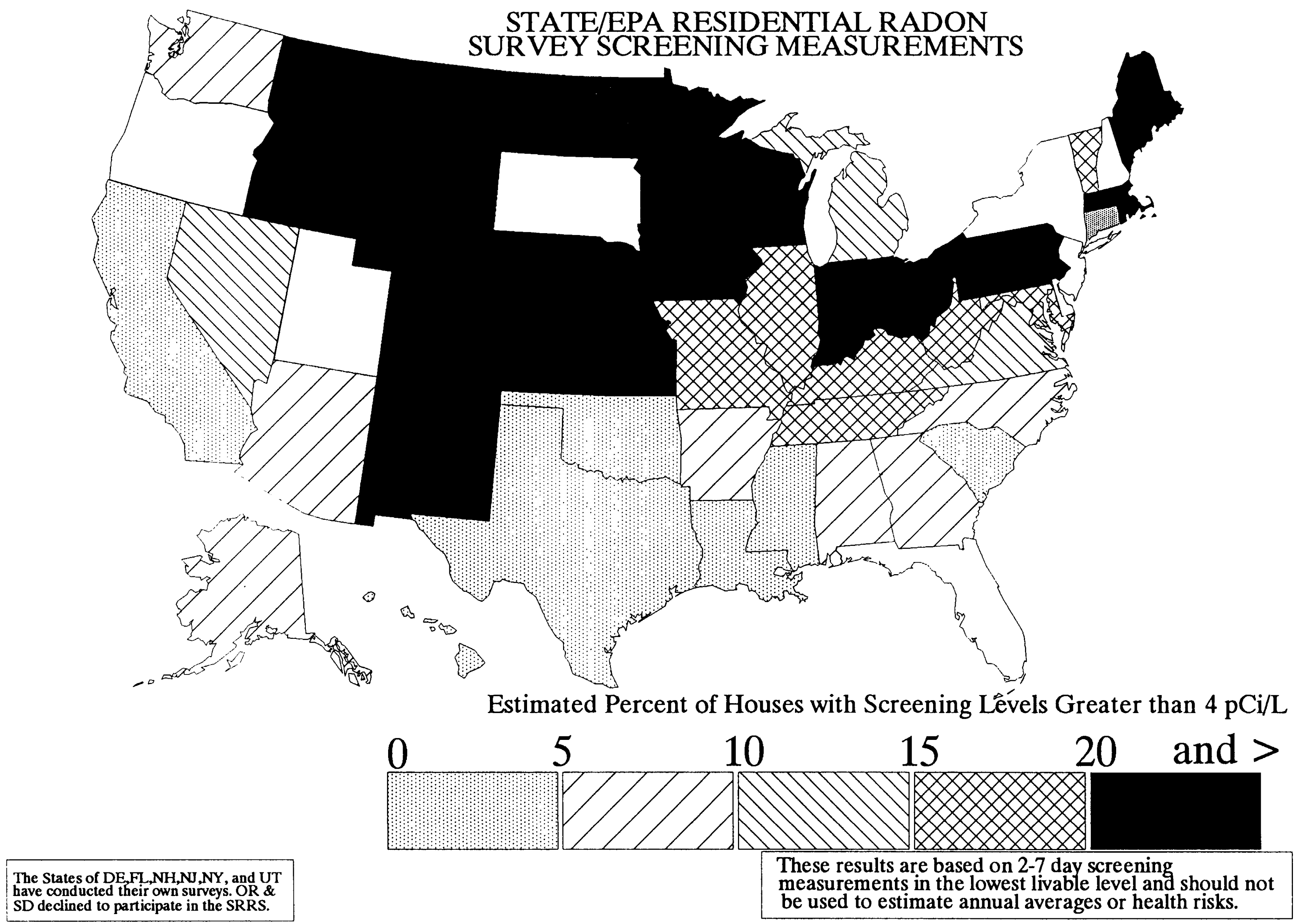

Figure 3. Percent of homes tested in the State/EPA Residential Radon Survey with screening indoor radon levels exceeding 4 pCi/L.

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): Eon or Eonothem	Era or Erathem	Period, System	Subperiod, Subsystem	Epoch	Series	Age estimates of boundaries in mega-annum (Ma)[1]
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 (P)	Late	Upper	
				Middle	Middle	
				Early	Lower	~330
			Mississippian (M)	Late	Upper	
				Early	Lower	360 (360–365)
		Devonian (D)		Late	Upper	
				Middle	Middle	
				Early	Lower	410 (405–415)
		Silurian (S)		Late	Upper	
				Middle	Middle	
				Early	Lower	435 (435–440)
		Ordovician (O)		Late	Upper	
				Middle	Middle	
				Early	Lower	500 (495–510)
		Cambrian (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 (pЄ), a time term without specific rank.

[4] Informal time term without specific rank.

APPENDIX B
GLOSSARY OF TERMS

Units of measure

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

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

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

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

Geologic terms and terms related to the study of radon

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

eolian Pertaining to sediments deposited by the wind.

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

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

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

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

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

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

formation A mappable body of rock having similar characteristics.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

placer deposit See heavy minerals

residual Formed by weathering of a material in place.

residuum Deposit of residual material.

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

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

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

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

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

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

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

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

shrink-swell clay See clay mineral.

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

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

slope An inclined part of the earth's surface.

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

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

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

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

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

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

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

uraniferous Containing uranium, usually more than 2 ppm.

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

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

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

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

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

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EPA Region 1 includes the states of Connecticut, Maine, Massachusetts, New Hampshire, Rhode Island, and Vermont. For each state, geologic radon potential areas were delineated and ranked on the basis of geology, soil, housing construction, indoor radon, and other factors. Areas in which the *average screening indoor radon level of all homes within the area* is estimated to be greater than 4 pCi/L were ranked high. Areas in which the average screening indoor radon level of all homes within the area is estimated to be between 2 and 4 pCi/L were ranked moderate/variable, and areas in which the average screening indoor radon level of all homes within the area is estimated to be less than 2 pCi/L were ranked low. Information on the data used and on the radon potential ranking scheme is given in the introduction to this volume. More detailed information on the geology and radon potential of each state in Region 1 is given in the individual state chapters. The individual chapters describing the geology and radon potential of the states in Region 1, though much more detailed than this summary, still are generalized assessments and there is no substitute for having a home tested. Within any radon potential area homes with indoor radon levels both above and below the predicted average likely will be found.

Figure 1 shows a generalized map of the physiographic/geologic provinces in Region 1. The following summary of radon potential in Region 1 is based on these provinces. Figure 2 shows average screening indoor radon levels by county, calculated from the State/EPA Residential Radon Survey data. Figure 3 shows the geologic radon potential of areas in Region 1, combined and summarized from the individual state chapters.

CONNECTICUT

The Western Uplands of western Connecticut comprise several terranes underlain by metamorphosed sedimentary and igneous rocks. Soils developed on the Proterozoic massifs and overlying till in the Proto-North American Terrane (area 23, fig. 1) have moderate to high permeability. Equivalent uranium is generally low and indoor radon averaged 2.5 pCi/L over the massifs. The carbonate shelf rocks of the Proto-North American Terrane (23, fig. 1) are predominantly marble, schist, and quartzite, all overlain in places by glacial till. Indoor radon averaged 2.8 pCi/L for homes built on the carbonate shelf rocks. Some homes built on parts of the Stockbridge Marble have elevated indoor radon levels. The Taconic Allochthons (24, 25, fig. 1) underlie several fault-bounded areas in the northern part of the Western Uplands. The dominant rock type is schist of varying composition. Equivalent uranium is generally moderate and permeability is low to moderate in this area. Indoor radon in the Taconic Allochthons averaged 2.7 pCi/L. Overall, these terranes have moderate radon potential.

Rocks of the Connecticut Valley Synclinorium (26, fig. 1) underlie most of the Western Uplands. These rocks are schist, gneiss, granite, and phyllite, predominantly granitic or aluminous in composition. Equivalent uranium is moderate to high with areas of very high equivalent uranium over granitic gneisses in the southern portion. The Pinewood Adamellite has high radioactivity and generates locally elevated indoor radon levels. Other granites and granitic gneisses associated with elevated indoor radon include the Harrison Gneiss, an Ordovician granite gneiss, and the Shelton Member of the Trap Falls Formation. These rocks all occur mainly in the

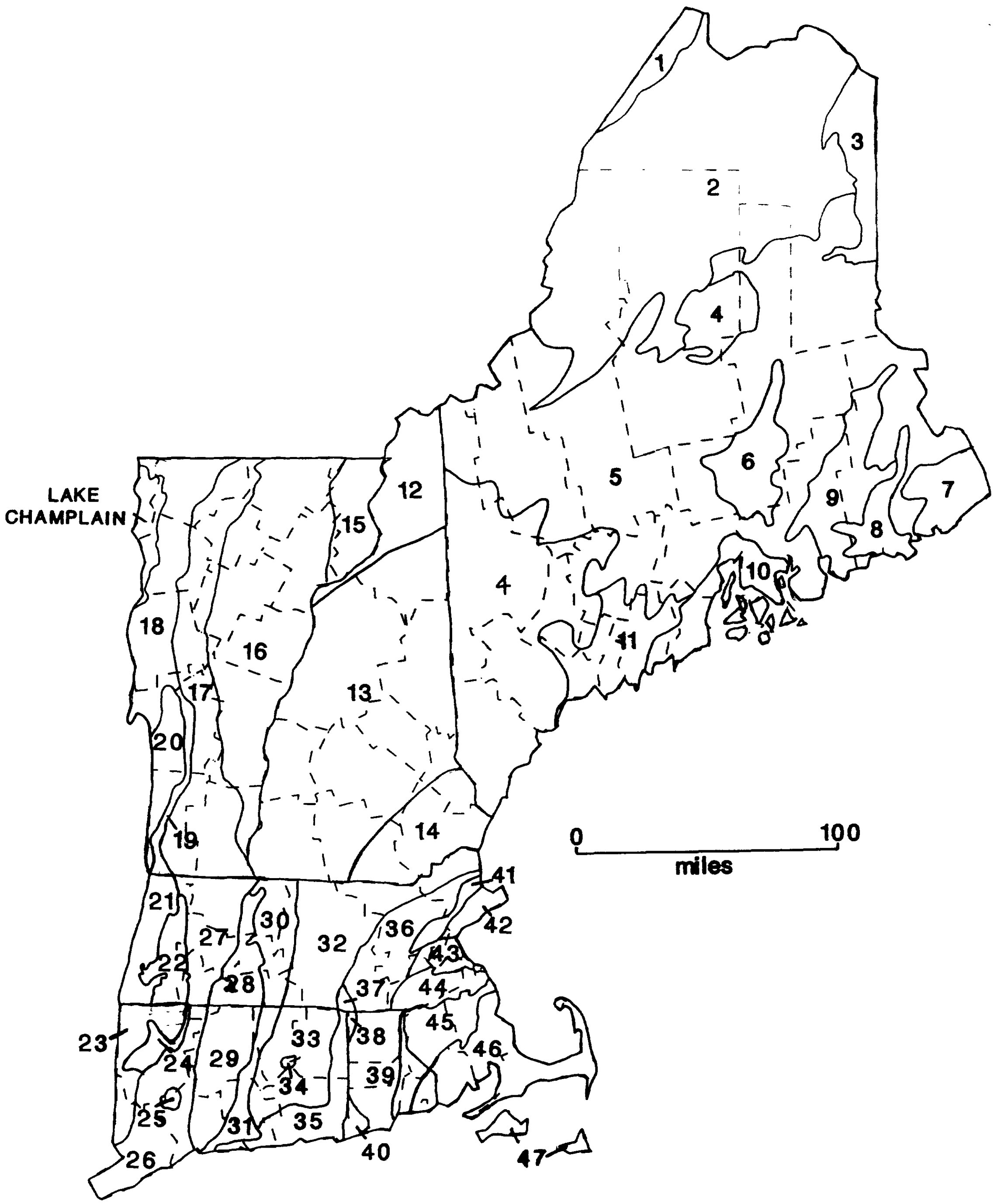


Figure 1. Geologic radon potential areas of EPA Region 1. 1, 5–Melange; 2–Seboomook Formation; 3–Metasedimentary rocks, predominantly carbonates; 4–Granite and high-grade metamorphic rocks; 6, 7, 8, 11–Glacial lake clay, marine clay; 9, 10–Penobscot Formation, granites, and minor metamorphic rocks; 12–Boundary Mountains Terrane; 13–Gander Terrane; 14–Avalonian Composite Terrane; 15–Northeastern Highlands; 16–Vermont Piedmont; 17–Green Mountains; 18–Champlain Lowland; 19–Vermont Valley; 20, 21–Taconic Mountains-Stockbridge Valley; 22–Berkshire Mountains; 23–Proto-North American Terrane; 24, 25–Taconic Allochthons; 26–Connecticut Valley Synclinorium; 27–Western Connecticut Valley Belt; 28, 29–Connecticut Valley (Mesozoic Basins); 30–Gneissic domes of the Eastern Connecticut Valley Belt; 31–Bronson Hill Anticlinorium; 32, 33–Merrimack Synclinorium; 34, 35, 37, 38, 40–Avalonian Terrane (includes Hope Valley subterrane); 36–Nashoba and Rhode Island Terranes; 39, 44, 46–Esmond-Dedham Terrane; 41–Newbury Basin volcanics; 42–Cape Ann and Peabody plutons; 43–Boston Basin; 45–Narragansett Basin; 47–Coastal Plain.

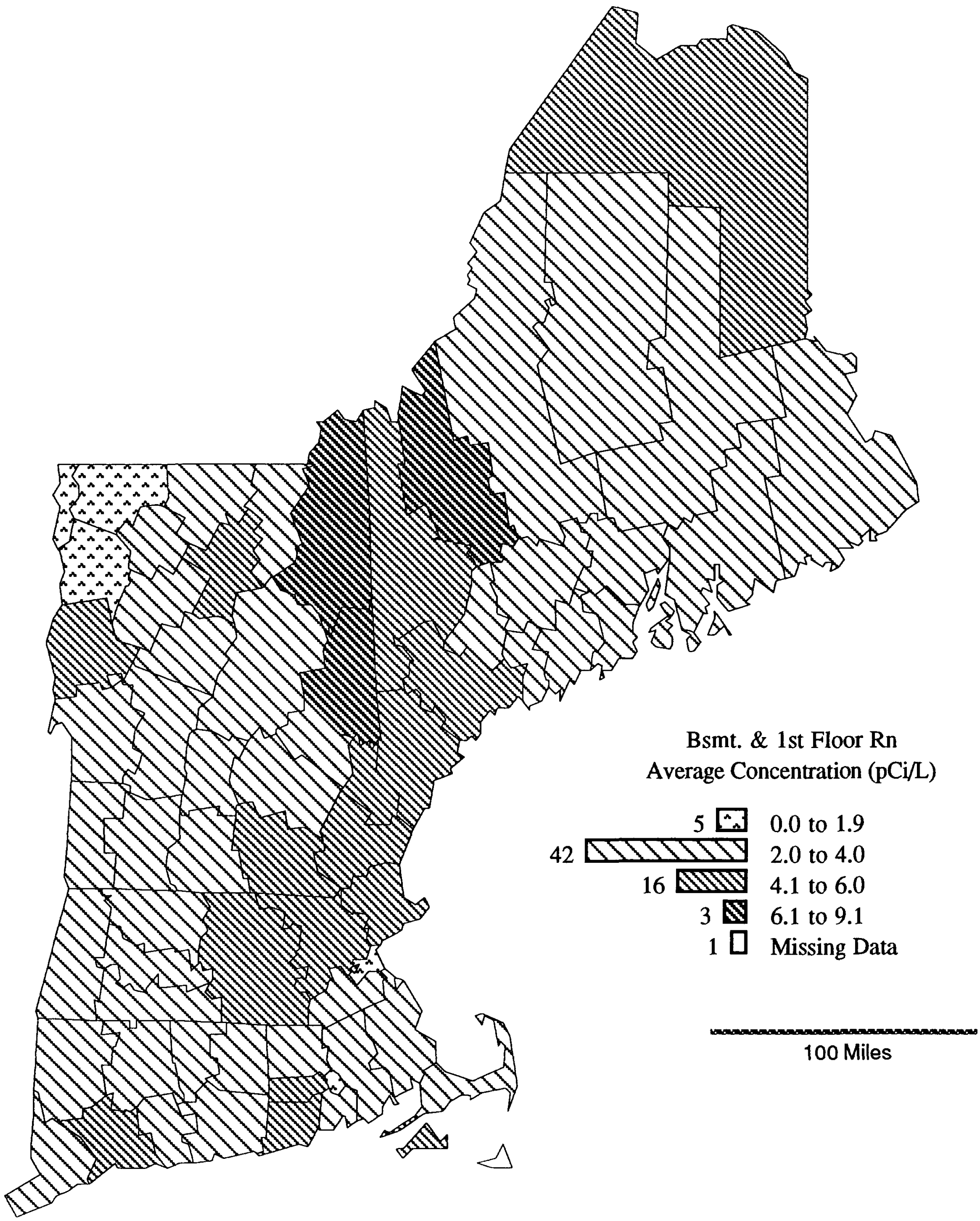


Figure 2. Average screening indoor radon levels, by county, for EPA Region 1. Data are from 2-7 day charcoal canister tests. Data from the EPA/State Residential Radon Survey, except for New Hampshire data, which are from the New Hampshire Division of Public Health Services radon survey. Histograms in map legend show the number of counties in each category.

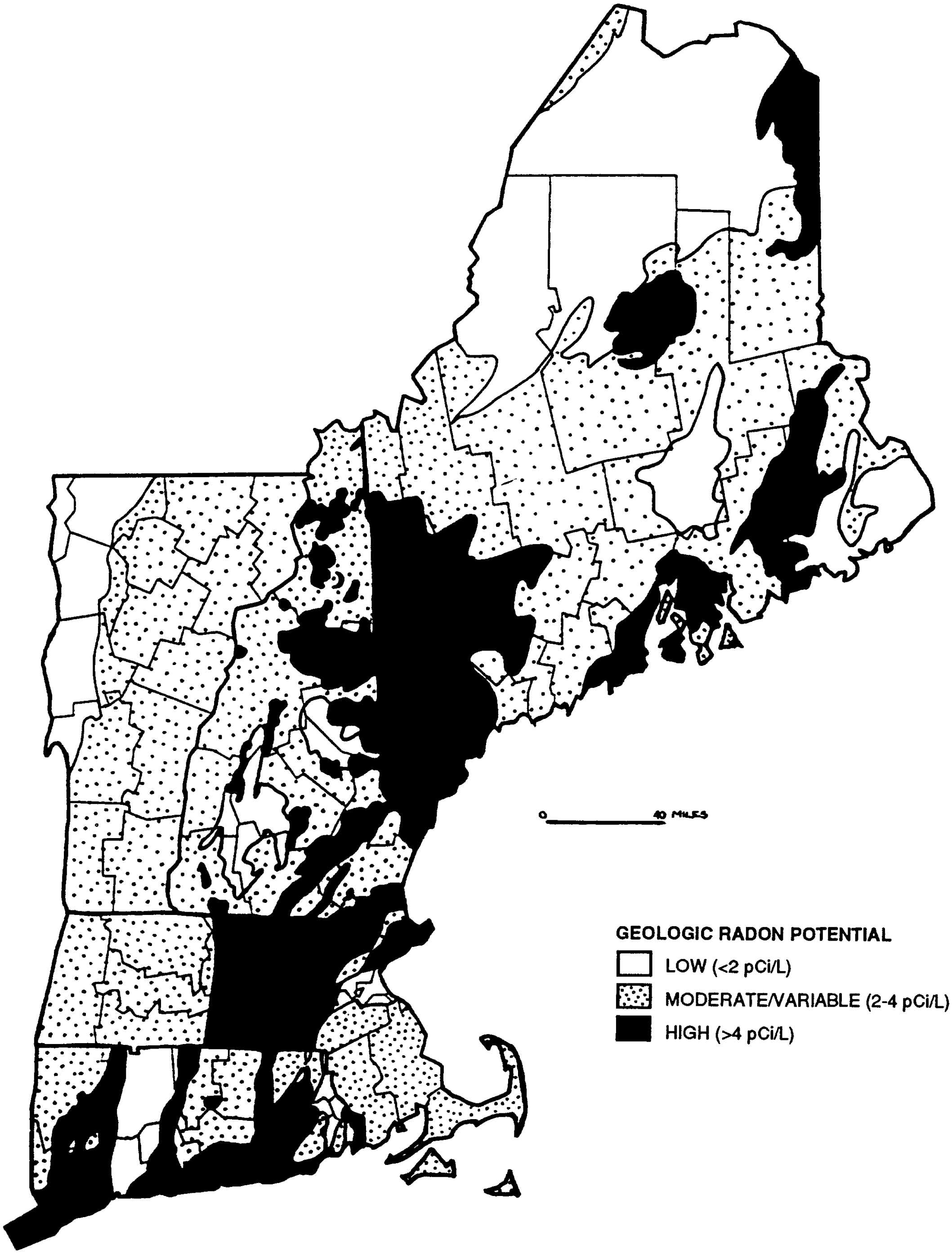


Figure 3. Geologic radon potential areas of EPA Region 1. For more detail, refer to individual state radon potential chapters.

southern part of the Connecticut Valley Synclinorium and are associated with the high radioactivity and with elevated indoor radon. The Nonewaug Granite and the Scranton Member of the Taine Mountain Formation are also associated with high aeroradioactivity and elevated indoor radon levels. Graphitic schist and phyllites may be the cause of elevated indoor radon levels associated with the Wepawaug Schist. Soils are derived from the rocks and overlying tills and have low to moderate permeability. Indoor radon averages 3.5 pCi/L in the Connecticut Valley Synclinorium. Because many of the rocks of this terrane have the potential to generate elevated radon levels, this area is assigned a high geologic radon potential.

The Central Lowlands of Connecticut (29, fig. 1) are underlain by Triassic and Jurassic sedimentary and volcanic rocks of the Newark Terrane. The average indoor radon in the Central Lowlands was 1.6 pCi/L. Radioactivity in the Hartford and Pomperaug basins is generally low and the soils have generally low to moderate permeability or are poorly drained. Overall, the Central Lowlands have a low radon potential. However, localized uranium occurrences in the upper New Haven Arkose, the middle Portland Formation, and possibly in the Shuttle Meadow, East Berlin, and Portland Formations could generate locally elevated indoor radon levels, but they are not expected to be common or widespread.

Rocks of the Bronson Hill Anticlinorium, in the Eastern Uplands of Connecticut (31, fig. 1) , include felsic and mafic schists and gneisses, quartzite, and granite gneiss. Radioactivity in the Bronson Hill is moderate to locally high, and equivalent uranium anomalies in the central part of the area appear to be associated with outcrops of granite gneiss. The soils have low to moderate permeability with areas of locally high permeability. The Glastonbury granite gneiss and graphitic schists in the Collins Hill Formation are likely to generate elevated indoor radon levels. The Monson Gneiss, and schist and granofels of the Middletown Formation, also generate high average indoor radon levels. Average indoor radon in the Bronson Hill Anticlinorium is 5.6 pCi/L, the highest among the geologic terranes of Connecticut. Overall, this area has a high radon potential.

The Merrimack Synclinorium, in the central part of the Eastern Uplands (33, fig. 1), is underlain by gneiss, schist, granofels, and quartzite that are intruded by granite gneiss, diorite, and gabbro. The area has moderate to high radioactivity. Soils have low to high permeability but most are in the low to moderate range. Indoor radon in the Merrimack Synclinorium averaged 2.7 pCi/L. The Canterbury granite gneiss, which occurs in several broad outcrop bands in the northern and central parts of the area, appears to be associated with elevated radioactivity and with moderate to high indoor radon levels. This area has moderate radon potential overall.

The Avalonian Terrane, along the eastern and southeastern borders of Connecticut (34, 35, fig. 1), is underlain by granite, granite gneiss, mafic gneiss, and amphibolite. Granitic rocks known to generate elevated indoor radon levels include the Waterford and Branford Gneisses, and the Hope Valley Alaskite Gneiss, which also has a high aeroradioactivity signature, as well as locally-occurring graphitic schist and gneiss in the Plainfield Formation. The overall radioactivity signature of the area is moderate to high. Soils of the Avalonian Terrane have low to high permeability, with granitic rocks producing sandy, more permeable soils, and mafic and volcanic rocks producing silty and sandy soils with slowly permeable, clayey substrata. The indoor radon average for this terrane is 3.3 pCi/L. Overall, this area has high radon potential.

MAINE

The rocks, surficial deposits, and geologic structures of Maine that are most likely to cause high (>4 pCi/L) indoor radon concentrations include: two-mica granite, alkaline and calc-alkalic granite, and granodiorite; pegmatites, faults and shear zones; and carbonaceous schist, slate, and phyllite. Deposits and rocks likely to cause moderate (2-4 pCi/L) to high (>4 pCi/L) indoor radon include soils developed on carbonate rocks, especially the interbedded slates and dolostones in south-central and northeastern Maine; glacial gravels, especially outwash, kames, and eskers; melange; granitic gneiss; high- to medium-grade metamorphic rocks, and contact metamorphosed rocks in the vicinity of plutons. Rocks and deposits with moderate to variable radon potential include felsic metavolcanic rocks, intermediate composition plutonic rocks, and glacial till. Rocks likely to cause low indoor radon (< 2 pCi/L) include metamorphosed coarse-grained clastic sedimentary rocks, mafic metavolcanic rocks, marine clays, and mafic plutonic rocks.

Most of Maine is underlain by Cambrian-Devonian stratified metamorphic rocks of igneous or sedimentary origin that we have ranked from low to high in radon potential. Uranium concentration generally increases with metamorphic grade and local uranium concentrations may be present in fractures and faults. Areas in northern Maine underlain by coarse-grained clastic metasedimentary rocks and tills derived from these rocks generally have low equivalent uranium and have soils with low permeability. Many of the rocks in this area belong to the Seboomook Formation (area 2, fig. 1). In central and southern Maine, indoor radon is low to moderate in areas underlain by coarse-grained clastic metasedimentary rocks. Formations such as the Vasselboro, which consists of interbedded carbonate rocks and clastic metasedimentary rocks and tends to be more calcareous in general, appears to have high indoor radon associated with it in southern Penobscot County. Central Maine (area 5, fig. 1) is a highly variable area–radon potential varies from moderate to locally high or low. Locally high areas may be associated with granites, kames, eskers, carbonate rocks, graphitic or carbonaceous schist, phyllite, and slate. Locally low areas may be associated with mafic plutonic rocks and clastic metasedimentary rocks. Indoor radon is highly variable in this area and the type and character of the rocks are variable over short distances.

Soils and glacial deposits derived from interbedded carbonate metasedimentary rocks and slates in the northeastern portion of the State (3, fig. 1) and in the south-central portion of the State (5, fig. 1) are associated with moderate and high indoor radon. Equivalent uranium is variable over these deposits but is higher than the dominantly clastic metasedimentary rocks. Soils, tills, eskers, and kames derived from these rocks generally have moderate to locally high permeability. The area underlain by these rock units in the northeastern part of Maine (area 3) has high radon potential, whereas the rocks in the south-central part (area 5) are assigned a moderate geologic radon potential.

Most of the carbonaceous or graphitic rock units in Maine have moderate to high equivalent uranium. Some high indoor radon may be associated with carbonaceous rocks of the Penobscot Formation in Knox County (area 10, fig. 1). Soils formed on carbonaceous and graphitic rocks in Maine have low to moderate permeability. Areas underlain by these rock units have high geologic radon potential.

Plutonic rocks of intermediate to mafic composition generally have low or variable radon potential. Diorite and mafic intrusives of the New Hampshire series have low equivalent uranium and comprise two northeast-trending belts along the southern coast and from southern Oxford County to central Picataquis County. However, two-mica granites, calc-alkaline granites, and alkalic plutonic rocks in Maine (in areas 4, 5, 9, fig. 1) have been ranked high in geologic radon potential. Uranium concentrations in these types of granites are commonly more than 3 ppm and are as high as several hundred ppm in Maine. Two-mica granites are most abundant in the southwestern part of the State and include the rocks of the Sebago Pluton. Calc-alkaline to alkaline granites are more abundant in the southern and central part of the State, particularly in the area northeast of Penobscot Bay and in the Katadhin pluton in central Maine (the part of area 4 in central Maine). Indoor radon averages are high in the southwestern counties of Maine, which may be due to the abundance of igneous plutons and high-grade metamorphic rocks in this area. Most of the areas underlain by igneous plutonic rocks and associated glacial deposits have moderate to locally high permeability.

Although there is no obvious anomalous radioactivity associated with major fault and shear zones in Maine, evidence from other areas of the Appalachians suggests that shear zones can create isolated occurrences of severe indoor radon, especially when they deform uranium-bearing rocks. The radon potential of melange, most of which is found in the northwestern part of Maine (area 1 and a small part of area 5, fig. 1), is not well known, but gray to black phyllitic rocks and deformed zones have the potential to produce at least moderate amounts of radon. We have tentatively ranked these rocks as moderate or variable in radon potential.

The effect of glacial deposits is difficult to assess in Maine because most till is relatively locally derived and is composed primarily of clasts of the surrounding bedrock. The areas of coarse-grained glacial deposits in southwestern Maine and the kame and esker deposits scattered throughout the State enhance the geologic radon potential due to their very high permeability; these units have moderate to high radon potential. The coarser glacial deposits appear to be associated with the igneous plutonic rocks and belts of calcareous and carbonate metasedimentary rocks. Along the coast, areas of slowly permeable marine and glaciomarine clay (areas 7, 8, 11, fig. 1) probably reduce the radon potential and they are assigned a low geologic radon potential. Glacial lake sediments with low permeability in Penobscot County (6, fig. 1) appear to be associated with low indoor radon. Till with compact, slowly permeable substrata is dominant in much of central and northern Maine and the rocks underlying these areas are metasedimentary and metavolcanic rocks that are generally low in uranium.

MASSACHUSETTS

The metamorphic rocks of the Taconic Mountains and carbonate sedimentary and metasedimentary rocks of the Vermont-Stockbridge Valley, in westernmost Massachusetts (area 21, fig. 1) , have been ranked moderate in geologic radon potential. Graphitic phyllites and schist of the Walloomsac Formation have moderate to high radioactivity associated with them and may produce locally elevated indoor radon levels. Elevated radon may also be associated with fault and shear zones, especially in the Taconic Mountains.

The Berkshire Mountains (area 22, fig. 1) have been ranked moderate overall in radon potential. Granitic to dioritic gneiss and schist have generally low equivalent uranium associated with them. Shear zones, pegmatites, and local accumulations of monazite in biotite schist and gneiss may be sources of locally high indoor radon levels. Soil permeability is low to moderate.

Metamorphic rocks of the Connecticut Valley Belt, flanking the Mesozoic basins of west-central Massachusetts (27, 30, fig. 1), have been ranked moderate in radon potential. Metasedimentary and metavolcanic gneisses and schists have generally low to moderate radioactivity associated with them. Soils have generally moderate permeability. The Pauchaug and Glastonbury granite gneisses, which form the cores of the Warwick and Glastonbury domes, as well as other locally-occurring granitic rocks in area 30 (fig. 1), may generate locally high indoor radon levels. Locally high radon levels are likely to be associated with an area of anomalous radioactivity at the south end of the Warwick dome and may be associated with faults and shears throughout the area.

Mesozoic sedimentary and igneous rocks of the Connecticut Valley (28, fig. 1) have been ranked moderate or variable in radon potential. Most of the sedimentary rocks have low radon potential but locally high indoor radon levels may be associated with Jurassic-age black shales and localized uranium deposits in fluvial sandstone and conglomerates. Geologic radon potential is low to moderate in glacial lake-bottom sediments, and moderate to high in glaciofluvial deposits including outwash, lacustrine delta deposits, and alluvium.

Granitic plutons of the Merrimack Belt, central Massachusetts (32, fig. 1), have been ranked high in radon potential. The metasedimentary rocks surrounding the plutons are predominantly phyllites and carbonaceous slates and schists with moderate to high radon potential. Mafic metamorphic rocks, which are less common in the Merrimack Belt, have generally low to moderate radon potential. Faults and shear zones may produce locally high radon concentrations.

Granitic plutonic rocks and metamorphic rocks of the Nashoba terrane (36, fig. 1), the northward extention of the Avalonian terrane (37, fig. 1), and granites of the Cape Ann and Peabody plutons, in northeastern Massachusetts (42, fig. 1), are ranked high in radon potential. They are associated with moderate to high radioactivity and the soils developed on these rocks have moderate to high permeability. Relationships between radon and underlying bedrock in eastern Massachusetts, particularly in the Merrimack zone and in these areas, are less distinct, probably due to the influence of glacial deposits that are made up of a mixture of the rock types underlying eastern Massachusetts and areas to the north. The glacial deposits generally have enhanced permeability and may have enhanced radon emanation due to the redistribution of rock components, mixing, and grain-size reduction effects of the glacial processes. Volcanic rocks and soils of the Newbury basin (41, fig. 1) are ranked moderate in radon potential.

The Esmond-Dedham terrane, southeastern Massachusetts (44, 46, fig. 1), is ranked moderate overall in geologic radon potential. This area includes a number of granite plutons and fault zones that may generate high radon levels, as well as mafic metasedimentary and metavolcanic rocks having low to moderate radon potential. Aeroradioactivity is generally low to moderate with one anomaly associated with granite of the Rattlesnake Hill Pluton. Soils in this area have low to moderate permeability.

Pennsylvanian sedimentary rocks of the Narragansett basin, southeastern Massachusetts (45, fig. 1), are associated with low to moderate radioactivity and low to moderate soil permeability, and have moderate geologic radon potential. The Norfolk basin is similar to the Narragansett basin and also has moderate radon potential. Proterozoic to Pennsylvanian sedimentary rocks of the Boston basin (43, fig. 1) have been ranked low in radon potential. Information on soil characteristics and radioactivity is unavailable for the Boston basin but radioactivity is assumed to be generally low based on the radioactivity of similar rocks elsewhere in the State. Soil characteristics are highly variable in urban areas due to human disturbance, and thus are considered to be variable for this assessment. Black shales and conglomerates in the Boston basin may have locally high radioactivity and may cause locally elevated indoor radon levels.

Sediments of the Coastal Plain are found primarily on Nantucket Island and Martha's Vineyard (47, fig. 1). Areas underlain by Cretaceous and Tertiary sediments have low radon potential, but areas underlain by the Martha's Vineyard and Nantucket moraines have moderate to locally high radon potential caused by their relatively higher permeability and better drainage characteristics compared to surrounding areas, and the crystalline rock source component of the moraines. This is also true of the Buzzard's Bay and Sandwich moraines on Cape Cod. Areas underlain by highly permeable glacial outwash may also generate locally elevated indoor radon levels if the soils are not too wet to preclude soil-gas transport.

NEW HAMPSHIRE

The Avalonian Composite Terrane, in southeastern New Hampshire (area 14, fig. 1), is underlain by the Merrimack Group, Massabesic Gneiss, the Rye Formation and several bodies of two-mica granites, alkalic plutonic rocks, and mafic plutonic rocks. Soils in this area have generally low permeability that is locally moderate to high. The Merrimack Group has low to moderate equivalent uranium, whereas other rocks have generally moderate to high equivalent uranium, particularly the Massabesic Gneiss, two-mica granites, and the extensive fault zones. The Merrimack Group and Rye Formation have overall moderate radon potential, with locally low radon potential. The Massabesic Gneiss, the granite intrusives, and the fault zones have high radon potential. Average indoor radon for the townships underlain by Avalonian rocks is predominantly moderate to high. Overall, the Avalonian Composite Terrane has been ranked moderate to high in radon potential.

About half of New Hampshire is underlain by Cambrian-Devonian stratified metamorphic rocks of igneous or sedimentary origin of the Gander (area 13, fig. 1) and Boundary Mountains (area 12) Terranes. These rocks have been ranked moderate in radon potential overall. The metasedimentary and metavolcanic rocks have variable uranium content, with increasing uranium as metamorphic grade increases, and contain local uranium concentrations in fractures and faults. Graphitic slates, phyllites, and schists are may also be possible sources of high indoor radon. Where indoor radon data are available, the stratified metamorphic rocks appear to be associated with low to moderate indoor radon in the western portion of the State and with higher indoor radon in the eastern portion of the State and in the vicinity of plutonic rocks. Intermediate to mafic plutonic rocks generally have low or variable radon potential. The Lake Winnipesaukee Quartz Diorite and the Kinsman Quartz Monzonite appear to have low equivalent uranium and low indoor radon associated with them, and are ranked low in geologic radon potential.

Several of the Oliverian domes have distinct radiometric highs associated with them except for the northernmost and largest of the Oliverian rocks in the northern Gander Terrane, which have low radioactivity. Indoor radon in the townships underlying this area is variable from low to high. The Oliverian rocks and intermediate composition plutonic rocks are ranked moderate or variable in geologic radon potential.

Two mica granites, calc-alkaline granites, and alkalic plutonic rocks in New Hampshire have been ranked high in radon potential. Uranium content of these granites is commonly more than 3 ppm and ranges to several hundreds of ppm. Two-mica granites occur throughout the central and eastern portions of New Hampshire. Calc-alkaline granites occur from east-central to northwestern New Hampshire. The largest body of calc-alkaline granite underlies the White Mountains and has very high radioactivity associated with it. Indoor radon levels in several townships in this area are high.

High radon concentrations in domestic water are associated with granites, pegmatites, and faults in some parts of New Hampshire. The radon in these wells may be high enough to contribute significantly to the radon content of the indoor air.

RHODE ISLAND

The radon potential of Rhode Island appears to be influenced most by the composition of the underlying bedrock and secondarily affected by glacial deposits. The greatest percentage of homes with 4 pCi/L or more of radon are concentrated in the southern part of the State over the Scituate and Narragansett Pier Igneous Suites, and parts of the Esmond Igneous Suite (area 39, fig. 1), as well as with two areas also noted for high uranium: the northwestern and southwestern corners of the State, underlain by the Sterling Plutonic group (38, 40, fig. 1), and in the East Bay Area, which is underlain by the granites of Southeastern Rhode Island. Igneous intrusive rocks of the Scituate Igneous Suite, rocks of the Hope Valley Group, granites of southeastern Rhode Island, the Narragansett Pier Granite, and alkalic granites of the Cumberland area have significant uranium concentrations and surface radioactivity. Many of the areas underlain by these rocks also have locally derived tills, kames and glacial lake deposits that may contribute significantly to the overall high radon potential. The lowest radon potential appears to be associated with the less-metamorphosed sediments of the Rhode Island Formation, which is overlain by glacial outwash deposits in the northern portion of the Narragansett Lowlands (45, fig. 1). Low to moderate radon appears to be associated with stratified metamorphic rocks of the Blackstone Group, the Harmony Group, the Plainfield Formation, parts of the Esmond Igneous Suite, and scattered stratified metamorphic rocks in the Narragansett Lowlands. These areas are ranked moderate or variable in geologic radon potential overall.

The effect of glacial deposits is complex because most of the materials making up the glacial deposits are locally derived and primarily reflect a collection of the surrounding bedrock. The majority of soils and glacial deposits are moderate to high in permeability and probably enhance the geologic radon potential. In the southern half of the State, stratified glacial deposits appear to have lower radioactivity than areas of till over the same bedrock. Stratified glacial deposits are most common along valley floors and in the Narragansett Basin, and are thicker and generally coarser than the till. The thickness of the stratified deposits may damp the radioactivity of the bedrock or indicate an overall lower radioactivity for the glacial deposit. Although the coarser stratified glacial sediments have higher permeability than some of the tills, their radon emanation coefficient tends not to be as high as for some tills. Tills commonly have higher radon emanation because of the higher proportion of finer-grained sediments. This is also true of some glacial lake deposits. Thick deposits of outwash sand and gravel blanket much of the northern Narragansett Lowlands and appear to have both low radioactivity and low indoor radon associated with them; this area is assigned a low geologic radon potential. The southern part of the Narragansett Lowlands and East Bay Area, however, have a significantly higher percentage of indoor radon readings exceeding 4 pCi/L. This may be due to the fact that the southern part of the Narragansett Lowlands and East Bay Area are dominated by thin glacial till containing components of uraniferous granite and phyllite; this area has a moderate or variable geologic radon potential. Another example of the influence of glacial deposits may be seen in the area of the Narragansett Pier Granite, where high percentages of homes have indoor radon levels greater than 4 pCi/L. The types of glacial deposits in this area include kames, glacial lake deposits, and till, which are known to have enhanced radon exhalation. These glacial deposits may also have significant source components in the adjacent Scituate Igneous Suite and Sterling Plutonic Group as well as the Narragansett Pier granite, all of which have some elevated uranium concentrations.

VERMONT

The geologic radon potential of the Champlain Lowlands (area 18, fig. 1) is low, with areas of locally moderate to high radon potential possible. The Vermont Valley (19, fig. 1) has generally moderate geologic radon potential. Clay-rich soils with low permeability dominate the lowlands and include glacial lake and marine clays, which probably reduce the radon potential significantly. Radioactivity is generally low, with a few scattered high and moderate areas that appear to be associated with the Clarendon Springs Formation and, possibly, with black shales and slates in surrounding rock units. Indoor radon levels in the counties underlain by the Champlain Lowlands are generally less than 4 pCi/L except in Addison County, where out of 26 readings, six were greater than 4 pCi/L and of these, two were greater than 20 pCi/L.

The Green Mountains (17, fig. 1) have been rated moderate in radon potential; however, the radon potential is actually highly variable. Areas with locally high radon potential are those underlain by metamorphic rocks of Proterozoic age, including quartzite; graphite- and pyrite-bearing schists and slates; migmatitic schist and gneiss; biotite-rich zones in mica schist; and schist and gneiss with high concentrations of the minerals monazite, allanite, and zircon; the Cheshire Quartzite; and local deposits of uranium in veins and fault zones. Mafic metamorphic rocks such as amphibolite, hornblende gneiss, gabbro, and serpentinite, have low geologic radon potential. Radioactivity is variable—low in the southern portion but containing local high radioactivity areas, moderate to high radioactivity in the central portion, and low in the north.

The Taconic Mountains (20, fig. 1) have moderate geologic radon potential. Radioactivity is generally moderate to high, and several rock types appear to have elevated levels of uranium, especially the carbonaceous sedimentary rocks of the Pawlet Formation. Elevated concentrations of uranium in the black to gray phyllites and slates are probably the principal radon sources in this area.

The Vermont Piedmont (16, fig. 1) has moderate but variable geologic radon potential. Much of the area is underlain by mafic rocks with low radon potential. Granites, granitic gneiss and schist, and carbonaceous or graphitic slate and phyllite have the potential to generate moderate to high indoor radon levels.

The Northeastern Highlands (15, fig. 1) have moderate radon potential. Plutonic igneous rocks are abundant in this area and in the northern half of the Vermont Piedmont, but only a few of the plutons have distinct radiometric anomalies associated with them. Indoor radon for counties underlain by these rocks is moderate with the exception of Caledonia County, in which 11 of the 51 indoor radon measurements in the State/EPA Residential Radon Survey were greater than 4 pCi/L.

PRELIMINARY GEOLOGIC RADON POTENTIAL ASSESSMENT OF CONNECTICUT

by
Linda C.S. Gundersen and R. Randall Schumann
U.S. Geological Survey

INTRODUCTION

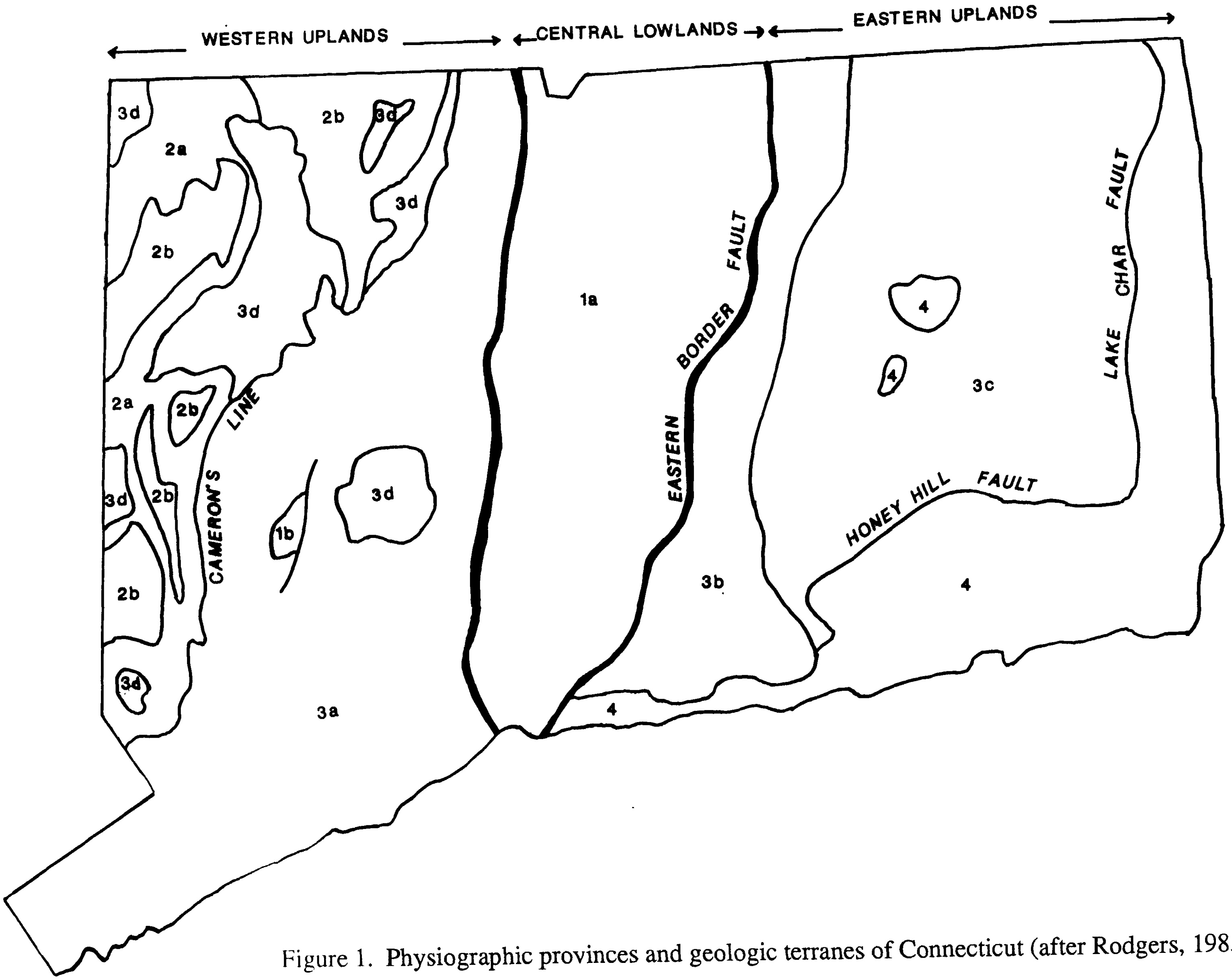
Radon potential in Connecticut varies from low to high. In measurements of 4798 homes sampled in the State/EPA Residential Radon Survey and the Connecticut Household Testing Program during 1986-88, the average for the state was 3.1 pCi/L and 20.3 percent of the homes tested had indoor radon levels exceeding 4 pCi/L. Of the eight counties in Connecticut, only New Haven County had an indoor radon average greater than 4 pCi/L. Averages for the rest of the counties were between 2 and 4 pCi/L. Most sedimentary rocks of the Hartford and Pomperaug basins have low geologic radon potential, whereas granites, granitic gneisses, and some graphitic schists and phyllites tend to generate elevated indoor radon levels and thus are assigned high radon potential. This chapter presents a discussion of the bedrock and glacial geology, soils, and radioactivity of Connecticut in the context of indoor radon.

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

PHYSIOGRAPHIC AND GEOGRAPHIC SETTING

The physiography of Connecticut (fig. 1) is in part a reflection of the underlying bedrock geology (fig. 2), and each major physiographic region is underlain by distinct geologic terranes (fig. 1). The surface of the land has also been shaped extensively by glaciers. There are three major physiographic regions in Connecticut: the Western Uplands, the Central Lowlands, and the Eastern Uplands. Elevation ranges from sea level along the Atlantic coast in the southern part of the State to 2,380 ft at Mt. Frissell in the Western Uplands.

The Western Uplands consists of rolling hills and mountains underlain by deformed sedimentary, igneous, and metamorphic rocks. In the northwestern portion of the Western Uplands, valleys, such as the Marble Valley, are underlain by carbonate rocks, whereas the mountains are formed from schist, gneiss, and granite. To the southwest, the terrain is gentler, more rolling hills underlain by schist. The northern part of the Western Uplands includes the southern extension of the Berkshire Mountains, and the Taconic Mountains, Housatonic Highlands, and Hudson Highlands form mountains along the State's western border.



GEOLOGIC TERRANES OF CONNECTICUT

1. Newark (Rift Valley) Terrane
   a. Hartford Basin
   b. Pomperaug Basin

2. Proto-North American (Continental) Terrane
   a. Carbonate shelf
   b. Proterozoic massifs "Grenville"

3. Iapetos (Oceanic) Terrane
   a. Connecticut Valley Synclinorium
   b. Bronson Hill Anticlinorium
   c. Merrimack Synclinorium
   d. Taconic Allochthons

4. Avalonian (Continental) Terrane

Figure 1. Physiographic provinces and geologic terranes of Connecticut (after Rodgers, 1985).

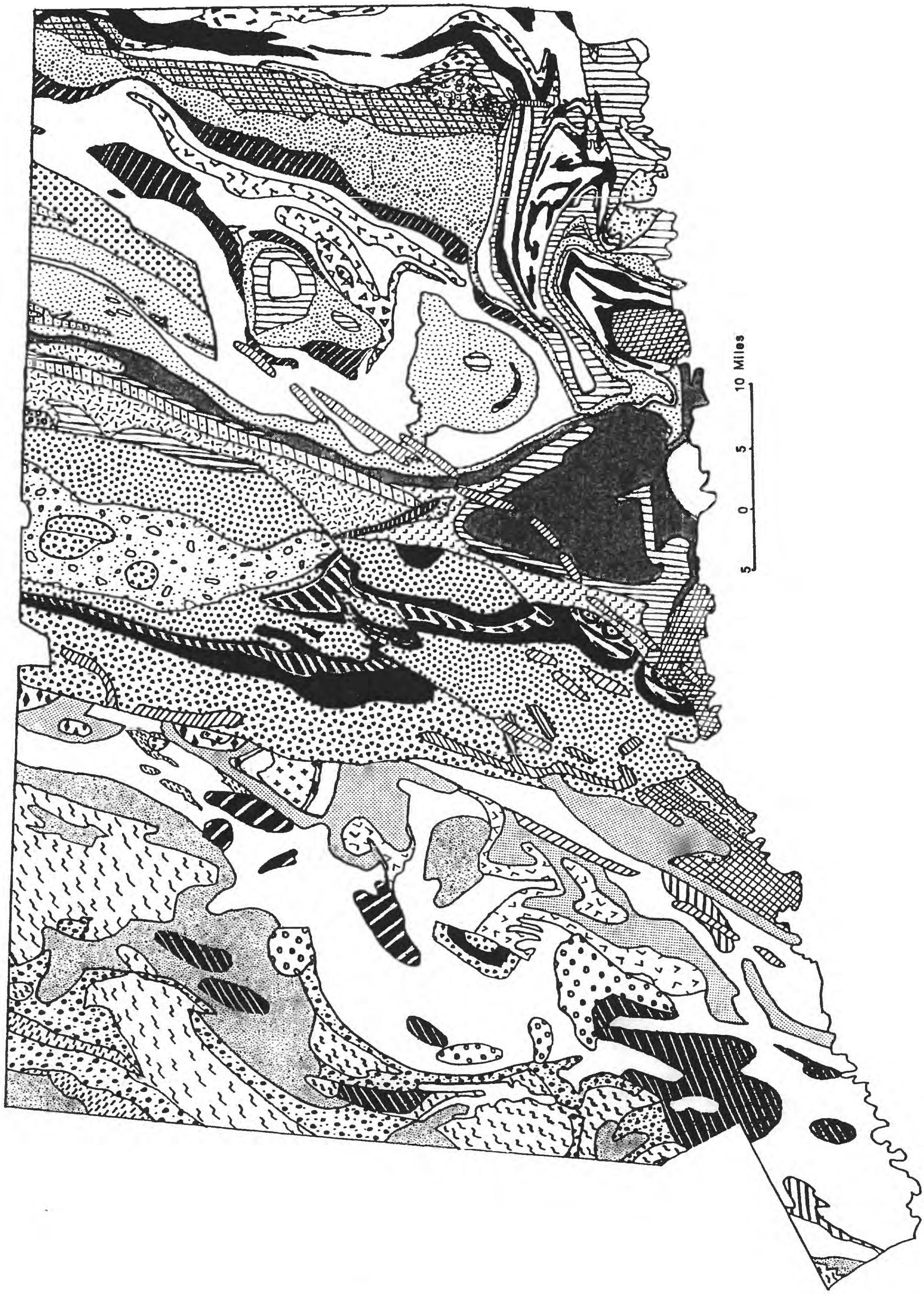


Figure 2. Generalized bedrock geologic map of Connecticut (modified from Bennison, 1976, using Rodgers, 1985).

GENERALIZED GEOLOGIC MAP OF CONNECTICUT
EXPLANATION

QUATERNARY
Undifferentiated alluvium and glacial deposits

TACONIC ALLOCHTHONS (DISPLACED IAPETOS TERRANE)

CAMBRIAN
Everett Schist: Schist and phyllite, composed of quartz, albite or oligoclase, muscovite, garnet, staurolite or chloritoid, and generally chlorite
Manhattan Schist: Gneiss and schistose gneiss, composed of quartz, oligoclase, microcline, biotite, and muscovite, and generally sillimanite and garnet. Amphibolite layers locally, especially near base.
Canaan Mountain Schist: Schist and schistose gneiss, composed of quartz, plagioclase, biotite, muscovite, and generally garnet and sillimanite; also layers of amphibolite and quartzite
Hoosac Schist: Schistose gneiss composed of quartz, biotite, plagioclase, muscovite, and generally garnet and sillimanite or kyanite.
Waterbury Gneiss: Schist and schistose gneiss, composed of biotite, quartz, oligoclase, kyanite (or sillimanite), and garnet, also locally microcline, irregularly mixed with granitoid gneiss, composed of oligoclase or andesine, quartz, biotite, and commonly microcline and muscovite (in Connecticut Valley Synclinorium)

ORDOVICIAN AND CAMBRIAN SHELF SEQUENCE

ORDOVICIAN
Walloomsac Schist: Schist or phyllite, composed of quartz, albite, and commonly garnet and staurolite or sillimanite (locally strongly retrograded to chlorite and muscovite). Locally feldspathic or calcareous near the base

Stockbridge Marble (including Inwood Marble) (**LOWER ORDOVICIAN AND CAMBRIAN**): Massive to layered marble, generally dolomitic but containing calcite marble in upper part, locally interlayered with schist or phyllite and with calcareous siltstone, sandstone, and quartzite
CAMBRIAN
Cheshire Quartzite: Mainly pure, white, glassy, tough quartzite
Dalton Formation (including Poughquag Quartzite and Lowerre Formation): Gneiss or feldspathic quartzite, composed of quartz, microcline, plagioclase, muscovite, biotite, and generally tourmaline; some schistose micaceous layers have sillimanite, commonly as quartz-sillimanite nodules rimmed with muscovite. Layers of purer quartzite in many areas, especially near the top or where the formation is thin

PROTEROZOIC MASSIFS – "GRENVILLE"

PROTEROZOIC
Pink granitic gneiss composed of quartz, microcline, oligoclase, and either biotite or muscovite or both, also locally amphibole or
Augen gneiss (including local term "Danbury Gneiss;"Granitic gneiss, composed of microcline (largely as megacrysts or augen up to 10 cm long), quartz, albite, or oligoclase, biotite and minor hornblende
Layered gneiss composed of quartz and plagioclase, with microcline locally in the light layers and abundant biotite and common hornblende in the dark layers; garnet or epidote locally. Layers and lenses of calc-silicate rock and amphibolite in some areas
Hornblende gneiss and amphibolite composed of hornblende and plagioclase, also commonly biotite and minor quartz; commonly interlayered with banded felsic gneiss. Locally contains calc-silicate rock or diopsidic calcite marble
Rusty mica schist and gneiss composed of quartz, plagioclase, biotite, muscovite, sillimanite, and locally garnet; some layers of feldspathic quartzite and garnetiferous amphibolite

NEWARK TERRANE
HARTFORD AND POMPERAUG MESOZOIC BASINS

JURASSIC
Buttress Dolerite: Basalt near contacts to fine-grained gabbro in the interior, composed of plagioclase and pyroxene with accessory opaques and locally devitrified glass, quartz or olivine

West Rock Dolerite: Basalt near contacts to fine-grained gabbro in the interior, generally massive with well-developed columnar jointing, composed of plagioclase and pyroxene with accessory opaques and locally devitrified glass, quartz, or olivine

Newark Supergroup
Portland Arkose: Arkose, siltstone and red to black fissile silty shale. Grades eastward into coarse conglomerate (fanglomerate)

b **Hampden Basalt** (Lower Jurassic): Greenish-gray to black (weathers bright orange to brown), fine- to medium-grained, grading from basalt near contacts to fine-grained gabbro in the interior, composed of pyroxene and plagioclase with accessory opaques and locally olivine or devitrified glass
Holyoke Basalt: Basalt near contacts to gabbro in the interior, composed of pyroxene and plagioclase with accessory opaques and locally olivine or devitrified glass
Shuttle Meadow Formation: Siltstone, and fine-grained silty sandstone, generally well and thinly laminated. In the southern part of the State includes a layer, up to 5 m thick, of blue, commonly sandy, fine-grained limestone or dolomitic limestone, grading laterally into calcareous siltstone. Coarser and more arkosic to east and south, grading into conglomerate near the eastern border fault
Talcott Basalt: Basalt near contacts to fine-grained gabbro in the interior, composed of pyroxene and plagioclase with accessory opaques and locally olivine or devitrified glass. Pillows in many places; volcanic breccia with fragmentary pillows in others

East Berlin Formation: Siltstone, silty and sandy shale, and fine-grained silty sandstone, generally well laminated and commonly well indurated, alternating with dark fissile shale; dolomitic carbonate common in cement, concretions, and thin argillaceous laminae. Local arkose; grades eastward into coarse conglomerate close to eastern border fault

UPPER TRIASSIC TO LOWER JURASSIC
New Haven Arkose: Arkose, interbedded with brick-red micaceous, locally shaly siltstone and fine-grained feldspathic clayey sandstone

IAPETOS (OCEANIC) TERRANE
CONNECTICUT VALLEY SYNCLINORIUM

DEVONIAN
Nonewaug Granite: Massive to layered granite composed of albite, microcline, quartz, and muscovite, with minor biotite and garnet.

ORDOVICIAN (?)
Granitic gneiss composed of sodic plagioclase, quartz, microcline, muscovite, and biotite, and locally garnet or sillimanite. Commonly contains numerous inclusions or layers of mica schist and gneiss

ORDOVICIAN
Litchfield Norite: Massive mafic rock (olivine norite, quartz norite, hypersthene pyroxenite), composed of labradorite, hypersthene, augite, and olivine in varying proportions, also hornblende and biotite (and minor quartz in quartz norite). Associated with small mineral deposits of pyrrhotite, pentlandite, and chalcopyrite
Brookfield Gneiss Speckled or banded, medium- to coarse-grained, massive to poorly foliated gneiss, composed of plagioclase, biotite, and hornblende, generally with quartz and K-feldspar, the latter commonly as megacrysts 1 to 3 cm across (also plagioclase megacrysts in darker rocks), locally associated with hornblende schist

Hartland Belt

DEVONIAN-SILURIAN
The Straits Schist: Schist composed of quartz, muscovite, biotite, oligoclase, garnet, and commonly staurolite and kyanite or sillimanite; graphitic almost throughout
Southington Mountain Member of Straits Schist: Massive adamellite, composed of microcline, albite, quartz, and muscovite with accessory fluorite. High radioactivity
Basal member of the Straits Schist: Layers of amphibolite, marble, calc-silicate rock, and quartzite within more uniform schist like that on either side. Minor, unevenly distributed mineralization in W, Bi, Cu, Ni, and other metals
Wepawaug Schist (Orange-Milford Belt): Schist or phyllite and metasiltstone, composed of quartz, muscovite or sericite, plagioclase, biotite, and in appropriate metamorphic zones chlorite, garnet, staurolite, and kyanite. Schist or phyllite generally graphitic

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ORDOVICIAN
Trap Falls Formation (may be equivalent in part of Golden Hill Schist) Well layered schist, composed of quartz, sodic plagioclase, biotite, muscovite, and garnet, locally with sillimanite or kyanite, interlayered with two-mica gneiss and granulite and with amphibolite
Carringtons Pond Member: Schist and light-gray, fine- to medium-grained gneiss, composed of interlayered medium- to dark-gray, rusty-weathering, medium-grained schist and light-gray, fine- to medium-grained gneiss, composed of quartz sodic plagioclase, biotite, muscovite, and garnet, schist locally contains sillimanite or kyanite; gneiss locally contains K-feldspar; amphibolite layers common
Schist and granulite member: Schist and fine-grained granofels, composed of quartz, sodic plagioclase, biotite, and muscovite; garnet common in schist
Cobble Mountain Formation: Schist and granofels, composed of quartz, oligoclase, muscovite, biotite, and garnet, and locally kyanite and staurolite or sillimanite. some amphibolite layers
Harrison Gneiss: (including Prospect Gneiss) Gneiss, composed of andesine, quartz, hornblende, and biotite (also locally K-feldspar as megacrysts 1 to 5 cm long). Thought to be metavolcanic equivalent of Brookfield Gneiss
Pumpkin Ground Member: Gneiss, composed of oligoclase, microcline, quartz, and biotite; some layers have numerous microcline megacrysts 1 to 5 cm across; others have hornblende. Minor layers of garnetiferous schist and gneiss
Beardsley Member: Gneiss, composed of plagioclase, quartz, microcline, hornblende, biotite, and epidote. Microcline may occur as megacrysts 1 to 3 cm across. Minor layers of garnetiferous schist and rarely of calc-silicate rock or marble
Nodular member: Harrison Gneiss containing prominent quartz-sillimanite nodules
Golden Hill Schist (may be equivalent to part of Trap Falls Formation) Schist and granofels, composed of quartz, muscovite, biotite, plagioclase, and garnet
Ratlum Mountain Schist: Interlayered schist and granofels, composed of quartz, oligoclase, muscovite (in the schist), Biotite, and garnet, also Gray, medium-grained, interlayered schist and granofels, composed of quartz, oligoclase, muscovite (in the schist), biotite, and garnet, also staurolite and kyanite in the schist. Numerous layers and lenses of amphibolite; also some of quartz-spessartine (coticule) and calc-silicate rock. Includes an amphibolite unit composed of massive amphibolite and hornblende gneiss, composed of hornblende and andesine, commonly with minor quartz and magnetite, and locally with garnet, biotite, and epidote
Rowe Schist (ORDOVICIAN TO CAMBRIAN): Schist, composed of quartz, muscovite, biotite, oligoclase, and generally garnet, staurolite, and kyanite or sillimanite. Layers of granofels common; also some layers of amphibolite, quartz-spessartine rock (coticule), and calc-silicate rock. Includes an amphibolite unit comprising generally massive amphibolite and hornblende gneiss, composed of hornblende and andesine
Taine Mountain Formation: Gneissic or schistose granofels, composed of quartz, oligoclase, biotite, muscovite, and garnet, and locally staurolite and kyanite or sillimanite
Whigville Member: Gneissic or schistose granofels, composed of quartz, oligoclase, biotite, muscovite, and garnet, and locally staurolite and kyanite or sillimanite
Scranton Mountain Member: Schist, composed of quartz, muscovite, biotite, plagioclase, garnet, and generally kyanite
Wildcat Member: Gneissic or schistose granofels, composed of quartz, oligoclase, biotite, muscovite, and garnet, and locally staurolite and kyanite or sillimanite
Basal member around Waterbury dome: Differs from rest of Taine Mountain Formation in being especially well layered and generally less micaceous and schistose

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ORDOVICIAN
INCLUDED IN THIS MAP UNIT (outcrops too small to be shown separately):
Pinewood Adamellite(PERMIAN): Massive adamellite, composed of microcline, albite, quartz, and muscovite with accessory fluorite. High radioactivity
Lamprophyre (DEVONIAN?): Badly altered dike rock, composed of biotite, augite, K-feldspar, and accessory apatite and sphene, plus secondary minerals
Ultramafic rock **(ORDOVICIAN OR OLDER)**, originally composed of olivine and pyroxene, now generally altered to tremolite, talc, chlorite, or serpentine

Shelton Member of Trap Falls Formation: Granitic gneiss, composed of sodic plagioclase, quartz, microcline, muscovite, and garnet (in tiny almost ubiquitous grains), also commonly minor biotite; generally interlayered with mica schist, biotite gneiss, and calc-silicate rock.

Hawley Formation (carbonaceous schist facies): Schist and granofels, composed of quartz, oligoclase, and biotite; some muscovite and graphite, rare garnet and kyanite or sillimanite. Layers of quartz-spessartine rock (coticule) common

Collinsville Formation (undivided): Mixture of schist, composed of quartz, oligoclase, biotite, muscovite, and garnet, and in place kyanite or sillimanite (Sweetheart Mountain Member), with hornblende gneiss described below; in many areas felsic and mafic striped metavolcanic rocks predominate
INCLUDED IN THIS MAP UNIT (outcrops too small to be shown separately):
Porphyry (dacite or rhyolite) **(PERMIAN):** Massive porphyry with phenocrysts of quartz, feldspar, and biotite; muscovite and accessory fluorite in ground mass
Syenite (PERMIAN): Massive syenite, composed of microcline, amphibole and biotite with accessory apatite and sphene

Hornblende gneiss member of Collinsville Fm.: Well-layered amphibolite and hornblende gneiss, composed of hornblende and plagioclase, commonly with biotite, garnet, or epidote, interlayered with light-gray felsic gneiss and pink quartz-spessartine rock (coticule). Grades into Bristol Gneiss; includes minor amounts of the Sweetheart Mountain Member of Collinsville Fm.

Bristol Gneiss: Gneiss, composed of plagioclase, quartz, and biotite, also muscovite and garnet in many layers, interlayered in places with dark amphibolite

Orange-Milford Belt

ORDOVICIAN
Maltby Lakes Metavolcanics: Greenstone, greenschist, and schist; also dark amphibolite to west and southwest. Upper part: Greenstone and greenschist, composed of epidote, albite, actinolite, and chlorite, and locally minor quartz, sericite, garnet, pyrite, or calcite. Mainly metavolcanic. Lower part: Greenschist, greenstone, and schist or phyllite, composed of albite and chlorite, plus quartz and sericite or epidote and actinolite. Mixed metavolcanic and metasedimentary rocks

Allingtown Metavolcanics: Greenstone, composed of epidote, actinolite, albite, and chlorite, commonly with abundant megacrysts of saussurite, interlayered with minor green phyllite, generally containing quartz and sericite. Dark amphibole in western outcrops

Oronoque Schist: Schist and granofels, composed of quartz, oligoclase or albite, muscovite or sericite, biotite or chlorite, and in western belt local garnet, staurolite, and kyanite. Small lenses of amphibolite or greenstone

BRONSON HILL ANTICLINORIUM

DEVONIAN(?)
Maromas Granite Gneiss: Granitic gneiss, composed of quartz and microcline with minor plagioclase and biotite. Central body is massive, but outlying strips are foliated and have accessory hornblende or garnet. Massive parts may be young anatectic intrusive rocks; foliated parts may include older felsic metavolcanic rocks belonging to the metavolcanic member of the Collins Hill Formation. Pegmatite bodies are common in the vicinity

DEVONIAN
Erving Formation: Granofels and schist, composed of quartz, plagioclase, and biotite, also muscovite in schist, and accessory garnet and kyanite

Littleton Formation: Alternating schist and micaceous quartzite, composed of quartz, muscovite, biotite, garnet, and oligoclase, also staurolite, graphite, and ilmenite, and in certain areas kyanite or sillimanite in schist

Mount Pisgah Member of Littleton Formation: Granofels or micaceous quartzite with some schist, composed of quartz, oligoclase, biotite, garnet, and sillimanite

SILURIAN
Fitch Formation: Calc-silicate rock, composed of quartz, biotite, calcite, actinolite, diopside, microcline, and locally garnet, scapolite, or epidote, interlayered with two-mica schist
Clough Quartzite: Quartzite and muscovitic quartzite, locally with garnet; conglomeratic (commonly with tourmaline) in lower part

ORDOVICIAN
Glastonbury Gneiss: Granitoid gneiss composed of oligoclase, quartz, microcline, and biotite (as patches), also epidote and hornblende in many areas, commonly associated with layers of amphibolite; else where minor muscovite and garnet

Collins Hill Formation: Schist, composed of quartz, oligoclase, muscovite, biotite, and garnet, and commonly staurolite, kyanite, or sillimanite, generally graphitic, interlayered with fine-grained two-mica gneiss, especially to the west, and with calc-silicate and amphibolite layers, also rare quartz-spessartine (coticule) layers

Metavolcanic member of Collins Hill Formation: Ranges from mafic to felsic, from dark layered amphibolite and hornblende schist, locally with garnet or epidote, to light-gray (in places purplish), laminated gneiss, composed of quartz, oligoclase, and biotite, in which some layers contain garnet (generally manganiferous) and hornblende or cummingtonite

Middletown Formation: Gneiss and granofels, ranging from quartz-biotite gneiss through felsic amphibole gneiss to amphibolite and characteristically containing anthophyllite or cummingtonite with or without hornblende. Also layers of calc-silicate rock and of biotite gneiss with quartz-sillimanite nodules

Upper member: Gneiss and granofels, composed of oligoclase, quartz, biotite, and amphibole (cummingtonite, anthophyllite, gedrite, or hornblende, or several of these), also garnet and chlorite. Many layers of amphibolite and biotite gneiss throughout

Lower member: Amphibolite and hornblende gneiss, commonly with garnet, diopside, or epidote, interlayered with light-gray gneiss composed of oligoclase, quartz, biotite, and generally one or more amphiboles, also garnet

Massive mafic rock (in Middletown Fm.): Massive amphibolite and metagabbro, composed of hornblende and plagioclase; in places with quartz and epidote, in others with patches of actinolite or anthophyllite, chlorite, and epidote or garnet. May be intrusive
Ultramafic rock: Ultramafic rock, originally composed of olivine and pyroxene, now generally altered to tremolite, talc, chlorite, or serpentine

Monson Gneiss: Gneiss and amphibolite; gneiss composed of plagioclase, quartz, and biotite, with hornblende in some layers and microcline in others; traces of garnet, epidote, and magnetite; map unit includes small outcrops of the Proterozoic Waterford Group

MERRIMACK SYNCLINORIUM

DEVONIAN OR SILURIAN

Scotland Schist: Schist, composed of quartz, muscovite, biotite, staurolite, and oligoclase, locally with kyanite or sillimanite; interlayered, especially below and to the west, with quartz-oligoclase-biotite schist and granofels and locally with quartzite; includes a quartzite unit: Quartzite, generally micaceous, interlayered with mica schist

SILURIAN-ORDOVICIAN

Bigelow Brook Formation

Upper member: Schist, composed of plagioclase, quartz, biotite, garnet, and sillimanite, locally with K-feldspar or cordierite, fissile layers commonly with graphite and pyrrhotite, interlayered with quartzose granofels with less biotite but with calc-silicate minerals

Middle member: Calc-silicate rock, composed of plagioclase, quartz, and diopside (locally hornblende and scapolite), interbedded with schist and granofels composed of plagioclase, quartz, biotite, and commonly garnet and sillimanite

Lower member: Granofels, composed of quartz, oligoclase, and biotite, commonly with garnet and sillimanite, interlayered with thinly fissile sillimanitic, graphitic, pyrrhotitic biotite schist and with calc-silicate rock

Southbridge Formation: Interlayered granofels and schist, composed of quartz, plagioclase, and biotite, with muscovite in schist, and amphibole, calc-silicate minerals or K-feldspar in certain layers; also locally mappable units and thinner layers of calc-silicate rock amphibolite, and sillimanite-garnet and sillimanite-graphite-pyrrhotite schist.

Hebron Gneiss: Schist, composed of andesine, quartz, biotite, and local K-feldspar, and greenish-gray, fine- to medium-grained calc-silicate rock, composed of labradorite, quartz, biotite, actinolite, hornblende, and diopside, and locally saprolite. Local lenses of graphitic two-mica schist

PS **Porphyritic member of Southbridge Formation:** Massive to layered gneiss, composed of quartz, oligoclase, microcline, and biotite, with megacrysts 1 to 2 cm long of microcline

ORDOVICIAN

Brimfield Schist: Interlayered schist and gneiss, composed of oligoclase, quartz, K-feldspar, and biotite, and commonly garnet, sillimanite, graphite, and pyrrhotite. K-feldspar partly as augen 1 to 3 cm across. Minor layers and lenses of hornblende- and pyroxene-bearing gneiss, amphibolite, and calc-silicate rock

Hornblende norite (DEVONIAN?): Massive rock, composed of bytownite, hornblende, and hypersthene

Foliated quartz diorite (DEVONIAN in part, ORDOVICIAN in part): Gneiss (locally strongly sheared, especially near contacts), composed of plagioclase, quartz, biotite, and hornblende, locally also pyroxene

Gneiss (metavolcanic) member of Brimfield Schist: Layered gneiss and schist, composed of oligoclase, quartz, and biotite; some gneiss and most schist layers contain garnet and sillimanite; some gneiss layers contain garnet, hornblende, or pyroxene or grade into amphibolite or calc-silicate rock. Probably includes metavolcanic rocks

Tatnic Hill Formation: Gneiss or schist composed of quartz, andesine, biotite, garnet, and sillimanite, locally kyanite, muscovite, or K-feldspar, interlayered with locally mappable units and thinner layers of rusty-weathering graphitic pyrrhotitic two-mica schist, amphibolite, and calc-silicate rock

Yantic Member: Schist, composed of quartz, oligoclase, biotite, and muscovite, some layers with garnet, staurolite, and kyanite or garnet and sillimanite, local epidote or K-feldspar; some layers of rusty-weathering graphitic, pyrrhotitic, two-mica schist

Fly Pond Member: Massive calc-silicate gneiss, composed of andesine, quartz, hornblende or actinolite, epidote, and commonly diopside, biotite, and scapolite; some layers are calcitic

Quinebaug Formation: Gneiss, composed of hornblende, andesine, biotite, and epidote, commonly with quartz or garnet, interlayered with amphibolite

Felsic gneiss member: Gneiss, composed of plagioclase, quartz, biotite, and muscovite, commonly with K-feldspar

Black Hill Member: Schist and granofels, composed of oligoclase, quartz, and biotite, commonly with hornblende or muscovite, and locally with calcite, garnet of epidote

DEVONIAN?
Foliated granitic gneiss: Gneiss, composed of phenocrysts of K-feldspar in a groundmass of plagioclase, quartz, K-feldspar, and biotite, with accessory sillimanite and garnet

DEVONIAN
Canterbury Gneiss: Gneiss, composed of quartz, oligoclase, microcline, and biotite, locally also muscovite or epidote, and generally with megacrysts 1 to 2 cm long of either or both feldspars
"Eastford gneiss phase": Gneiss, composed of quartz, microcline, oligoclase or albite, biotite, and muscovite

Lebanon Gabbro: Locally sheared gabbro, composed of hornblende, labradorite, and opaques. Some bodies contain biotite and quartz; some smaller ones are nearly pure hornblende with local augite.
Dioritic phase: Foliated or sheared gneiss, composed of plagioclase, biotite, quartz, and generally hornblende

Preston Gabbro (MIDDLE ORDOVICIAN OR OLDER): Massive gabbro, composed of labradorite, augite, and opaques, generally with hornblende, locally hypersthene or olivine or both
Dioritic phase: Medium-grained diorite and quartz diorite, gneissic where sheared near contact, composed of plagioclase, hornblende, and biotite, and locally quartz and relic pyroxene

AVALONIAN (CONTINENTAL) TERRANE
AVALONIAN ANTICLINORIUM

PERMIAN
Narragansett Pier Granite: Granite, composed of microcline, oligoclase, quartz, and biotite and accessory muscovite and magnetite. Considerable associated pegmatite
Mafic phase: Massive granite, like the Narragansett Pier Granite but with more biotite and locally hornblende

PROTEROZOIC Z?
Sterling Plutonic Group
Hope Valley Alaskite Gneiss: Alaskitic gneiss, composed of microcline, quartz, albite or oligoclase, and minor magnetite, and locally biotite and muscovite. Lineation formed by rods of quartz. Locally contains quartz-sillimanite nodules
Potter Hill Granite Gneiss: Granitic gneiss, composed of microcline, quartz, oligoclase (or albite), biotite, and magnetite, minor muscovite, and local garnet
"Scituate" Granite Gneiss (probably not equivalent to type Scituate in Rhode Island, which is probably Devonian): Granitic gneiss, composed of microcline, quartz, albite or orthoclase, biotite, hornblende, and magnetite. Megacrysts of microcline up to 3 cm long; lineation formed by splotches of biotite or by rods of quartz

Porphyritic phase of Potter Hill Granite Gneiss: Granitic gneiss, composed of microcline (much of it as megacrysts up to 4 cm long), quartz, oligoclase, biotite, and magnetite
Ponaganset Gneiss: Gneiss, composed of oligoclase, quartz, microcline (mostly as megacrysts to to 8 cm long), biotite, magnetite, and generally hornblende; also garnet and muscovite where hornblende is absent

Light House Gneiss: Granitic gneiss, composed of K-feldspar, oligoclase, quartz, biotite, and magnetite, with local muscovite but no garnet
Branford Gneiss: Granitic gneiss, composed of oligoclase, K-feldspar, quartz, biotite, garnet, magnetite, and muscovite
Stony Creek Granite Gneiss: Granite or granite gneiss, composed of oligoclase, K-feldspar, and quartz with minor biotite and magnetite, sporadic garnet (in foliated varieties), and local muscovite. Commonly contains granite and pegmatite of Narragansett Pier type (and probably age). In much of area both granites occur as innumerable veins penetrating other units or as larger bodies full of inclusions of those units, which can be mapped through the bodies of granite

PROTEROZOIC Z?

Waterford Group: Gneiss, composed of plagioclase, quartz, and biotite, with hornblende in some layers and microcline in others. Some layers of amphibolite

Rope Ferry Gneiss: Gneiss, composed of plagioclase, quartz, and biotite, with hornblende in some layers and microcline in others. Some layers of amphibolite

Mamacoke Formation: Gneiss, composed of plagioclase, quartz, and biotite, sillimanite, garnet, hornblende or microcline in certain layers; in upper part locally contains quartz-sillimanite nodules or thin layers of quartzite, amphibolite, or calc-silicate rock

Westerly Granite (PERMIAN): Granite, composed of oligoclase or albite, quartz, and K-feldspar, with minor biotite and accessory muscovite, magnetite, allanite, and sphene

New London Gneiss: Granodioritic gneiss, also interlayered light-gray gneiss and dark-gray amphibolite; gneiss generally medium grained; composed of oligoclase, quartz, biotite, and magnetite, also microcline in massive gneiss

Joshua Rock Member: Gneiss composed of microperthite, quartz, albite, aegerine-augite, and magnetite; rare riebeckite

Plainfield Formation: Interlayered quartzite, phyllite, (locally graphitic) and gneiss composed of quartz, oligoclase, and biotite (rarely microcline), medium- to dark-gray schist composed of quartz oligoclase, biotite, sillimanite, and garnet, dark-gray or green gneiss composed of plagioclase, quartz, biotite, and hornblende (commonly with diopside), amphibolite, diopside-bearing quartzite, and calc-silicate rock. In places contains quartz-sillimanite nodules

Quartzite unit: Quartzite, also feldspathic and micaceous quartzite containing quartz-sillimanite nodules

FAULT-RELATED ROCKS

Silicified rock and mylonite along Mesozoic faults (PROBABLY JURASSIC): Close network of quartz veins and veinlets cutting each other and older rock. In places, incompletely replaced rock shows strongly mylonitic texture

Mylonite along Paleozoic faults (PALEOZOIC): Intensely granulated quartz, plagioclase, biotite, and epidote, in places with hornblende and microcline and commonly with secondary minerals. In places has been silicified

The Central Lowlands, also called the Connecticut Valley, is a downfaulted block of land underlain by sedimentary and igneous rocks. The terrain is level to flat with few areas of hills and ridges; elevations range from sea level to about 300 ft. The Central Valley is divided by a ridge of volcanic rock called the Metacomet Ridge, which runs almost the entire length of the valley in both Connecticut and Massachusetts.

The Eastern Uplands are underlain by rolling hills of schist, gneiss, and granite. Elevations reach over 1000 ft in the northern hills and decrease to less than 700 ft towards the south. Elevation is at sea level at the Atlantic coast. Along the western edge of the Eastern Uplands, a group of long ridges, including the prominent Bolton Ridge, which runs from the Massachusetts state line southward to Portland, Connecticut, have the most rugged topography of the region. Another less prominent group of ridges runs along the Rhode Island-Connecticut border south to North Stonington, where the ridges change to a generally east-west trend, ending at the Connecticut River in Lyme (Bell, 1985). The central part of the Eastern Uplands consists mainly of rounded, rolling hills.

The population of Connecticut was approximately 3,287,116 in 1990, including 79 percent urban population (fig. 3). The climate is moderate, with winter temperatures averaging 32 °F and winter snowfall averaging 3-5 ft; summers average between 70 °F and 75 °F. Average annual precipitation ranges from 44 to 52 inches (fig. 4).

BEDROCK GEOLOGY

The following discussion of bedrock geology is derived from the Bedrock Geological Map of Connecticut by Rodgers (1985). A general geologic map is given for reference in figure 2. It is suggested, however, that the reader refer to the detailed State Geologic Map of Connecticut and to other detailed geologic maps and information available from the Connecticut Department of Environmental Protection's Natural Resources Center (Levere, 1991). The geology of Connecticut has been divided into several terranes and sub-terranes (fig. 1). These terranes reflect the geologic processes (plate tectonics) that produced the rocks seen today. The Avalonian terrane was thrust against the continent of Proto-North America approximately 450-250 million years ago. This collision closed the intervening Iapetos Ocean and deformed the two terranes and the sediments of the Iapetos Ocean floor, forming the schists, gneisses and granites that underlie the Western and Eastern Uplands. About 235 million years ago, the terranes began breaking apart, forming a rift basin. The Newark Terrane is the erosional remnant of that rift basin.

The Western Uplands

The Western Uplands contain the Proto-North American Terrane and part of the Iapetos Terrane. Carbonate shelf rocks and Proterozoic-age massifs comprise the Proto-North American Terrane, whereas schist of the Connecticut Valley Synclinorium and the Taconic Allochthons comprise the Iapetos Terrane. The oldest rocks of the Western Uplands are the complexly folded and faulted crystalline rocks of the Proterozoic massifs. These rocks underlie much of the northern and western portions of the province and are infolded with younger metasedimentary rocks of Paleozoic age. Layered gneiss, hornblende gneiss and amphibolite, micaceous schist and quartz-feldspar gneiss are the principal rock types. Pink granitic gneiss forms irregular masses throughout the sequence and augen gneiss occurs locally. The layered gneiss contains alternating bands of light and dark minerals with minor layers and lenses of calc-silicate rock and amphibolite. Hornblende gneiss and amphibolite is composed of hornblende and feldspar with biotite and minor

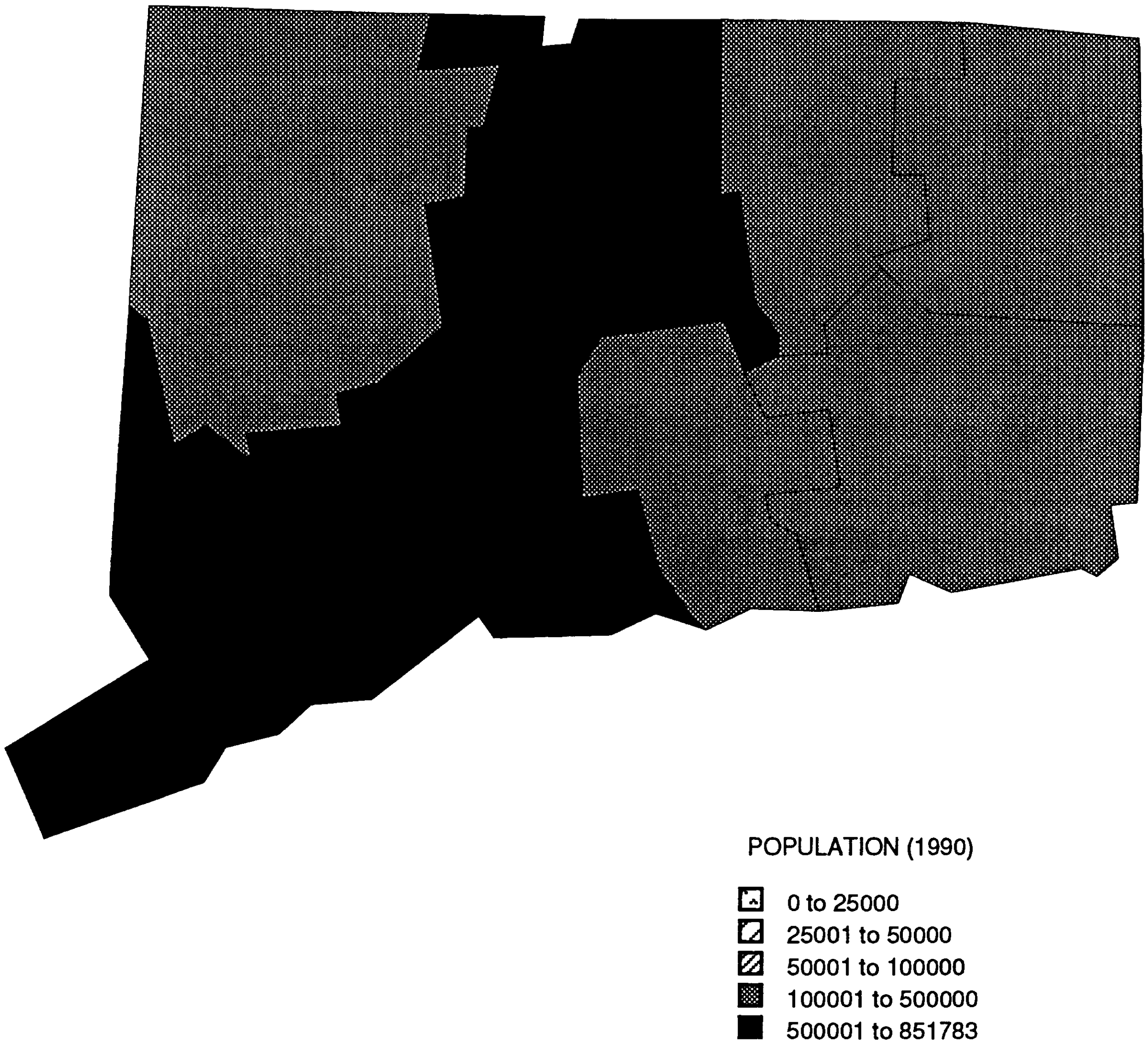


Figure 3. Population of counties in Connecticut (1990 U.S. Census data).

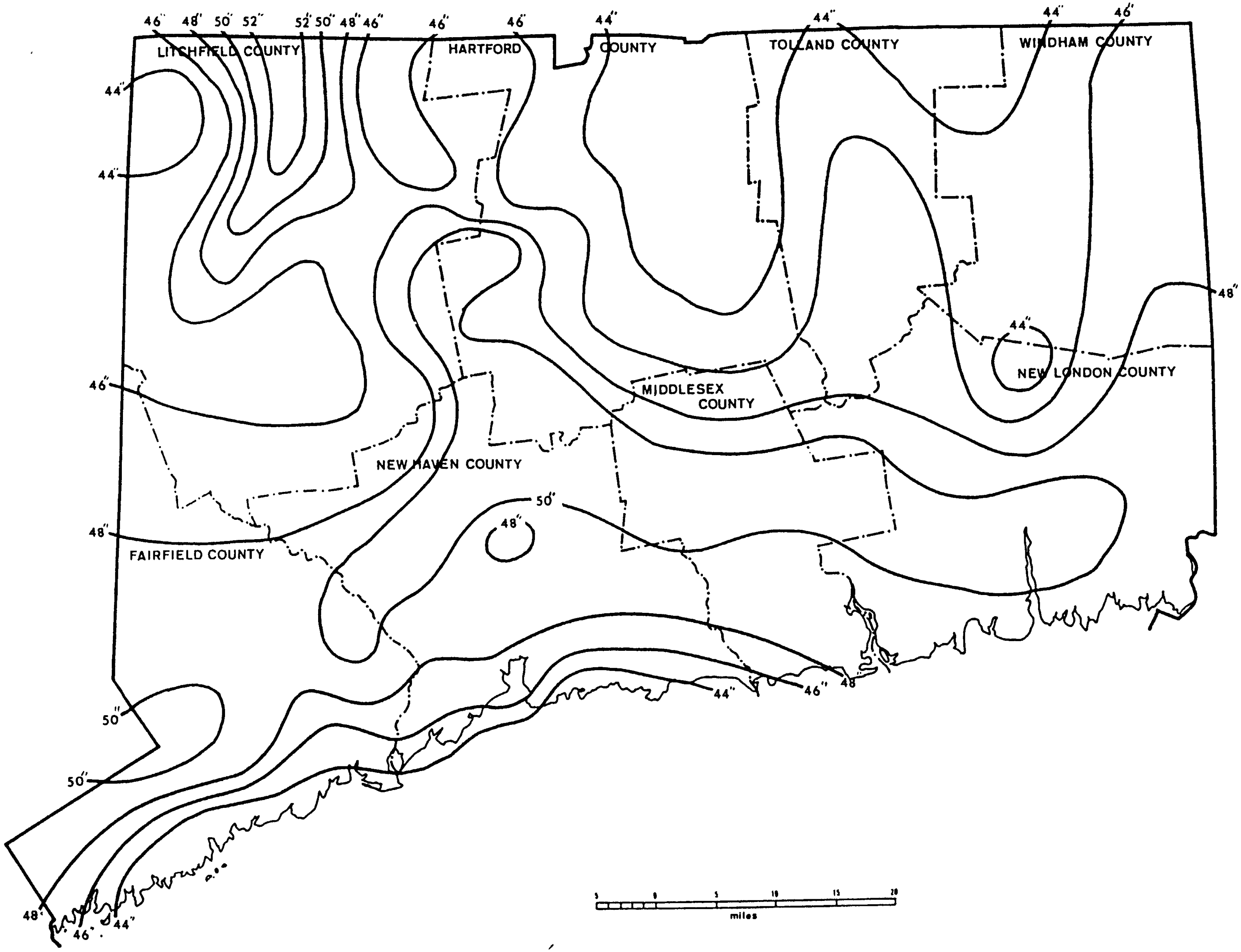


Figure 4. Average annual precipitation in Connecticut (modified from Smith, 1974).

quartz. These are commonly interlayered with banded felsic gneiss and locally contain calc-silicate rock or diopsidic calcite marble. Much of the schist and gneiss has a distinct iron staining referred to as rusty weathering.

Ordovician and Cambrian metasedimentary rocks comprise the carbonate shelf sequence found in the western portion of the province. Cambrian-age clastic rocks appear to be the oldest rocks of the sequence and consist of highly variable, locally schistose quartzite of the Dalton Formation. This is overlain by a thick sequence of carbonate rocks called the Stockbridge Marble, a calcic to dolomitic massive marble with layers of calcareous siltstone, sandstone, quartzite, phyllite, and schist. Unconformably overlying the Stockbridge Marble is the Ordovician-age Walloomsac Schist, consisting of quartzose schist and phyllite locally with garnet, staurolite, or sillimanite.

The Taconic Allochthons are fault-bounded rock bodies thrust over the above-described units. The Taconic Allochthons contain Cambrian-age metamorphic rocks of the Everett Schist, Canaan Mountain Schist, Hoosac Schist, and Manhattan Schist. The Everett, Cannan Mountain, and Hoosac Schists are found in the northernmost bodies of the Allochthon. The Everett Schist is comprised of aluminous schist and phyllite. The Cannan Mountain Schist is well-layered mica schist and schistose gneiss with layers of amphibolite and quartzite. The Hoosac Schist is aluminous schist and poorly-layered schistose gneiss. The southern exposures of the Taconic Allochthons are made up of the Manhattan Schist, a rusty-weathering, biotite gneiss and schistose gneiss with minor amphibolite.

More than half of the Western Uplands is underlain by the schist, gneiss, and phyllite of the Connecticut Valley Synclinorium. The northwestern portion of the synclinorium is underlain predominantly by aluminous schist, with minor amphibolite and calc-silicate rock of the Rowe Schist and the Ratlum Mountain Schist. Ordovician-age granite gneiss and the Ordovician Brookfield Gneiss, consisting of granodioritic and dioritic gneiss, lie to the south of the schists and in smaller areas to the north, where the exposures also include the Litchfield Norite. The Harrison Gneiss, a light- to dark gray mafic gneiss, is exposed in the southwestern part of the State, and outcrops of the Harrison extend northward along the eastern edge of the Western Uplands to the southwest corner of Hartford County. The Trap Falls Formation overlies the Harrison Gneiss and is exposed in the southern part of the Western Uplands. It consists of gray to silvery, rusty-weathering schist and lighted-colored gneiss. The Golden Hill Schist, exposed in eastern Fairfield County near the Long Island Sound, may be equivalent to part of the Trap Falls Formation.

The eastern part of the Connecticut Valley Synclinorium is underlain by schist, gneiss, and phyllite. The oldest rocks in this area are those of the Cambrian Waterbury Gneiss, a gneiss and schistose gneiss irregularly mixed with granite gneiss, forming the Waterbury Dome in the vicinity of Waterbury in north-central New Haven County. The Ordovician Taine Mountain Formation, consisting of "pin stripe" gneissic and schistose granofels, and the Collinsville Formation, comprising felsic and mafic schist and gneiss, are exposed throughout the eastern Connecticut Valley Synclinorium. The Bristol Gneiss, a felsic gneiss interlayered in places with amphibolite, is exposed in the vicinity of Bristol in southwestern Hartford County, with a smaller outcrop near Collinsville in west-central Hartford County. The Hawley Formation, a gray, rusty-weathering, carbonaceous schist, is exposed in thin bands in the northeastern part of the area. The Cobble Mountain Formation, consisting of gray to silvery schist and granofels, underlies an area just east of Barkhamsted Reservoir near the Massachusetts border. The Silurian-Devonian Straits Schist is exposed in wide bands along the eastern edge of the Western Uplands from the Massachusetts border almost to the Atlantic coastline. It is a silvery to gray, coarse-grained schist that is graphitic almost throughout. The Devonian Nonewaug Granite intrudes the Rowe and Ratlum Mountain Schists in the northern and central part of the area, and the Permian-age Pinewood Adamellite, a light gray granite, intrudes the Trap Falls Formation in the vicinity of Pinewood Lake in southeastern Fairfield County. Intrusive rocks ranging in age from Devonian to Jurassic are found, primarily as dikes, throughout the area.

The southeasternmost part of the Connecticut Valley Synclinorium is an area referred to as the Orange-Milford Belt, separated from the rest of the area by the East Derby Fault. It is underlain by rocks of Ordovician to Devonian age, including the Oronoque Schist, a light colored schist and granofels; the Allingtown and Maltby Lakes Metavolcanics, comprising greenstone, schist, and phyllite; and the Wepawaug Schist, comprising graphitic schist and phyllite, and metasiltstone.

The Central Lowlands (Newark Terrane, including the Hartford and Pomperaug Basins)

Late Triassic-early Jurassic continental sedimentary and igneous rocks of the Newark Supergroup (Froelich and Olsen, 1984) occur in two half-graben basins extending from north to south in the central part of the State. Each basin is underlain by eastward-dipping strata that are folded into broad synclines along the faulted eastern margin. The Hartford basin is the largest of the Mesozoic basins, occupying the Central Lowlands and extending northward into Massachusetts. The basal Triassic New Haven Arkose consists of fluvial arkosic sandstone, conglomerate, and siltstone, forming a wide band on the western side of the basin. It is more conglomeratic along its basal contact with older rocks to the west. The New Haven Arkose is overlain by a narrow belt of complexly-faulted Jurassic volcanic and sedimentary rocks that include the Talcott Basalt, Shuttle Meadow Formation, Holyoke Basalt, East Berlin Formation, and the Hampden Basalt. The Shuttle Meadow and East Berlin Formations comprise a mixture of sandstone and conglomerate and red and black lacustrine shales. The Talcott, Holyoke, and Hampden Basalts are tholeiitic basalt flows. The eastern part of the Hartford basin is a wide belt of sedimentary rocks of the Jurassic Portland Formation. The lower part of the Portland consists of lacustrine black shales and red siltstones and the upper part consists of fluvial sandstones and conglomerates. Along the eastern margin of the basin, all of the formations intertongue with alluvial fan conglomerates composed of the older rocks immediately outside of the basin.

The Pomperaug basin is a tiny half graben west of the Hartford basin, near the center of the Western Uplands. It has the same stratigraphic sequence as the Hartford basin, but all of the units are proportionally thinner within the basin. Jurassic diabase dikes and sills intrude the sedimentary rocks of both basins.

The Eastern Uplands

The Eastern Uplands consist of the Bronson Hill Anticlinorium and the Merrimack Synclinorium of the Iapetos Terrane, and the Avalonian Terrane. The Ordovician Monson Gneiss, an interlayered gneiss and amphibolite, is the oldest rock unit in the Bronson Hill Anticlinorium. It covers much of the southern part of the area and forms a relatively narrow outcrop band along the eastern side of the Anticlinorium. It is overlain by the Middletown Formation, consisting of gneiss, granofels, hornblende gneiss, amphibolite, and metagabbro, which is equivalent to the Ammonoosuc Volcanics of New Hampshire. These are overlain by the Collins Hill Formation, containing rusty-weathering, graphitic schist interlayered with two-mica gneiss, and mafic to felsic metavolcanic rocks; the Clough Quartzite; the Fitch Formation, consisting of calc-silicate rock and two-mica schist; the Littleton Formation, consisting of schist, micaceous quartzite, and granofels; and the Erving Formation, comprising granofels and schist. Intrusive rocks include the Ordovician

Glastonbury Gneiss, which forms a wide band in the northern and central part of the area, and the Devonian Maromas Granite Gneiss, which is exposed in thin bands adjacent to the Monson and Glastonbury Gneisses. Massive mafic and ultramafic rocks, thought to be intrusive, are found within exposures of the Middletown Formation.

The Merrimack Synclinorium lies east of the Bronson Hill Anticlinorium and underlies the central part of the Eastern Uplands (fig. 1). The Ordovician-age Quinebaug Formation, consisting of mafic gneiss, amphibolite, schist, and granofels, and the Preston Gabbro, are the oldest rocks in the Synclinorium, and they underlie the easternmost part. These are overlain by the Tatnic Hill Formation, consisting of gneiss and schist with thin layers of graphitic pyrrotitic schist, amphibolite, and calc-silicate rock; the Brimfield Schist, a gray, rusty-weathering, interlayered schist and gneiss; and the Hebron Gneiss, consisting of interlayered dark gray schist and calc-silicate rock with local lenses of graphitic two-mica schist. The Southbridge Formation, comprising interlayered granofels and schist, and porphyritic gneiss, is exposed mainly in the northern part of the area. It is overlain by the Bigelow Brook Formation, consisting of fissile schist with graphite and pyrrhotite and interlayered schist and granofels. The Scotland Schist underlies a large part of the central Merrimack Synclinorium. It is composed of schist and granofels that is interlayered locally with quartzite. Intrusive rocks include the Lebanon Gabbro and Canterbury (granitic) Gneiss, which intrude metamorphic rocks in the central part of the area, and smaller intrusions of hornblende norite and foliated quartz diorite and granitic gneiss, all of Devonian age.

The Avalonian Terrane occupies the eastern and southern parts of the Eastern Uplands, separated from the Merrimack Synclinorium by the Lake Char Fault (fig. 1). Relatively small windows of Avalonian Terrane rocks are also found in the central part of the Merrimack Synclinorium near Willimantic in southwestern Windham County. Most of the rocks of the Avalonian Terrane are Proterozoic in age. The Plainfield Formation consists of interlayered quartzite, locally graphitic phyllite, gneiss, amphibolite, and calc-silicate rock. It is overlain by the Waterford Group, consisting of the Rope Ferry Gneiss, New London Gneiss, and Mamacoke Formation gneiss. These are intruded by a number of granitic gneisses, including the Light House Gneiss; Branford Gneiss; Stony Creek Granite Gneiss; the Sterling Plutonic Group, consisting of the Hope Valley Alaskite Gneiss, Potter Hill Granite Gneiss, Ponaganset Gneiss, and "Scituate" Granite Gneiss, which is probably not equivalent to the Scituate Granite Gneiss in Rhode Island (Rodgers, 1985); and the Permian-age Narragansett Pier and Westerly Granites. The Narragansett Pier Granite also has a mafic phase, containing biotite and hornblende, which underlies a small area in the southeasternmost part of the State.

GLACIAL GEOLOGY

Deposits of five or possibly six Pleistocene glacial advances in New England have been recognized or inferred from surface or subsurface data (Stone and Borns, 1986); however, only two till units are identified in Connecticut by Stone and others (1992). Glacial deposits exposed at the surface in Connecticut are of Late Wisconsin age. Glaciers moved in a dominantly N-S or NNW-SSE direction across the State, terminating on Long Island at their maximum extent. In Late Wisconsin time, two main glacial lobes advanced across Connecticut. The Hudson-Champlain Lobe advanced across New York and western Connecticut. The Connecticut Valley Lobe covered the remainder of the State and carved the Connecticut River Valley. Glacial Lake Hitchcock occupied the northern part of the Connecticut Valley from approximately 16,500 years ago until about 13,500 years ago (Stone and Borns, 1986). Silt and clay glacial lake deposits occupy the floor of the Connecticut Valley from the northern border of the State to just south of Berlin in south-central Hartford County (fig. 5). The final retreat of Wisconsinan glaciers from Connecticut occurred about 12,000 years ago (Stone and Borns, 1986).

Glacial deposits in Connecticut range from a few feet to several hundred feet in thickness (Stone and others, 1992). Figure 5 is a generalized map of glacial deposits in Connecticut. Till, sometimes also referred to as drift or ground moraine, is the most widespread glacial deposit (fig. 5). Till was deposited directly by glacier ice and it is composed of a poorly sorted matrix of sand, silt, and clay containing variable amounts of rounded cobbles and boulders. Glacial landforms typically associated with till include drumlins, kettles, and moraines. Stratified glacial deposits were laid down by glacial meltwater in streams and lakes in front of the retreating ice margin. They are characterized by layers of poorly-sorted to well-sorted gravel, sand, silt, and clay (Stone and others, 1992). Ice-contact stratified drift (referred to as stratified glacial deposits on fig. 5) includes deposits of kames, eskers, lacustrine deltas, and kame moraines. These coarse-grained deposits range from poorly sorted to well sorted and consist of sand, gravel, cobbles, and boulders, with varying amounts of silt and clay, though they generally contain considerably less fine-grained material than till. Outwash consists of layers of sand and gravel deposited by glacial meltwater streams. Outwash is generally the coarsest-grained class of glacial deposits because most of the silt and clay was removed by the rapidly-moving water. Glacial lake-bottom deposits consist primarily of finely bedded silt and clay.

In the upland areas of the State, till is the most common type of glacial deposit, occurring as a discontinuous layer that is thickest in drumlins and on the northwest slopes of hills. The matrix of most tills is composed dominantly of sand and silt, but clayey tills occur in areas in which a fine-grained bedrock source is present. Stratified glacial deposits averaging 10-40 feet thick, but locally as much as 200 feet thick, overlie till in small upland valleys and north-sloping pockets between bedrock hills (Stone and others, 1992). In the Central Lowlands, stratified glacial deposits are the predominant surficial deposit type. They generally overlie till and average 50-100 feet in thickness. Glacial lake deposits cover most of the northern part of the Connecticut Valley (fig. 5).

The color and lithology of the tills vary across the State and reflect the characteristics of the local bedrock from which the till is derived. The sedimentary rocks of the Central Lowlands produce tills that are brown to red-brown in color; siltstones contribute a significant amount of fine-grained material. Fragments of basalt and dolerite that occur adjacent to the sedimentary rocks are commonly found in the reddish-brown tills of the Central Lowlands. Deposits derived from quartzite tend to be sandy, containing abundant quartz sand grains and quartzite fragments. Marbles produce fine-grained, light-colored, calcareous (calcium carbonate rich) glacial deposits. Dark-colored schists and phyllites produce fine-grained, dark-colored tills. Muscovite schists produce lighter-colored tills containing abundant mica flakes. Schists and gneisses containing abundant iron sulfides produce reddish-brown tills, commonly with iron cements. Glacial deposits derived from granitic rocks are generally light-colored and sandy. Mafic rocks such as amphibolite and hornblende gneiss produce dark-colored glacial deposits containing abundant iron minerals. Light- to medium-gray schists and gneisses underlie more than half of Connecticut and produce gray to yellowish-gray, silty and sandy tills (Stone and others, 1992).

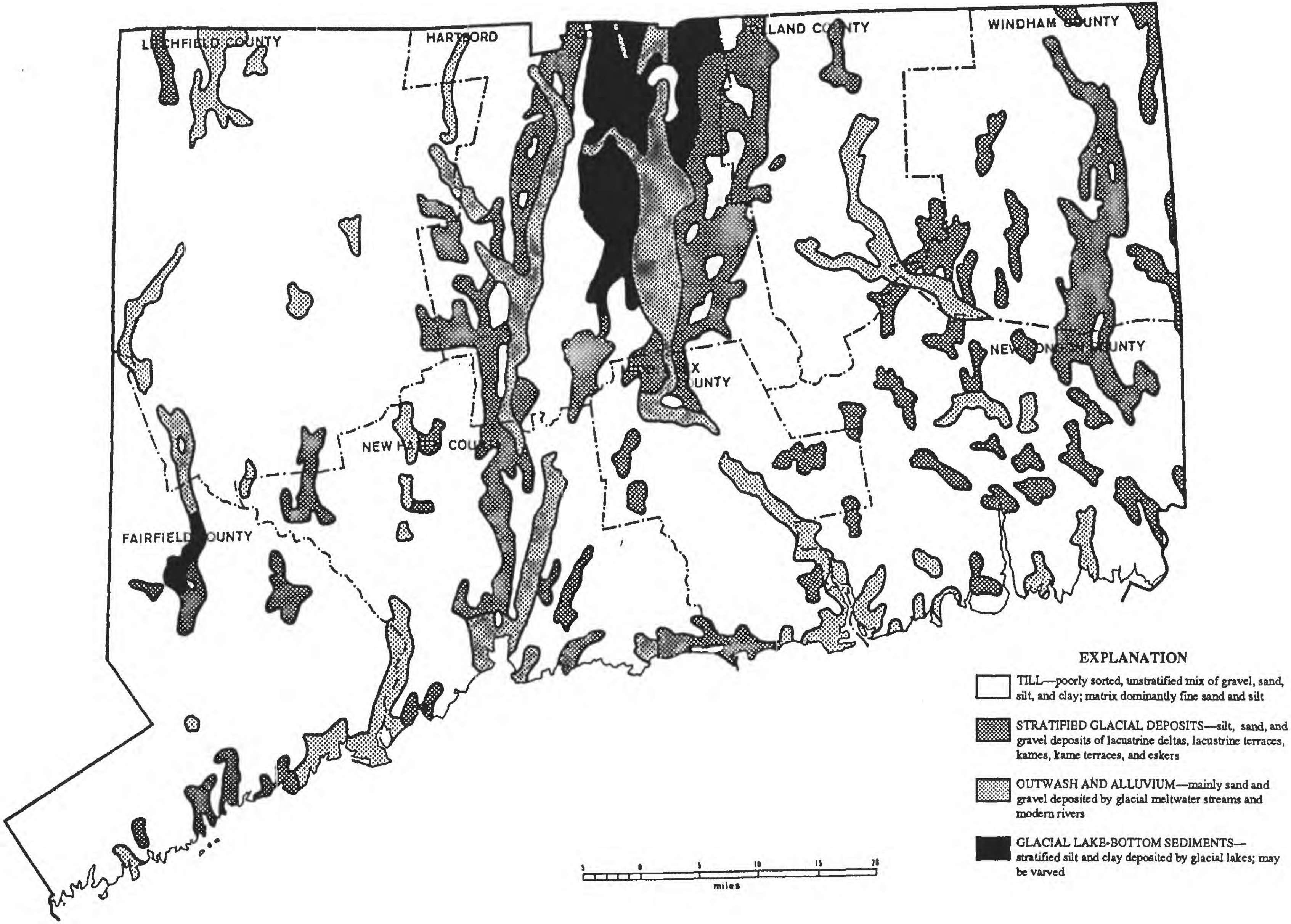


Figure 5. Generalized map of glacial deposits in Connecticut (after Flint and others, 1959, and Stone and others, 1992).

SOILS

Soils in Connecticut include, in order of abundance, Inceptisols, mineral soils with horizons of alteration or accumulation of metal oxides such as iron, aluminum, or manganese; Entisols, mineral soils with no discernible horizons because their parent material is inert (such as quartz sand) or because the soils are very young; and Histosols, organic soils such as peats or mucks which occur along coastlines or in river valleys (Hill and others, 1980). A generalized soil map of Connecticut (fig. 6) and the following descriptions of soils in the State are condensed from Gonick (1978) and Hill and others (1980).

Soils formed in glacial till derived from gneiss, schist, and granite occur in the Eastern and Western Uplands. These soils are typically described as shallow, moderately well-drained to excessively drained, stony, silty and sandy loams. Many of these soils have a firm, clayey subsurface horizon. Permeability of these soils ranges from low to high, but most soils in this area have low to moderate permeability (fig. 6). Soils formed on stratified deposits (outwash, ice-contact deposits, and alluvium) derived from gneiss, schist, and granite in the Eastern and Western Uplands are deep, poorly-drained to well-drained, gravelly, silty and sandy loams with moderate to high permeability. These soils are generally formed on terraces (Gonick, 1978) and are underlain by sand and gravel deposits.

Soils formed on glacial till derived from limestone, dolomite, and marble, and soils formed on stratified deposits derived from limestone and marble occur in the Western Uplands along the Connecticut-New York border. These soils are deep, moderately well-drained to excessively drained, calcareous, gravelly, sandy and silty loams. Soils developed on glacial till are generally found in upland areas and have low to moderate permeability, whereas soils developed on stratified deposits typically occur on terraces and have high permeability (Hill and others, 1980).

Soils of the Central Lowlands include gravelly, silty and sandy loams developed on glacial till derived from sandstone, shale, conglomerate, and basalt; and silty and sandy loams developed on stratified deposits derived from sandstone, shale, conglomerate, and basalt (fig. 6). These soils have a distinctive red color acquired from the underlying red sandstone bedrock (Hill and others, 1980). The soils developed on glacial till are generally sited on uplands whereas those developed on stratified deposits are typically found on terraces (Gonick, 1978). Soils developed on glacial deposits in the Central Lowlands are typically well-drained to excessively drained but have low to moderate permeability. Soils developed on stratified deposits in the Central Lowlands have moderate to high permeability but drainage characteristics range from poorly drained to well drained. Soils in the northern part of the Central Valley west of the Connecticut River are formed on silt and clay glacial lake deposits with low permeability (Hill and others, 1980). Several of the soil units in this area are classified as wet, particularly those developed on glacial lake deposits, floodplains, and low-lying terraces (fig. 6). Some of the soils along the coast and locally in the Connecticut River Valley are organic soils with silty substrata developed on low-lying wetlands that are commonly flooded (fig. 6).

Descriptions of these soils as silty or sandy loams generally apply to the uppermost soil layer. Many of the soils have a subsurface horizon in which iron and aluminum oxides and(or) clays have accumulated. Soils with clayey B horizons, including many of the soils developed on glacial deposits, can inhibit radon transport to the surface but may have sufficient permeability below the B horizon to allow significant lateral radon transport, allowing radon to enter a building's foundation if the basement extends below the depth of the B horizon.

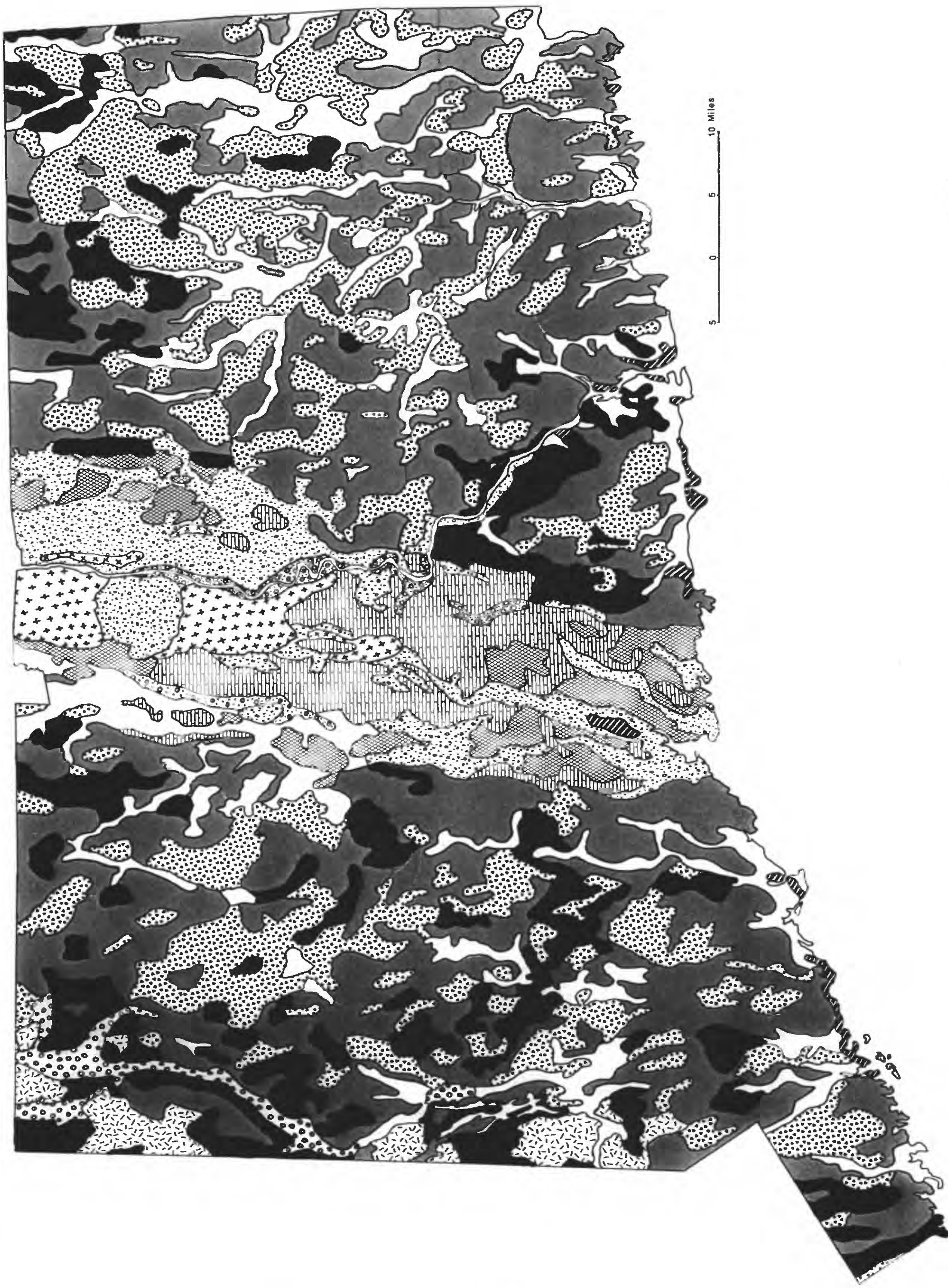


Figure 6. Generalized soil map of Connecticut (modified from Hill and others, 1980).

GENERALIZED SOIL MAP OF CONNECTICUT
EXPLANATION

SOILS OF THE EASTERN AND WESTERN HIGHLANDS FORMED IN GLACIAL TILL DERIVED FROM GNEISS, SCHIST, AND GRANITE

stony, silty and sandy loams—*moderate permeability*

silty and loamy soils with firm substrata—*low permeability*

silty soils with friable substrata—*moderate to high permeability*

SOILS OF THE EASTERN AND WESTERN HIGHLANDS FORMED IN STRATIFIED DEPOSITS DERIVED FROM GNEISS, SCHIST, AND GRANITE

sandy and gravelly soils—*high permeability*

SOILS OF THE WESTERN HIGHLANDS FORMED IN GLACIAL TILL DERIVED FROM LIMESTONE AND SCHIST

calcareous sandy and silty loams—*low to moderate permeability*

SOILS OF THE WESTERN HIGHLANDS FORMED IN STRATIFIED DEPOSITS DERIVED FROM LIMESTONE AND SCHIST

calcareous, gravelly, sandy and silty loams—*high permeability*

SOILS OF THE CENTRAL LOWLANDS OF THE CONNECTICUT RIVER VALLEY FORMED IN GLACIAL TILL DERIVED FROM SANDSTONE, SHALE, CONGLOMERATE, AND BASALT

gravelly, silty and sandy loams—*low to moderate permeability*

silty and sandy loams with firm substrata—*low permeability*

SOILS OF THE CENTRAL LOWLANDS OF THE CONNECTICUT RIVER VALLEY FORMED IN STRATIFIED DEPOSITS DERIVED FROM SANDSTONE, SHALE, CONGLOMERATE, AND BASALT

gravelly and sandy soils—*high permeability*

silts and clays formed on glacial lake deposits—*low permeability*

silty and sandy alluvial soils—*moderate permeability*

SOILS OF COASTAL LOWLANDS AFFECTED BY TIDAL WATER

organic soils with silty substrata—*moderate permeability, wet*

RADIOACTIVITY

An aeroradiometric map of Connecticut (fig. 7a) compiled from NURE flightline data (Duval and others, 1989) shows radioactivity of surficial materials in the State. Low radioactivity (<1.5 ppm eU) is found in the northernmost Western Uplands associated with Proterozoic gneiss of the Berkshire Mountains, in several parts of the Central Lowlands associated with Jurassic igneous rocks, and along the eastern border of the State in the Eastern Uplands associated with Proterozoic schist. Moderate radioactivity (1.5-2.5 ppm) covers most of Connecticut, including the northern half of the Western Uplands, most of the Central Lowlands and northern portions of the Eastern Uplands. High radioactivity (>2.5 ppm) is associated with rocks of the Connecticut Valley Synclinorium, especially Ordovician-age granitic gneiss in the southern half of the synclinorium. High radioactivity is also prevalent in Bronson Hill Anticlinorium and is associated with granitic rocks in parts of the Avalonian Terrane and Merrimack Synclinorium. A moderate to high radioactivity anomaly clearly follows the path of the Connecticut River and may reflect the radioactivity of bedrock exposed by river erosion relative to the generally lower radioactivity of surrounding till.

The Connecticut Geological Survey has also compiled a map using total gamma radioactivity (compiled from Popenoe, 1964, 1966) and percent of indoor radon greater than 4 pCi/L in the State/EPA Residential Radon Survey of Connecticut. This map is shown in figure 7b. Areas of highest radioactivity are the southern Connecticut Valley Synclinorium and the Avalonian Terrane. In both of these areas, high radioactivity appears to be most closely associated with granites and granitic gneisses. Scattered high radioactivity areas in the Merrimack Synclinorium and in the northern and central parts of the Connecticut Valley Synclinorium also appear to be associated with granitic rocks and locally with graphitic schist, particularly the Straits Schist. Towns located in areas of high radioactivity (700-900 counts per second total gamma radioactivity) also had the highest percentage of homes with indoor radon levels exceeding 4 pCi/L (fig. 7b).

A carborne gamma radioactivity conducted by the Connecticut Geological Survey (Thomas, 1987) also confirms these correlations. Total-count gamma radioactivity was measured in traverses covering 1367 miles in all parts of the State. When analyzed by geologic terrane, it was found that the Merrimack Synclinorium and Avalonian Terrane had the highest radioactivity, and that radioactivity was lowest over the Newark Terrane.

INDOOR RADON

The State of Connecticut has conducted extensive indoor radon testing and data analysis. The Connecticut Department of Health Services conducted a Household Testing Program (HTP) in which short-term charcoal canister tests were made in 3378 homes during 1987-88. These data were combined with indoor radon measurements from the Connecticut Radon Survey, in which 202 homes were tested using three-month alpha-track tests, and with data from the State/EPA Residential Radon Survey, representing a total of 5036 homes, or about one percent of single family homes in Connecticut (Siniscalchi and others, 1991). Of the 169 towns in Connecticut, 20 have average indoor radon levels exceeding 4 pCi/L. The averages range from 4.03 to 8.33 pCi/L, and the towns, in order from highest to lowest, are Guilford, Sprague, Woodstock, Ansonia, Branford, Morris, Bethany, Voluntown, Weston, Westport, Hampton, Madison, Haddam, Canterbury, Scotland, Oxford, Putnam, Woodbridge, Glastonbury, and Thompson.

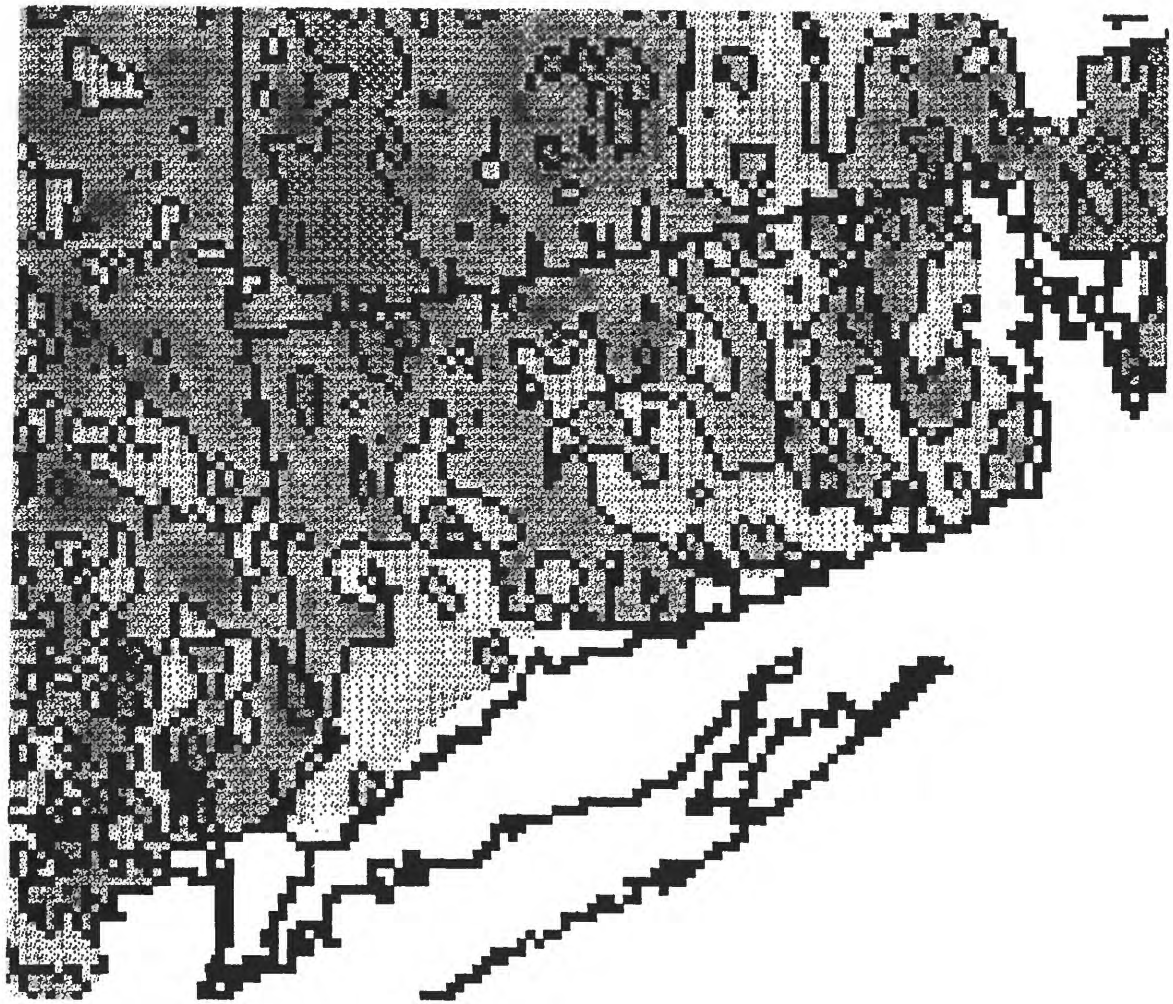
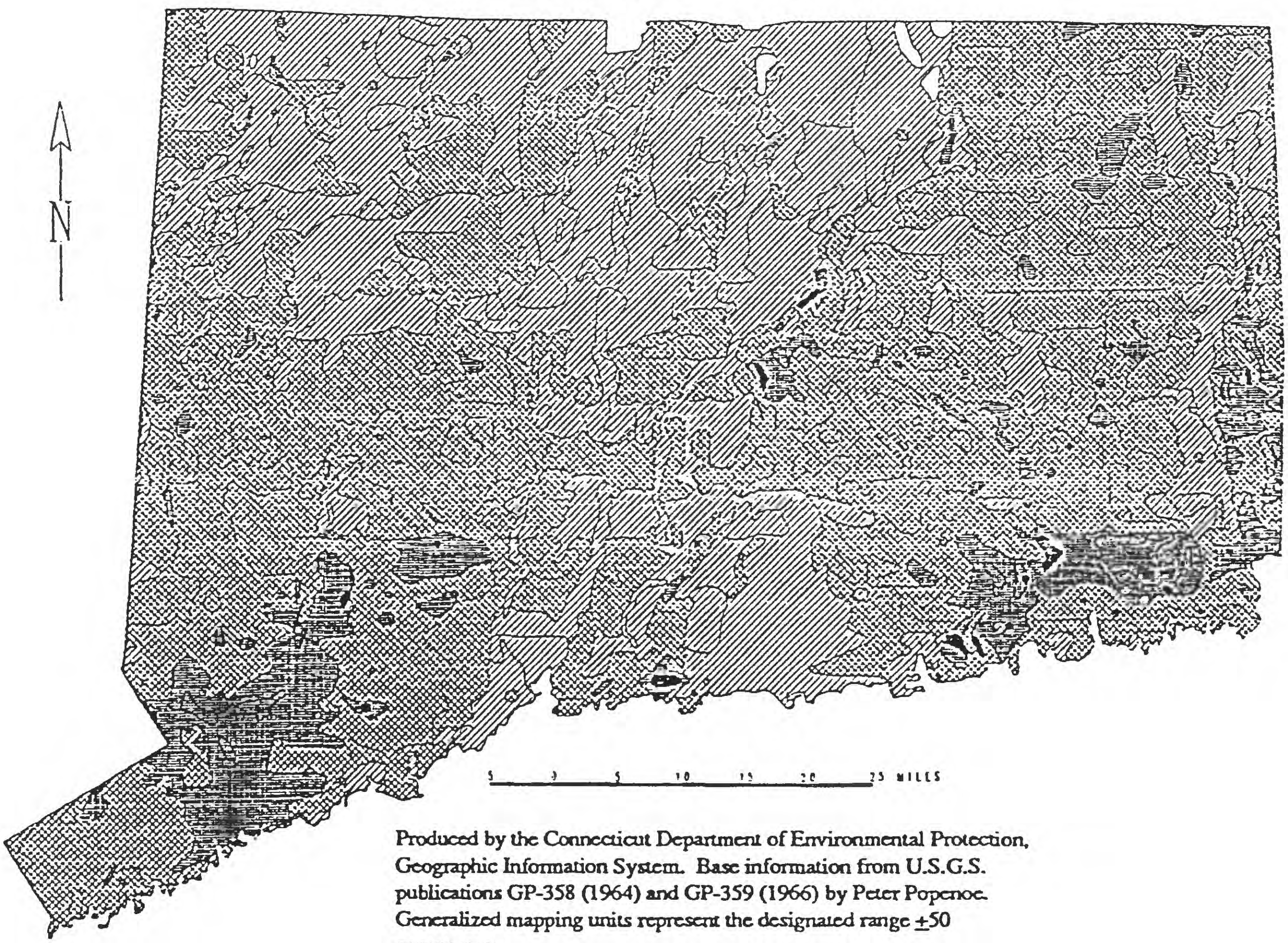
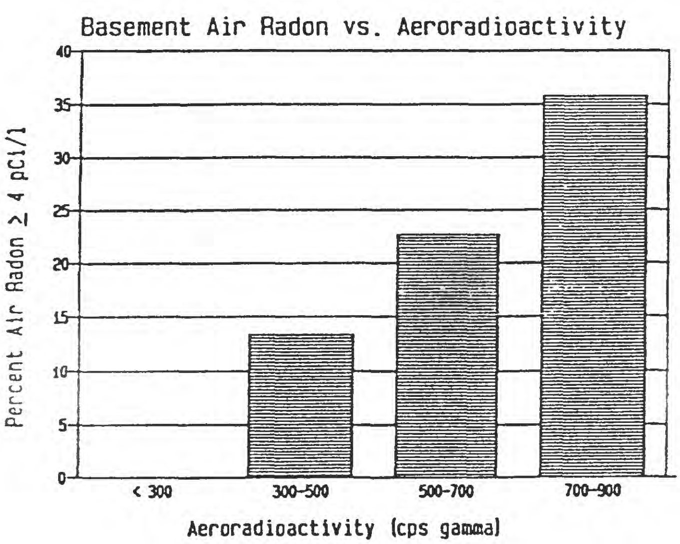


Figure 7a. Aerial radiometric map of Connecticut (after Duval and others, 1989). Contour lines at 1.5 and 2.5 ppm equivalent uranium (eU). Pixels shaded at 0.5 ppm eU increments; darker pixels have lower eU values; white indicates no data.

GENERALIZED AERORADIOACTIVITY MAP OF CONNECTICUT
WITH RADON POTENTIAL ASSESSMENTS





Legend

Aeroradioactivity +50 cps gamma	Frequency % >4 pCi/l
< 300	0
300-500	13.3
500-700	22.6
700-900	35.7
> 900	—

Radioactivity unit boundary: inferred, well defined, or gradational.

GIS

Figure 7b. Total-count aeroradioactivity map of Connecticut and comparison of aeroradioactivity with screening indoor radon levels (from Thomas, 1990).

Data from the HTP were analyzed by geologic terrane by the Connecticut Geological Survey (M.A. Thomas, personal communication, 1991). The values represent winter basement charcoal canister tests in a total of 4798 homes from two surveys: the 1986-1987 State/EPA Residential Radon Survey and the 1987-88 Connecticut Household Testing Program. These data are summarized in Table 1 by geologic terrane and Table 2 by county. They are also shown by county in figure 8. A map of counties is included for reference (fig. 9). In this grouping the highest arithmetic mean, and the only one exceeding 4 pCi/L, was 5.56 pCi/L for 493 homes tested in the Bronson Hill Anticlinorium (Table 1). The indoor radon readings were also grouped by individual rock unit as shown on the bedrock geological map of Connecticut (Rodgers, 1985). Rock units generating indoor radon averages exceeding 4 pCi/L are dominantly granitic rocks in the Connecticut Valley Synclinorium, Bronson Hill Anticlinorium, and the Avalonian Terrane, and, locally, volcanic rocks in the Newark Terrane (M.A. Thomas, personal communication, 1991).

TABLE 1. Connecticut indoor radon summary by geologic terrane.
Numbers refer to map of geologic terranes (fig. 1). Data from the Connecticut Geological Survey (M.A. Thomas, personal communication, 1991).

Geologic Terrane	# of Homes	Geometric Mean	Arithmetic Mean
Newark Terrane (1)	589	1.18	1.55
Proto-NA Terrane			
Carbonate Shelf (2a)	116	1.83	2.8
Proterozoic Massifs (2b)	88	1.73	2.47
Iapetos Terrane			
Ct Valley Syn. (3a)	1568	2.19	3.46
Bronson Hill Ant. (3b)	493	2.68	5.56
Merrimack Syn. (3c)	802	1.84	2.69
Taconic Allocth. (3d)	208	1.58	2.7
Avalonian Terrane (4)	907	1.9	3.32
Lake Char Fault	4	1.24	1.1

TABLE 2. Connecticut indoor radon summary by county.
Data represent 2-7 day charcoal canister measurements. Data from M.A. Thomas (1990 and personal communication).

County	Number of Homes	Geometric Mean	Arithmetic Mean	Maximum	%>4 pCi/L
Fairfield	865	2.09	3.16	98.4	21
Hartford	375	1.48	2.49	80.9	14
Litchfield	805	1.95	3.10	75.0	21
Middlesex	496	1.82	2.91	47.2	20
New Haven	701	2.24	5.04	485.0	29
New London	842	1.70	2.75	72.6	17
Tolland	307	1.70	2.29	18.9	14
Windham	407	2.09	3.04	45.4	21

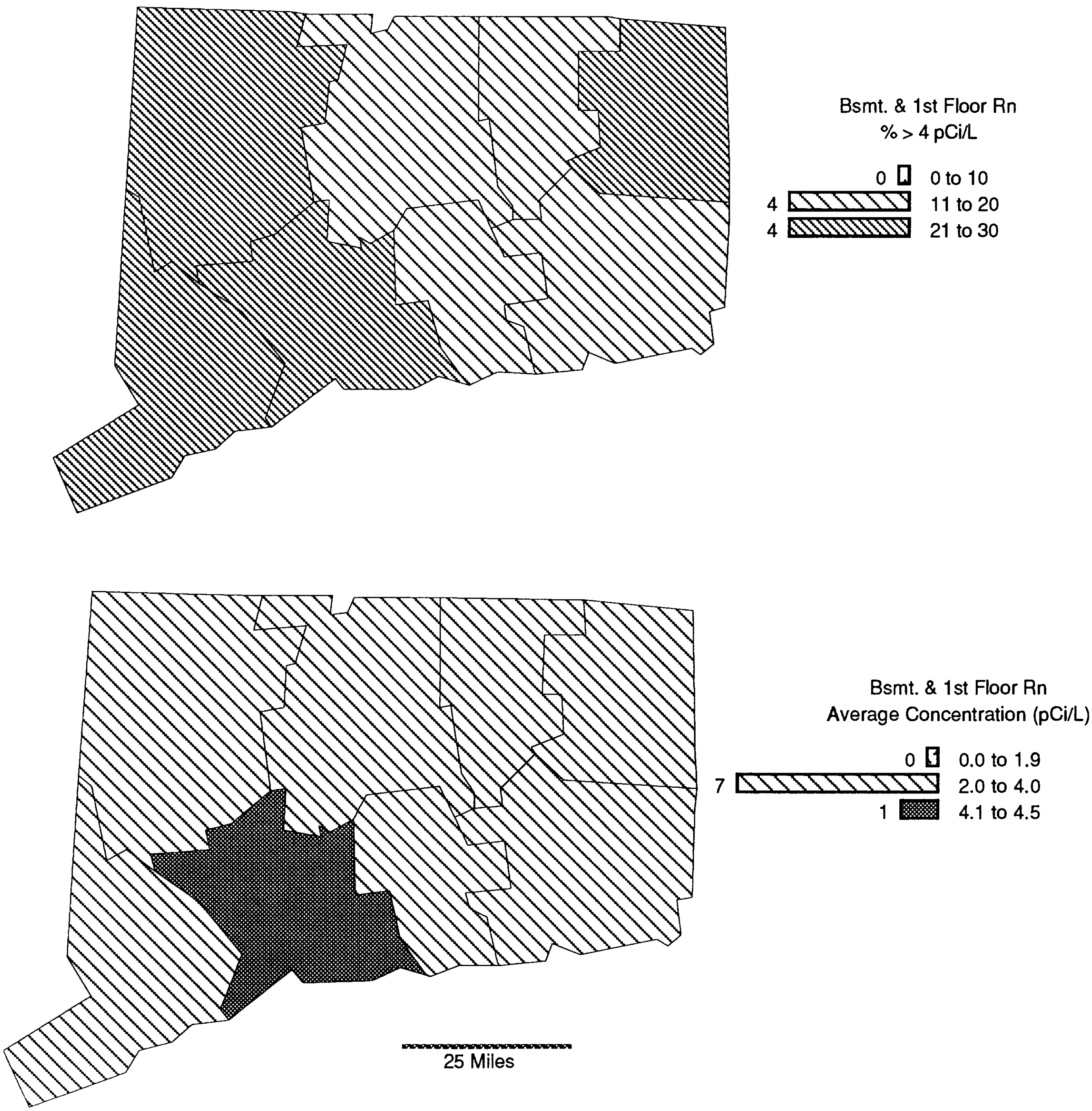


Figure 8. Screening indoor radon data from the 1986-1987 EPA/State Residential Radon Survey and the Connecticut 1987-88 Household Testing Program. Data are from 2-7 day charcoal canister tests. Histograms in map legends show the number of counties in each category. Unequal category intervals were chosen to provide reference to decision and action levels.

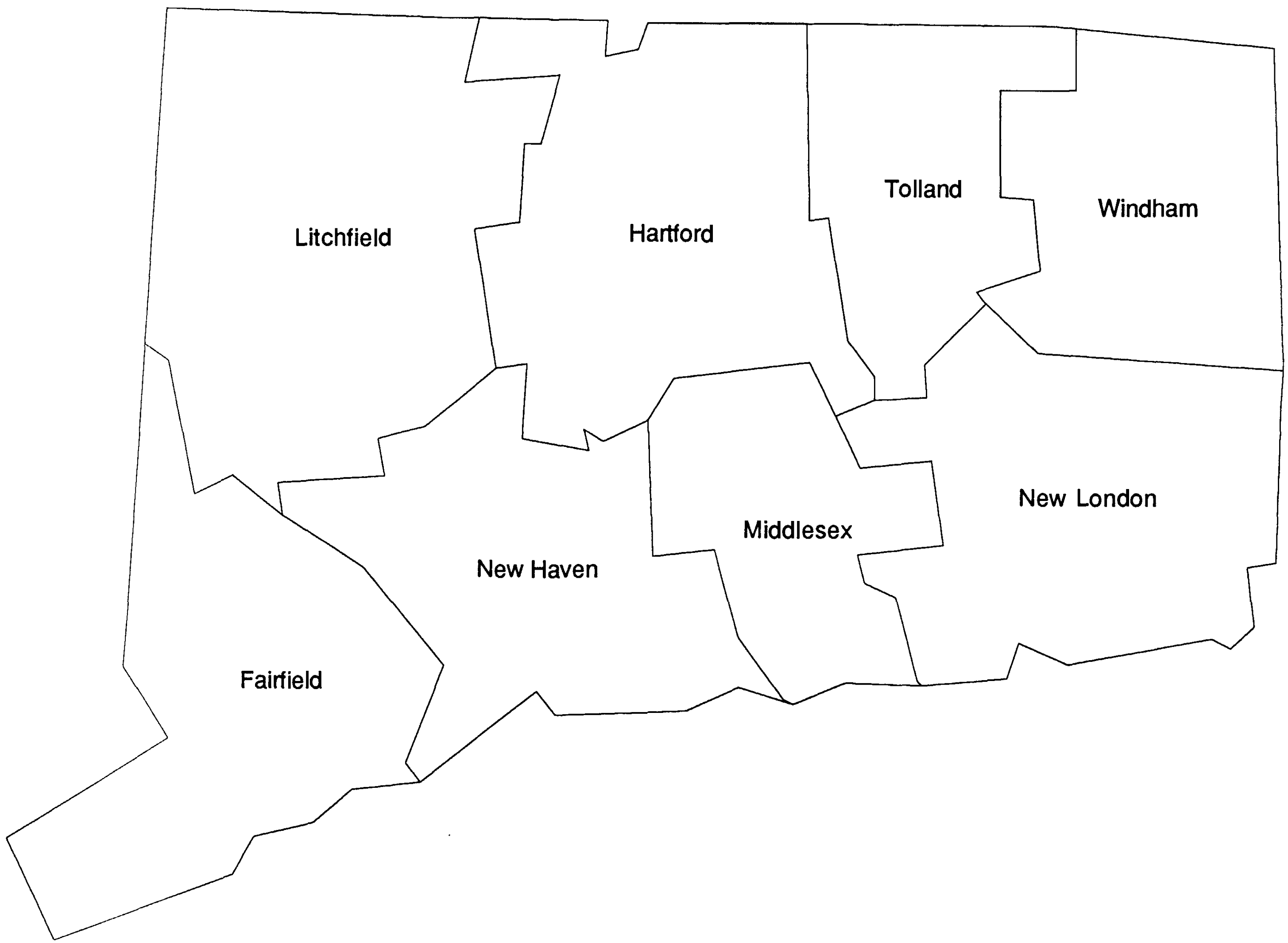


Figure 9. Connecticut counties.

GEOLOGIC RADON POTENTIAL

Western Uplands

The Western Uplands comprise several terranes underlain by metamorphosed sedimentary and igneous rocks. Soils developed on the Proterozoic massifs and overlying till in the Proto-North American Terrane have moderate to high permeability. Equivalent uranium (fig. 7a) is generally low and indoor radon averaged 2.47 pCi/L over the massifs. The carbonate shelf rocks of the Proto-North American Terrane are predominantly marble, schist, and quartzite, overlain by glacial till. Equivalent uranium over this area is generally low and the soils have low to moderate permeability. Indoor radon averages 2.8 pCi/L for homes built on the carbonate shelf rocks. Some homes built on units a and c of the Stockbridge Marble have elevated indoor radon levels in the summary of indoor radon levels by underlying rock type (here designated SRRT for convenience) compiled by the Connecticut Geological Survey (M.A. Thomas, personal communication, 1991). Overall, this terrane has moderate radon potential.

The Taconic Allochthons underlie several fault-bounded areas in the northern part of the Western Uplands. The dominant rock type is schist of varying composition. Equivalent uranium is generally moderate and permeability is low to moderate in this area. Indoor radon in the Taconic Allochthons averaged 2.7 pCi/L. This area has an overall moderate radon potential.

Rocks of the Connecticut Valley Synclinorium underlie most of the Western Uplands. These rocks are schist, gneiss, granite, and phyllite, predominantly granitic or aluminous in composition. Equivalent uranium is moderate to high with areas of very high equivalent uranium over granitic gneisses in the southern portion. The Pinewood Adamellite produces a distinct high radioactivity anomaly on the equivalent uranium map (fig. 7a) and generates locally elevated indoor radon levels. Other granites and granitic gneisses associated with elevated indoor radon include the Harrison Gneiss, an Ordovician granite gneiss (map unit Og on the bedrock geologic map of Connecticut (Rodgers, 1985)), and the Shelton Member of the Trap Falls Formation. These rocks all occur mainly in the southern part of the Connecticut Valley Synclinorium and are associated with the high radioactivity on figure 7a and with elevated indoor radon levels in the SRRT. The Nonewaug Granite and the Scranton Member of the Taine Mountain Formation underlie areas in the northern and central part of the area and are also associated with high aeroradioactivity and elevated indoor radon levels. Graphitic schists and phyllites commonly contains elevated concentrations of uranium, and is known to be associated with elevated indoor radon levels in other parts of New England and other areas (Gundersen and others, 1988; Ratté and Vanecek, 1980). Graphitic schist and phyllites may be the cause of elevated indoor radon levels associated with the Wepawaug Schist. Soils are derived from the rocks and overlying tills and have low to moderate permeability. Indoor radon averages 3.46 pCi/L in the Connecticut Valley Synclinorium. Because many of the rocks of this terrane have the potential to generate elevated radon levels, this area is assigned a high geologic radon potential.

Central Lowlands

The Central Lowlands are underlain by Triassic and Jurassic sedimentary and volcanic rocks. The average indoor radon in the Newark Terrane was 1.55 pCi/L. Outcrops of the Jurassic Talcott Basalt and Buttress Dolerite are associated with indoor radon averages exceeding 4 pCi/L in a sample of 10 homes in the SRRT. Radioactivity in the Hartford and Pomperaug basins is generally low and the soils have generally low to moderate permeability or are poorly drained. Overall, the Newark Terrane has a low radon potential. However, uranium occurrences have been reported associated with copper in the upper New Haven Arkose, and in the middle Portland Formation associated with carbonaceous debris in fluvial crossbeds, in the Hartford basin (Robinson and Sears, 1988). Similar copper deposits that are also probably uranium-rich are known from many locales within these units and in the same units within the Pomperaug basin. Although no occurrences have been reported, black shales and gray sandstones in the Shuttle Meadow, East Berlin, and Portland Formations in both basins also may have some elevated uranium. These uranium occurrences may cause localized indoor radon problems but are not expected to be common or widespread. The basalts and diabase, lower New Haven Arkose, and upper Portland Formation are not likely to have significant uranium concentrations, except possibly along fractures, and are generally low in radon potential.

Eastern Uplands

Rocks of the Bronson Hill Anticlinorium include felsic and mafic schists and gneisses, quartzite, and granite gneiss. Radioactivity in the Bronson Hill is moderate to locally high, and equivalent uranium anomalies in the central part of the area (fig. 7a) appear to be associated with outcrops of granite gneiss. The soils have low to moderate permeability with areas of locally high permeability. The Glastonbury granite gneiss and graphitic schists in the Collins Hill Formation are likely to generate elevated indoor radon levels. The Monson Gneiss, and schist and granofels of the Middletown Formation, also generate average indoor radon levels between 4.3 and 10.1 in the SRRT. Average indoor radon in the Bronson Hill Anticlinorium is 5.56 pCi/L, the highest among the geologic terranes of Connecticut (Table 1). Overall, this area has a high radon potential.

The Merrimack Synclinorium is underlain by gneiss, schist, granofels, and quartzite that are intruded by granite gneiss, diorite, and gabbro. The area has moderate to high radioactivity on the NURE map (fig. 7a) and had the highest radioactivity in the Connecticut Geological Survey's carborne survey (Thomas, 1987). Soils have low to high permeability but most are in the low to moderate range. Indoor radon in the Merrimack Synclinorium averaged 2.69 pCi/L. The Canterbury granite gneiss, which occurs in several broad outcrop bands in the northern and central parts of the area, appears to be associated with elevated radioactivity (fig. 7a) and with elevated indoor radon levels (average of 4.1 pCi/L for 39 homes tested in the SRRT). This area has moderate radon potential overall.

The Avalonian Terrane is underlain by granite, granite gneiss, mafic gneiss, and amphibolite. Granitic rocks known to generate elevated indoor radon levels (averages greater than 4 pCi/L in the SRRT) include the Waterford and Branford Gneisses, and the Hope Valley Alaskite Gneiss, which also has a high aeroradioactivity signature (fig. 7a), as well as locally-occurring graphitic schist and gneiss in the Plainfield Formation. Overall, the radioactivity signature of the area is moderate to high. Soils of the Avalonian Terrane have low to high permeability, with granitic rocks producing sandy, more permeable soils, and mafic and volcanic rocks producing silty and sandy soils with slowly permeable, clayey substrata. The indoor radon average for this terrane is 3.32 pCi/L. Overall, this area has high radon potential.

SUMMARY

For the purpose of this assessment, Connecticut has been divided into eight geologic radon potential areas (fig. 10) and each area assigned a Radon Index (RI) and a Confidence Index (CI) score (Table 3). The RI is a semi-quantitative measure of radon potential based on geology, soils, radioactivity, architecture, and indoor radon. The CI is a measure of the relative confidence of the RI assessment based on the quality and quantity of the data used to assess geologic radon potential. (see the Introduction chapter to this regional booklet for more information).

The Newark Terrane, consisting of the Hartford and Pomperaug basins, is the only area of Connecticut ranked as having low radon potential. Areas with moderate or variable geologic radon potential include the Proterozoic massifs, carbonate shelf, and Taconic Allochthons, and the Merrimack Synclinorium in the eastern part of the State. Areas with high radon potential include the Connecticut Valley Synclinorium, Bronson Hill Anticlinorium, and Avalonian Terrane, particularly those parts underlain by granitic rocks and by tills with granites, granite gneisses, or other uraniferous rocks, such as graphitic schists and phyllites, as a major source component. Faults and shear zones in many parts of the State have the potential to generate locally high indoor radon.

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

TABLE 3. RI and CI scores for geologic radon potential areas of Connecticut.

FACTOR	Newark Terrane RI	Newark Terrane CI	Carbonate Shelf RI	Carbonate Shelf CI	Proterozoic massifs RI	Proterozoic massifs CI
INDOOR RADON	1	3	2	3	2	3
RADIOACTIVITY	1	2	1	2	1	2
GEOLOGY	2	3	1	3	2	3
SOIL PERM.	1	3	2	3	2	3
ARCHITECTURE	3	-	3	-	3	-
GFE POINTS	0	-	0	-	0	-
TOTAL	8	11	9	11	10	11
	Low	High	Mod	High	Mod	High

FACTOR	Connecticut Valley Synclinorium RI	Connecticut Valley Synclinorium CI	Bronson Hill Anticlinorium RI	Bronson Hill Anticlinorium CI	Merrimack Synclinorium RI	Merrimack Synclinorium CI
INDOOR RADON	2	3	3	3	2	3
RADIOACTIVITY	2	2	2	2	2	2
GEOLOGY	3	3	2	3	2	3
SOIL PERM.	2	3	2	3	2	3
ARCHITECTURE	3	-	3	-	3	-
GFE POINTS	0	-	0	-	0	-
TOTAL	12	11	12	11	11	11
	High	High	High	High	Mod	High

FACTOR	Taconic Allochthons RI	Taconic Allochthons CI	Avalonian Terrane RI	Avalonian Terrane CI
INDOOR RADON	2	3	2	3
RADIOACTIVITY	2	2	2	2
GEOLOGY	2	3	3	3
SOIL PERM.	2	3	2	3
ARCHITECTURE	3	-	3	-
GFE POINTS	0	-	0	-
TOTAL	11	11	12	11
	Mod	High	High	High

RADON INDEX SCORING:

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

Possible range of points = 3 to 17

CONFIDENCE INDEX SCORING:

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

Possible range of points = 4 to 12

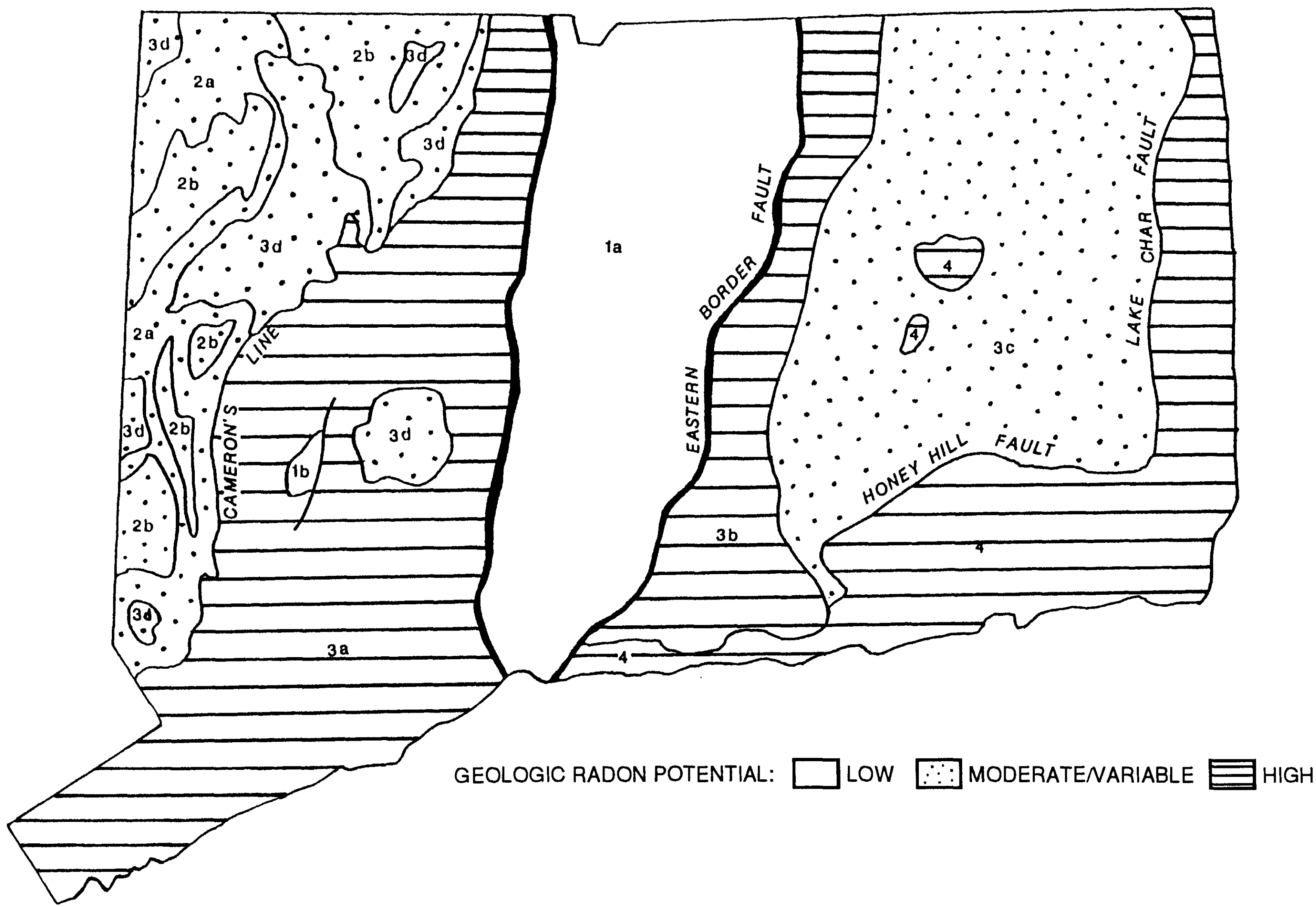


Figure 10. Geologic radon potential areas of Connecticut. Numbers on map refer to geologic terranes (see figure 1 for names).

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PRELIMINARY GEOLOGIC RADON POTENTIAL ASSESSMENT OF MAINE

by
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INTRODUCTION

This chapter presents a discussion of the bedrock and glacial geology, soils, and radioactivity of Maine in the context of indoor radon. A number of studies on radon in Maine's water supplies (summarized in Norton and others, 1989; Paulsen, 1991; and Clausen, 1990) and on related health factors (Hess and others, 1983; Lanctot, 1985) have been conducted. During the winter of 1989-1990, as part of the State/EPA Residential Radon Survey, 839 randomly selected homes throughout the State were measured for indoor radon. The percentage of homes with measurements greater than 4 pCi/L was 29.9 and the average indoor radon in the State was 4.0 pCi/L. Examination of these indoor radon data in the context of geology, soil parameters, and radioactivity suggests that the majority of counties with high (> 4 pCi/L) indoor radon are underlain by uranium-bearing granites and high-grade metamorphic rocks, particularly in the southern portion of the State. High indoor radon may also be associated with pegmatites, major fault zones, and carbonaceous slate, phyllite, and schist. Elevated levels of radon in domestic water are associated with granites, pegmatites, and faults in Maine. The radon in these wells may be high enough to contribute significantly to the radon content of the indoor air.

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

PHYSIOGRAPHIC AND GEOGRAPHIC SETTING

The physiography of Maine (fig. 1) is a result of the influence of bedrock geology (fig. 2) and continental glaciation. Six major physiographic provinces have been delineated in Maine: the Northern Maine Lowlands, Boundary Mountains Highlands, Lobster Mountain-Moose River Lowlands, Central Maine Highlands, Central Maine Lowlands, and the Coastal Province (Hanson and Caldwell, 1989). Elevations in Maine range from sea level, along the coastline in the southern part of the State, to 5268 ft at Mt. Katahdin in north-central Maine.

The Northern Maine Lowlands is the largest province, covering roughly the northern one-third of Maine. It is underlain primarily by Cambrian through Devonian, low-grade metasedimentary and volcanic rocks. Elevations range from a few hundred feet in the northern part to over 2000 ft in the southwestern part (Denny, 1982). Relief is lowest in the broad valleys of the Upper St. John River and its tributaries in the north, and increases toward the gently rolling,

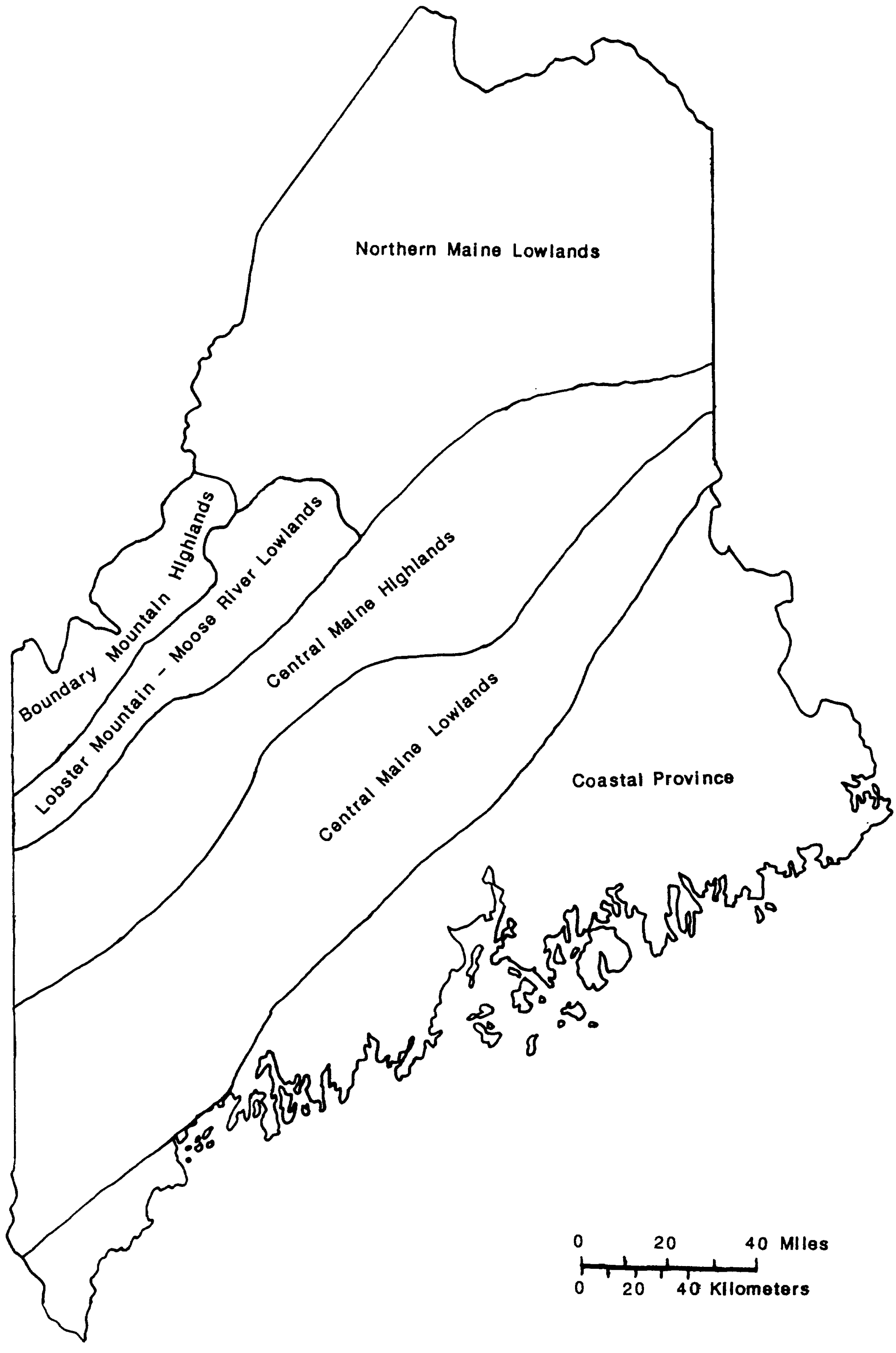


Figure 1. Physiographic regions of Maine (modified from Hanson and Caldwell, 1989).

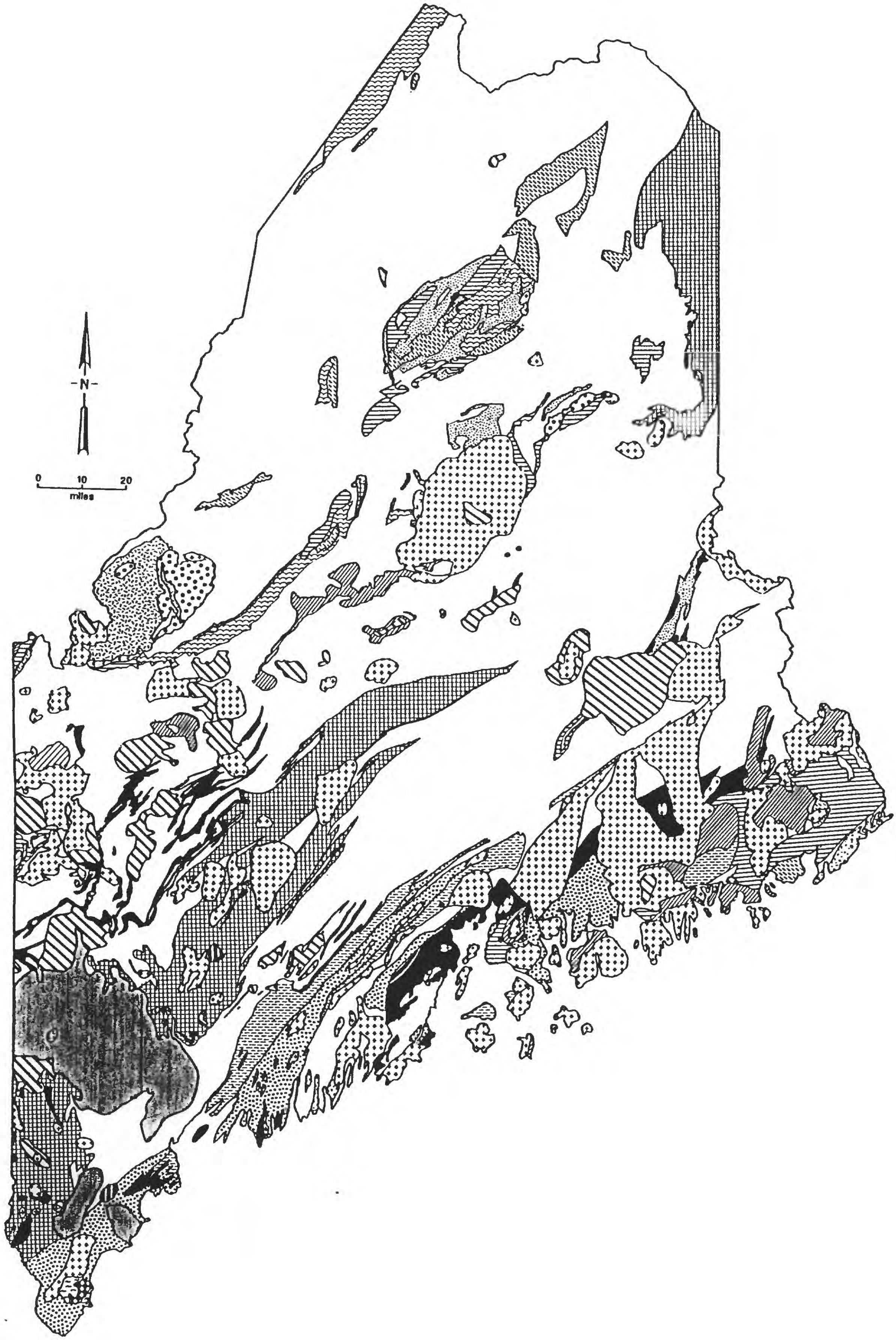


Figure 2. Generalized bedrock geologic map of Maine (after Osberg and others, 1985).

GENERALIZED GEOLOGIC MAP OF MAINE (FIG. 2)

EXPLANATION

Stratified metamorphic rocks

Clastic and carbonate sedimentary rocks and their metamorphic equivalents (Coastal Province)

Devonian - Proterozoic
Appleton Ridge Formation (Fm.); Gonic Fm.
Silurian - Proterozoic
Berwick Fm.; Eliot Fm.; and Kittery Fm.
Ordovician - Proterozoic
The quartzite member of the Cape Elizabeth Fm.; Ellsworth Fm.; and Macworth Fm.
Proterozoic
Coombs Limestone; Ogier Point Fm., Rockport Fm.; and Rocks of Islesboro (includes local outcrops of limestone member).

Mafic to felsic volcanic rocks and their metamorphic equivalents (Coastal Province)

Volcanic member of the Cushing Fm.; mafic to felsic volcanic member of the Cape Elizabeth Fm.; metasedimentary, metavolcanic, and calc-silicate rocks of the Passagassawakeag block; and Spring Point Fm. (Includes local outcrops of Spurwink Limestone, limestone member of the Cushing Fm., and interbedded pelite and quartz sandstone of the Passagassawakeag block.)

Clastic and carbonate sedimentary rocks and their metamorphic equivalents

Devonian
Beck Pond Limestone; Carrabassett Fm.; Chapman Sandstone; Edmunds Hill Andesite; Hildreths Fm.; Hedgehog Fm.; Heald Mountain Rhyolite; Ironbound Mountain Fm.; Matagamon Sandstone; Perry Fm.; Parker Bog Fm.; Seboomook Fm.; Swanback Fm.; Tarratine Fm.; Tomhegan Fm.; Traveler Rhyolite; and Trout Valley Fm.
Devonian - Silurian
Allagash Fm.; Bell Brook Fm.; Bar Harbor Fm.; Castine Fm.; Calderwood Fm.; Daggett Ridge Fm.; Fogelin Hill Fm.; Frost Pond Shale; Fish River Lake Fm.; Madrid Fm.; undifferentiated sedimentary rocks in areas of extreme migmatization; and undifferentiated sedimentary rocks of the Spider Lake, Chandler Pond, and Third Lake Fms.
Devonian - Ordovician
Bucksport Fm.; Digdeguash Fm.; and Flume Ridge Fm.
Silurian
Burnt Brook Fm.; undifferentiated pelites, conglomerates, and sandstones in the Allsbury Fm.; Frenchville Fm.; rocks of the Fivemile Brook Sequence; Greenvale Cove Fm.; Hersey Fm.; Hardwood Mountain Fm.; Jemtland Fm.; Maple Mountain Fm.; New Sweden Fm.; Perry Mountain Fm.; pelites of the Quoddy Fm.; Rangeley Fm.; Ripogenus Fm.; the Anasagunticook Member and limestone of the Sangerville Fm.; Smyrna Mills Fm.; The Forks Fm.; and Waterville Fm.
Silurian - Ordovician
Aroostook Fm.; Frontenac Fm. (excluding the Canada Falls Volcanic Member); Lobster Lake Fm.; Nine Lake Fm.; and Vassalboro Fm.

Ordovician
Benner Hill Fm.; Chase Lake Fm.; Chandler Ridge Fm.; Depot Mt. Sequence; Dry Wall Volcanic Rocks; Kamankeag Fm.; andesite and basalt of the Lobster Mt. Volcanic Complex; Madawaska Lake Fm.; Pile Mountain Argillite; Quimby Fm.; and Wassataquoik Chert.
Ordovician - Cambrian
Sulfidic quartz sandstone and lithic sandstone/pelite of the Cookson Fm.; Dead River Fm.; Megunticook Fm.; Sawmill Fm.; and Southeast Cove Fm.
Cambrian
Grand Pitch Fm.

Sulfidic - carbonaceous pelites and their metamorphic equivalents

Devonian
Temple Stream Member of the Seboomook Fm.
Devonian - Silurian
Sulfidic pelite of the Rindgemere Fm. and Towow Fm.
Silurian
Sulfidic pelite of the Sangerville Fm., Anasagunticook Member, and Small Falls Fm.
Ordovician
Blind Brook Fm.; sulfidic pelite of the Benner Hill Fm.; and pelite of the Kamankeag Fm.
Ordovician - Cambrian
Cookson Fm. (excluding sulfidic quartzose sandstone and lithic sandstone/pelite members) Penobscot Fm. (excluding the basalt member).
Ordovician - Proterozoic
Sulfidic pelite member of the Cushing Fm. and the Scarboro and Diamond Island Fm.s.

Interbedded pelites and limestones and/or dolostones and their metamorphic equivalents

Devonian - Silurian
Rindgemere Fm. (excluding sulfidic pelite member) and Towow Fm.
Silurian
Sangerville Fm. (excluding Anasagunticook Member and sulfidic pelite), Spragueville Fm.
Silurian - Ordovician
Carys Mills Fm.

Melange-deformed and sheared phyllite, slate, and breccia

Ordovician
Kennebec Fm.
Ordovician - Cambrian
Chase Brook Fm.; Hurd Mountain Fm.; and Saint Daniel Fm.
Cambrian
Hurricane Mountain Fm.

Mafic volcanic rocks and their metamorphic equivalents

Silurian
Basalt member of the Dennys Fm. and the basalt member of the Leighton Fm.
Silurian - Ordovician
Canada Falls Volcanic Member of the Frontenac Fm.
Ordovician
Bluffer Pond Fm. and Winterville Fm.
Ordovician - Cambrian
Basalt member of the Penobscot Fm.
Cambrian
Caucomgomoc Lake Fm. and Jim Pond Fm.
Proterozoic
North Haven Fm.

Mafic to felsic (and undetermined) volcanic rocks and their metamorphic equivalents

Devonian
Eastport Fm.
Devonian - Ordovician
Undifferentiated mafic to felsic volcanic rocks.
Silurian
Mafic to felsic volcanic rock member of the Dennys Fm.; Edmunds Fm.; and Quoddy Fm. (excluding the pelite member).
Silurian - Ordovician
Dunn Brook Fm.
Ordovician
Ammonoosuc Volcanics and Lobster Mountain Volcanic Complex.
Ordovician - Cambrian
Mafic to felsic volcanic rocks of the Cookson Fm.

Felsic volcanic rocks and their metamorphic equivalents

Devonian - Silurian
Undifferentiated volcanic rocks of the Spider Lake and Chandler Pond Fm s.
Ordovician
Munsungun Lake Fm. and Shin Brook Fm.

Plutonic igneous rocks

Cretaceous intrusive rocks

Alkali feldspar quartz syenite, quartz monzodiorite, quartz diorite, alkali feldspar syenite, monzodiorite,and some gabbro-diorite-ultramafic compositions.

Triassic granite

Alkali feldspar granite and granite.

Triassic syenite

Alkali feldspar quartz syenite and alkali feldspar syenite (includes some triassic mafic to felsic volcanic rocks).

Mesozoic granite

Granite with hornblende locally as an accessory mineral.

Mesozoic syenite

Foid-bearing syenite.

Carboniferous granite

Granite with locally abundant muscovite.

Carboniferous quartz-poor intrusives

Syenite and/or gabbroic-dioritic-ultramafic rocks.

Devonian granite

Granite and alkali feldspar granite, locally porphyritic; hornblende and muscovite are common accessory minerals.

Devonian granodiorite - syenite

Granodiorite to syenite, locally porphyritic; may contain hornblende and/or muscovite as accessory minerals

Devonian quartz-poor intrusive rocks

Gabbroic-dioritic-ultramafic rocks, locally associated with rocks of quartz diorite composition.

Silurian granite

Granite

Silurian quartz-poor intrusive rocks

Gabbroic-dioritic-ultramafic rocks.

Ordovician granite

Granite locally associated with granodiorite.

Ordovician granodiorite/quartz monzonite

Granodiorite to quartz monzonite, locally containing hornblende as an accessory mineral.

Ordovician quartz-poor intrusive rocks

Gabbroic-dioritic-ultramafic rocks.

Cambrian intrusive rocks

Locally occurring quartz diorite and gabbro, diorite, and ultramafic rocks.

Basement rocks

Gneiss and granofels of the Chain Lakes Massif rounded hills in the south. The Lobster Mountain-Moose River Lowlands are essentially a southwestern arm of the Northern Maine Lowlands that extends just beyond the New Hampshire state line. They are underlain by Devonian and older metasedimentary and volcanic rocks, except for the southern tip of the lowland, which is underlain by igneous and high-grade metamorphic rocks. The linear ridges and valleys of this area resemble the Valley and Ridge Province of the Appalachians, though on a much smaller scale. Elevations range from a few hundred feet on the valley floors to over 3800 ft at Hurricane Mountain, with elevations of 2000 ft or more common on the ridgetops.

The Boundary Mountain Highlands lie to the north of the Lobster Mountain-Moose River Lowlands (fig. 1). An irregular topography has developed on the crystalline rocks underlying this province. The mountainous areas are underlain by more resistant gneiss, granofels, hornfelsic and volcanic rock, and fine-grained plutonic rocks, whereas the valleys are underlain primarily by coarse-grained plutonic rocks (Hanson and Caldwell, 1989). Linear hills and small ridges are common in the northernmost part of the province. Although the terrain is rugged, the relief is less than in the Central Maine Highlands, and the elevations of the mountain peaks decrease from east to west. Most of the mountain peaks in this region are less than 4000 ft and have relief of 1200 ft or less (Hanson and Caldwell, 1989).

The Central Maine Highlands extend from the New Hampshire border to the New Brunswick border near Houlton and comprise several mountain ranges, including the Mahoosuc Range, Blue Range, Bigelow Range, Squaw Mountain-Ragged Mountain Range, Onawa Range, Katahdin and Traveler Ranges, Chase Mountain Range, and Oakfield Hills (Hanson and Caldwell, 1989). The highlands are formed almost entirely on a broad belt of regionally-deformed, Silurian and Devonian metasedimentary rocks and Devonian plutonic rocks. Topography is strongly related to the regional structure and to the occurrence of plutons. The average elevation of the mountains, as well as the relief, decreases toward the northeast. Elevations range from about 600 ft in valleys in the northern part to 5268 ft at Mt. Katahdin, near the central part of the province. A number of peaks in the southwestern part of the province are higher than 4000 ft (Hanson and Caldwell, 1989).

The Central Maine Lowlands are adjacent to and southeast of the Central Maine Highlands. They are an area of low relief, generally less than 100 ft. Most of the province is underlain by erosionally-weak slate, phyllite, metasandstone, and limestone. Highlands are local ridges of more resistant sandstone or irregular hills underlain by contact metamorphic rocks, with altitudes less than 1500 ft (Hanson and Caldwell, 1989).

The Coastal Province is an area of low uplands developed on metasedimentary, metavolcanic, and igneous plutonic rocks. Some of the peaks are in areas of contact metamorphism adjacent to plutonic rocks. Many of the low mountains reach elevations of more than 1000 ft (Denny, 1982). East of the Penobscot River, streams flow over plutonic rocks and have strong southward orientations that follow the major trend of joint and fracture systems in the rocks. West of the Penobscot River, streams in the area flow over metasedimentary rocks and generally exhibit a southwestward trend, parallel to regional faults and to the structural orientation of the rocks. North of the Saco River, the coastline is highly indented, and many of the peaks near the shore are separated by narrow bays. The southern coastline is smoother, most likely due to the parallel orientation of the shore with regional structure, to less extensive glacial excavation of the shoreline, and to the presence of thicker deposits of glaciomarine sediments (Hanson and Caldwell, 1989).

In 1990 the population of Maine was 1,227,928, including 58 percent urban population (fig. 3). Population density is approximately 36.2 per square mile. There are three climatic regions in Maine: the southern portion of the State, which is influenced by coastal air masses; the southern interior region, with a climate between that of the northern and southern areas; and the northern regions, which have a harsher climate, averaging 100 or more inches of snow per year. Average annual temperatures range from 37° F in the north to 45° F in the south. Annual precipitation averages 40-46 inches (fig. 4).

GEOLOGIC SETTING

The geology of Maine is complex and the names of rock formations and the way rocks are grouped have changed with time. It is beyond the scope of this report to resolve the complicated stratigraphy of the State, therefore this description of the geology tries to convey the major rock types of Maine, especially as they pertain to the radon problem. Descriptions in this report are derived from Tucker and Marvinney (1989) and Osberg and others (1985). A general geologic map is given in figure 2. It is suggested, however, that the reader refer to the most recent State geologic map (Osberg and others, 1985) as well as other detailed geologic maps available from the Maine Geological Survey for more information.

In figure 2, the geology of Maine has been subdivided into general rock groups based on the origin of the rocks, age, and the dominant rock types. We have also tried to group the rocks according to their probable radon potential based on radioactivity and known uranium concentrations (these data are presented in a following section). Maine is underlain by Precambrian to Paleozoic metamorphosed sedimentary and volcanic rocks that have been pervasively intruded by Paleozoic mafic to felsic plutons. Metamorphic grade of the rocks decreases from southwest to northeast (fig. 5a) and metamorphic grade is locally high near the plutons. Many of the rocks in the State have been folded and faulted during several major orogenies. A tectonic map showing some of the major structures in Maine is shown in figure 5b.

The most areally extensive group of rocks in figure 2 (patterned white) consists of Cambrian through Devonian metasedimentary rocks that are predominantly clastic but contain minor amounts of carbonate rock. In the Connecticut Valley-Gaspe Synclinorium, the Aroostook-Matapedia belt, and the Moose River Synclinorium, these rocks are mostly part of the Seboomook Formation. The Seboomook Formation is cyclically-layered dark sandstone and slate. In the Northern Boundary Mountains, the feldspathic sandstone, slate, phyllite, schist, greenstone, and felsic metavolcanics of the Frontenac and the Ironbound Mountain Formations are the principal rock units. The Notre Dame anticlinorium is underlain by an unusual rock, termed melange, that consists of sheared and deformed slate, phyllite, and breccia. The Munsungun-Winterville Anticlinorium is underlain by Cambrian-Devonian felsic and mafic metavolcanic rocks and Cambrian melange. The eastern portion of the Aroostook-Matapedia Belt is underlain by Ordovician-Devonian sandstone, graywacke, slate, metavolcanic rocks, shale, limestone, and dolostone. The Ordovician-Silurian shales and carbonate rocks of the Cary Mills and Spragueville Formation have been grouped separately in figure 2.

The Weeksboro-Lunkoos Anticlinorium is underlain mostly by varigated slate and phyllite with thin quartzite interbeds of the Cambrian Grand Pitch Formation. Ordovician andesites and basalts bound the southern part of the anticlinorium and the eastern edge of the Devonian Katahdin pluton, which divides the anticlinorium into two parts. Ordovician diorite plutons intrude both parts of the anticlinorium. Black phyllite with melange textures of the Hurricane Mountain

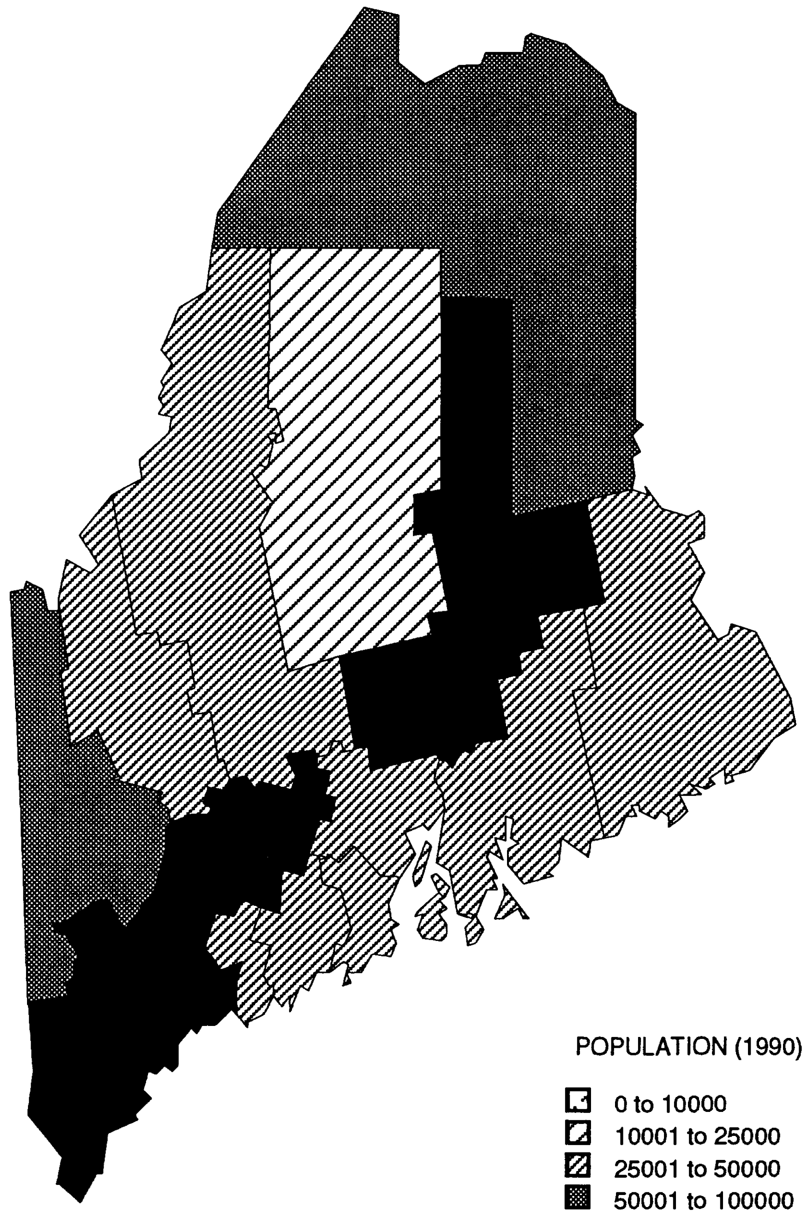


Figure 3. Population of counties in Maine (1990 U.S. Census).

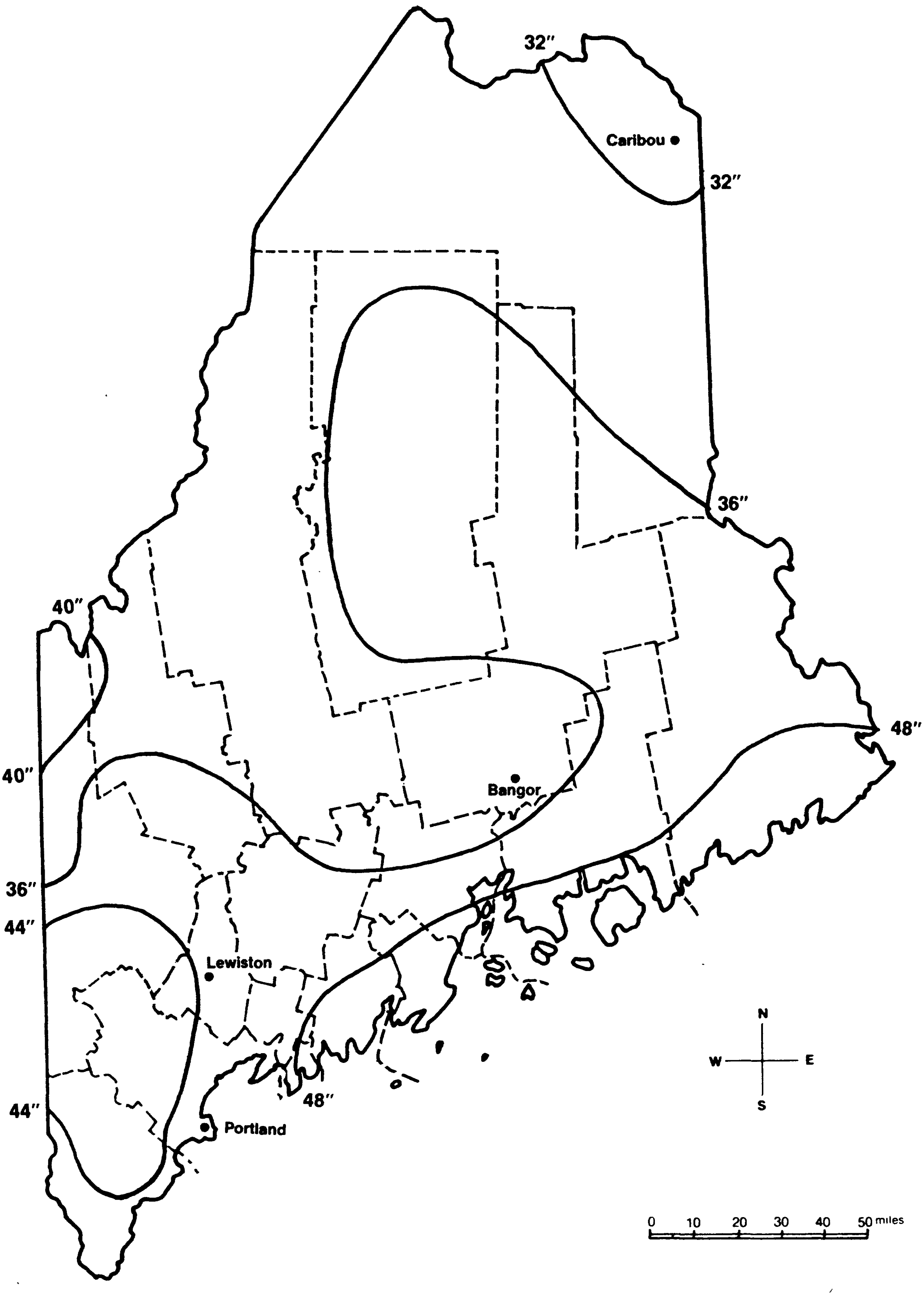


Figure 4. Average annual precipitation in Maine (from Facts on File, 1984).

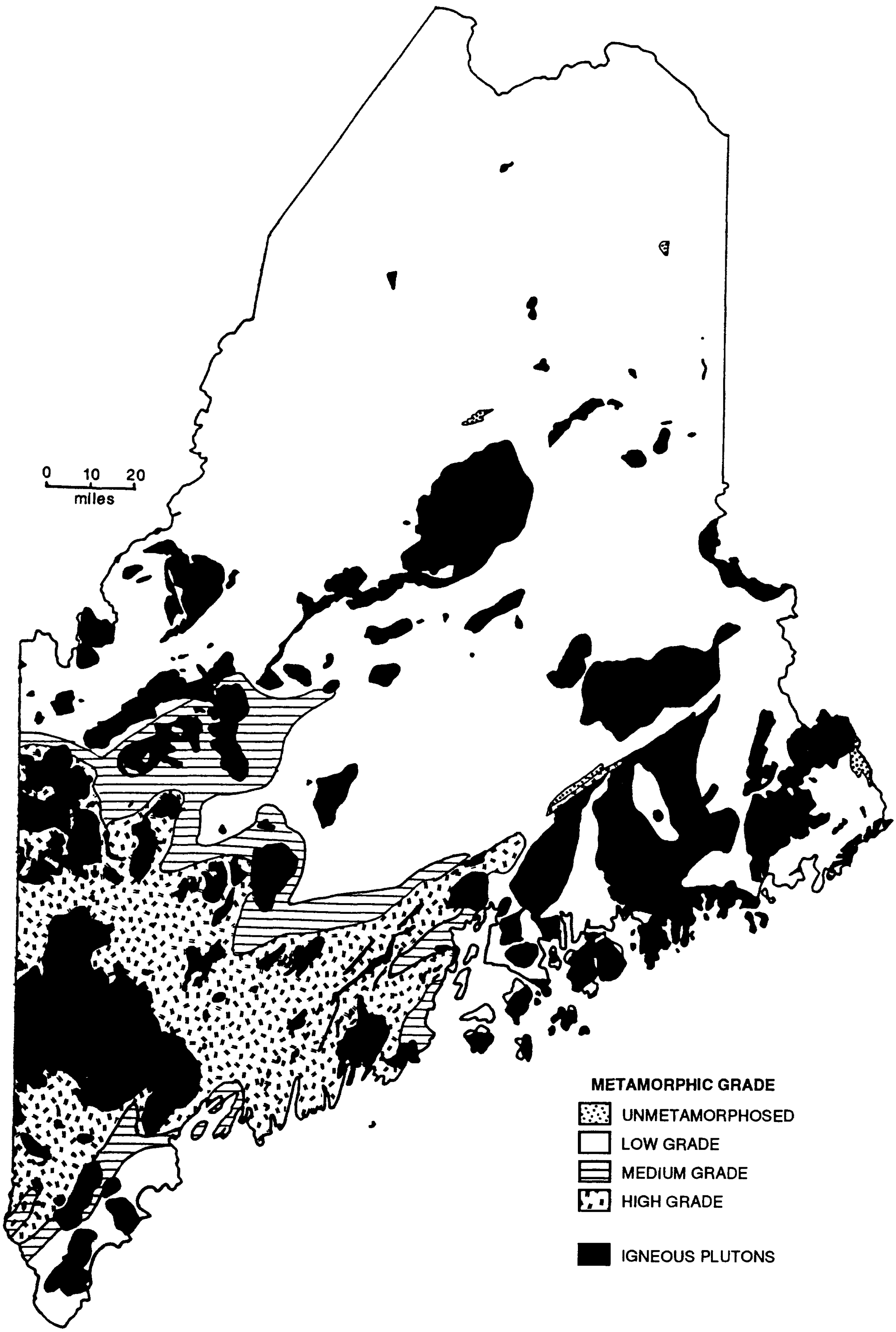


Figure 5a. Generalized map of metamorphic zones in Maine (modified from C.V. Giodotti, in Osberg and others, 1985).

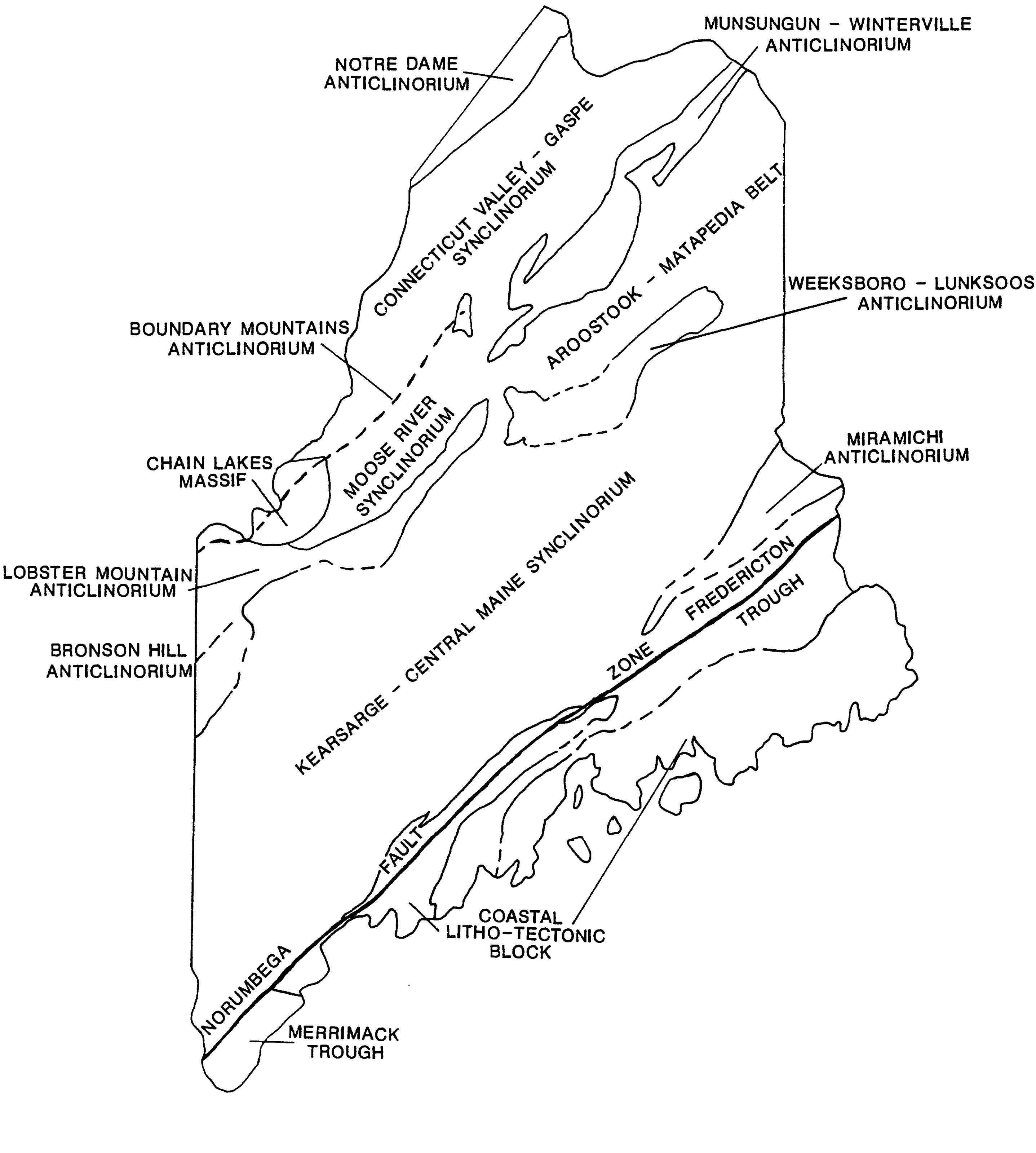


Figure 5b. Tectonic map of Maine (modified from Osberg and others, 1985).

Formation occurs in the western side of the anticlinorium, which is mostly underlain by unnamed Cambrian-Ordovician metapelite and metagraywacke.

The oldest rocks in Maine are Precambrian rocks exposed in the Chain Lakes Massif and the Coastal Province. The Chain Lakes Massif, which underlies part of the Boundary Mountains Highland and forms the core of the Boundary Mountains anticlinorium, consists predominantly of gneiss and granofels (metamorphic rocks with little or no layering). In the lower unit of the massif, the granofels and gneiss contain large clasts of quartz, mafic and felsic plutonic and volcanic rock, and sedimentary rocks. These clasts occur within a matrix of quartz, feldspar, mica, sillimanite, and chlorite. The granofels and gneiss of the lower unit grade into more layered gneiss in the upper unit, including quartz-feldspar gneiss and schist, felsic metavolcanic rocks, quartzite, black schist, and amphibolite. Surrounding the Chain Lakes massif are Cambrian through Devonian metasedimentary, metavolcanic, and plutonic rocks.

The Bronson Hill and Lobster Mountain Anticlinoria are mostly underlain by Cambrian and Ordovician metavolcanic and metasedimentary rocks. Three units dominate the Lobster Mountain Anticlinorium: greenstone, keratophyric metavolcanics, and metagraywacke of the Cambrian Jim Pond Formation; the Hurricane Mountain Formation melange; and slate or phyllite with equal proportions of metavolcanic feldspathic, chlorite-rich arenite of the Cambrian-Ordovician Dead River Formation. Andesitic and basaltic volcanics of the Ordovician Lobster Mountain Volcanic Complex occur at the northeastern end of the anticlinorium. The Bronson Hill Anticlinorium is mostly underlain by the Dead River Formation but also has significant areas underlain by metapelites of the Cambrian-Ordovician Azicohos Formation, and metagraywacke, metaconglomerate, and sulfidic metapelite of the Ordovician Quimby Formation. The stratified rocks of both anticlinoria are intruded by Devonian alkalic and calc-alkalic granite and diorite plutons.

The Kearsarge-Central Maine Synclinorium occupies a broad belt in south-central Maine that is mostly underlain by Silurian and Devonian metasedimentary rocks. The Sebago Pluton, consisting of Carboniferous two-mica granite, dominates the southwestern part of the area, and Devonian alkalic and calc-alkaline granites and diorites are common along the western, northern, and southeastern parts of the synclinorium.

Most of the southern boundary of the Kearsarge-Central Maine Synclinorium is occupied by a broad belt of slightly calcareous graywacke with sulfidic phyllite and mica schist interbeds of the Silurian Vassalboro Formation. The less pelitic Hutchins Corners Formation is found in the southwest. Northwest of the Vassalboro-Hutchins Corners belt, phyllite with quartzite and graywacke interbeds of the Silurian Waterville Formation and graywacke with minor phyllite of the Sangerville Formation both contain prominent limestone members. These units comprise the checked pattern on the geologic map (fig. 2) in the west-central part of the synclinorium. The northern half of the synclinorium is dominated by slightly calcareous quartz graywacke and lesser phyllite of the Silurian-Devonian Madrid Formation, and north of that, gray pelites with rhythmic interbeds of graywacke sandstone and siltstone of the Devonian Carabasset Formation. The eastern margin of the synclinorium is underlain by phyllite with quartzite and graywacke interbeds and limestone of the Silurian Allsbury Formation and sandstone and phyllite of the Silurian Smyrna Mills Formation. The southwesternmost corner of the synclinorium is underlain by metapelite with limestone and dolostone interbeds of the Silurian-Devonian Rindgemere Formation. Gray metapelite, metagraywacke, and metavolcanics of the Devonian Littleton Formation underlie a significant area northwest of the Sebago Pluton along the New Hampshire state line. Black, sulfidic phyllite characterizes the Silurian Small Falls Formation and the

Devonian Towow Formation, which comprise narrow outcrop bands in the northwestern part of the synclinorium. Black, sulfidic phyllites also occur at the base of the Sangerville Formation and within the Rindgemere Formation.

The Miramichi Anticlinorium is mostly underlain by red to gray chloritic graywacke grading up to gray shale, then sulfidic, carbonaceous slate of the Cambrian (?) Baskahegan Formation. This is overlain by unnamed Ordovician felsic metavolcanics, then gray to black slate and graywacke of the Belle Lake Formation. Devonian rocks underlie small areas and include polymict conglomerate and sandstone of the Daggett Ridge Formation and gray slate with sandstone, conglomerate, and limestone of the Hartin Formation.

Over 100 plutons intrude the metasedimentary and metavolcanic rocks of the coastal province. Most of these are Devonian alkalic to calc-alkaline granites or two-mica granites, but include Devonian diorites in the east, and Carboniferous granites and a small Mesozoic alkaline granite in the west. From Kittery Point to Old Orchard Beach, the rocks of the Coastal Province are predominately metasiltstones and phyllites of the Kittery and Berwick Formations. A sequence of Proterozoic to Ordovician rocks dominated by metasedimentary and metavolcanic schist, gneiss, phyllite, and amphibolite of the Cushing, Cape Elizabeth, and Sebascodegan Formations stretches from Old Orchard Beach, throughout most of Casco Bay, north along the Norumbega Fault Zone to Bangor. Black, sulfidic phyllite and mica schist are minor components of the Cushing and Cape Elizabeth Formations and comprise the Diamond Island Formation. In Penobscot Bay, Proterozoic rocks comprise an older sequence of schist and gneiss with greenstone, unconformably overlain by quartzite, slate, and limestone. A small area west of Penobscot Bay is underlain by Ordovician schist and quartzite of the Benner Hill sequence. Across the northern part of Penobscot Bay is Cambrian-Ordovician quartzite and mica schist of the Megunticook Formation, which is overlain by black, sulfidic mica schist of the Penobscot Formation. The Penobscot also crops out in fault blocks that form a northeast-trending belt to St. Croix Bay, where equivalent rocks are called the Cookson Formation. South of the belt of Penobscot Formation and its equivalents between Penobscot Bay and Pleasant Bay, Proterozoic to Ordovician rocks are dominated by phyllite and siliceous siltstone of the Ellsworth Formation and its equivalent schist of the Columbia Falls Formation. East of Pleasant Bay to Passamaquoddy Bay, Silurian to Devonian mafic and felsic metavolcanics of the Quoddy, Dennys, and Eastport Formations dominate. The Quoddy Formation also contains significant intervals of black, sulfidic siltstone and argillite. The Fredericton Trough is dominated by graywacke sandstone and siltstone and gray phyllite and slate of the Devonian Digdeguash and Flume Ridge Formations, and to the southwest, by feldspathic graywacke and gray biotite schist of the Bucksport Formation.

GLACIAL GEOLOGY

Stratigraphic evidence from New England and the Gulf of Maine indicates that there were at least four, and as many as six, glacial advances in this region during the Pleistocene epoch. Three Wisconsinan (Late Pleistocene) till units have been identified in Maine from surface and subsurface data (Stone and Borns, 1986). The "lower till" is probably early Wisconsinan in age, it is typically compact, and it has a weathered zone or paleosol at the top (Stone and Borns, 1986). The "middle till" is middle Wisconsinan or early late Wisconsinan and it is overlain by a layer of laminated sand and silt that is in turn overlain by the "upper till". The middle till is not found in glacial deposits in southern New England, suggesting that the glacial advance(s) associated with the middle till did not reach the southern part of the region (Stone and Borns, 1986). The late Wisconsin till ("upper till") is a single surface till with a dominantly silty to sandy matrix. Variations in dominant grain size, color, and stoniness of the till are closely related to bedrock geology (Stone and Borns, 1986).

Glaciers moved in a generally northwest-southeast direction across Maine. Glacial retreat is recorded in the Maine coastal zone by a 30-km-wide belt of end moraines aligned roughly parallel to the coastline and by coarse-grained glaciomarine delta and fan deposits (Borns, 1973). After glaciers retreated from the area, the sea inundated the Maine coastal zone when sea level rose due to glacial melting. The sea occupied the area from about 13,800 years BP to about 11,500 years BP, when post-glacial rebound caused the land surface to re-emerge above sea level.

Figure 6 is a generalized map of glacial deposits in Maine. Three main classes of glacial deposits are shown on the map—till, glaciofluvial deposits, and glaciolacustrine and glaciomarine sediments. Each of these general units is further subdivided into units which reflect the origin of the deposits in more detail. Till is the most common and widespread type of glacial deposit in Maine. It is an unsorted deposit of gravel, sand, silt, and clay, with occasional cobbles and boulders. Thickness of the till ranges from a thin, discontinuous veneer of less than one meter to more than 10 meters in some valleys, but it is generally in the range 1.5-4 m thick (Richmond and Fullerton, 1987). Till is typically thinner on uplands and thicker in valleys. The composition of the till commonly reflects the local bedrock. There are two main types of till in Maine. Loamy till (also called basal till) is a calcareous to non-calcareous loam, silt loam, clay loam, or silty clay loam. Loamy till is locally clayey where it is underlain by shale and locally sandy where it is underlain by coarse-grained crystalline rocks. It is commonly compact in the lower part. Clast composition of loamy till varies but commonly includes limestone, shale, siltstone, sandstone, conglomerate, quartzite, graywacke, slate, argillite, granite, diorite, gabbro, diabase, and volcanic or metavolcanic rocks (Richmond and Fullerton, 1987). Sandy loamy till (also called ablation till) is a calcareous to non-calcareous sandy loam, with some loamy sand, loam, and silt loam, commonly containing pebbles and boulders. Clast composition of sandy loamy till includes granite, pegmatite, granodiorite, rhyolite, diorite, gabbro, basalt, gneiss, schist, argillite, quartzite, and tuff (Richmond and Fullerton, 1987). Both types of till are exposed at the surface across most of Maine as ground moraine deposits. Glacial landforms typically associated with till include drumlins, kettles, and moraines.

Glaciofluvial deposits are stratified sediments deposited by glacial meltwater adjacent to or in front of the ice margin. These ice-marginal or ice-contact deposits include kames, kame terraces, kame moraines, eskers, and outwash deposits. Characteristic of all types of glaciofluvial deposits is their coarse texture, being composed primarily of sand and gravel. Kame terraces formed between the edge of a glacier and a valley wall. Kame moraines are deposits of gravel that formed in front of the glacier and have topography similar to that of a till moraine. Eskers are sinuous ridges composed of outwash sand and gravel deposited by rivers that flowed in tunnels underneath an ice sheet or valley glacier. Outwash gravel was deposited by rivers that drained the melting glaciers. Outwash occurs in relatively narrow valley deposits, in sheets covering large areas, or in fan-shaped deposits.

Glaciolacustrine (lake) and glaciomarine (ocean) sediments are layered silts, clays, and sands. Because valleys and lowlands were the sites of final melting of stagnant ice masses, drainage was blocked and many small lakes developed. Larger lakes were dammed by glacial ice or by moraines. Lake bottom sediments are composed of silt and clay, shallow-water sediments are composed primarily of sand, and beach and delta deposits contain primarily sand and gravel. Marine sediments have characteristics similar to lacustrine sediments, in that they also are classified

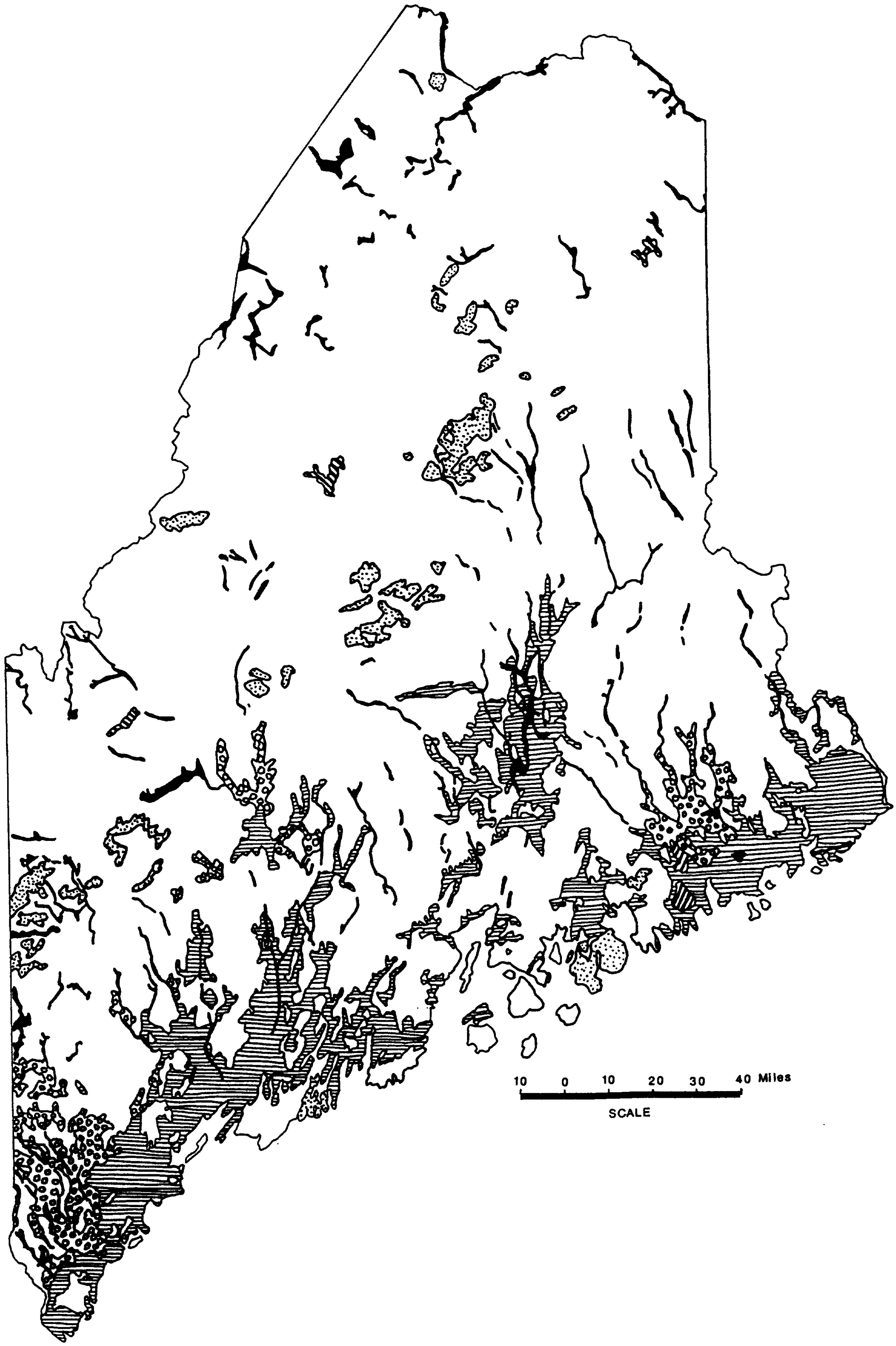


Figure 6. Generalized glacial geologic map of Maine (after Thompson and Borns, 1985).

GENERALIZED GLACIAL GEOLOGIC MAP OF MAINE EXPLANATION

TILL—unstratified mix of gravel, sand, silt, and clay; includes stagnation moraine deposits in northern Maine

MORAINE—irregular ridge of till formed at the margins of retreating glaciers; commonly overlain by marine sediments in southern Maine

GLACIOFLUVIALDEPOSITS—mainly sand and gravel deposits of kames, kame terraces, kame moraines, eskers, outwash, and recent alluvium

LAKE-BOTTOM SEDIMENTS— stratified silt and clay deposited by glacial lakes; may be varved

COARSE-GRAINED LAKE AND MARINE SEDIMENTS— sand and gravel deposits of lacustrine deltas, and marine and lacustrine terraces and beaches

MARINE CLAY—stratified silt and clay deposited by postglacial marine incursions

BEDROCK EXPOSURES

into fine-grained bottom deposits, sandy shallow-water deposits, and sand and gravel beach and deltaic deposits. Marine sediments were deposited in a relatively wide belt along the coast of Maine when sea level rose and the ocean invaded the southeastern part of the State.

SOILS

Soils in Maine include, in decreasing order of abundance, Spodosols, mineral soils with subsurface accumulations of organic matter and compounds of aluminum and iron; Inceptisols, mineral soils with weakly expressed subsurface horizons of alteration or accumulation of metal oxides such as iron, aluminum, or manganese; Entisols, mineral soils with little evidence of soil development because their parent material is inert (such as quartz sand) or because the soils are very young; and Histosols, wet organic-rich soils (peat and muck) in swamp and marsh environments (Rourke and others, 1978; U.S. Soil Conservation Service, 1987). Figure 7 is a generalized soil map of Maine. The following discussion is condensed from Rourke and others (1978). State- and county-scale soil survey reports should be consulted for more detailed descriptions and information.

Much of the State is covered by loamy soils developed on glacial till derived from limestone, shale, and slate. Two units of these till-derived soils are shown on the generalized soil map of Maine (fig. 7). One unit consists of poorly- to well drained, moderately permeable, silty, sandy, and gravelly loams. The other unit consists of poorly- to well drained, silty, sandy, and, locally, gravelly loams, with a firm compact substrata and low permeability. Both types of till soils are generally shallow in upland areas and deeper in lowlands. These soils tend to be well drained on steeper slopes and poorly drained in flatter lowland areas.

Soils developed on deposits of glacial outwash, kames, deltas, eskers, and alluvium are shallow to deep sands and gravels with high permeability. Soils developed on terraces, eskers, and other upland or steeply-sloping areas are well- to excessively drained. Soils in valley bottoms and other low-lying areas are poorly drained and are commonly wet at least part of the year. Included in this map unit are organic soils (Histosols) that formed in kettle holes and adjacent to eskers, kame terraces, and deltas. Histosols are poorly drained and are wet most of the time.

Soils developed on marine and lacustrine sediments, till, and bedrock include deep, poorly- to moderately well drained silts and clays developed on marine and lacustrine deposits; and shallow to deep, moderately well- and well drained, silty and sandy loams developed on bedrock and till. The soils developed on marine and lacustrine deposits have low permeability and cover the majority of land area represented by this map unit. Soils developed on bedrock and till have moderate to locally high permeability. These soils are typically found on coastal upland areas and moraines, whereas the soils derived from marine and lake-bottom sediments occupy low-lying coastal areas (fig. 7).

RADIOACTIVITY

An aeroradiometric map of Maine, synthesized from the National Uranium Resource Evaluation (NURE) flightline data (Duval and others, 1989), is shown in figure 8. High radioactivity in Maine is predominately associated with uranium-rich two-mica granites, calc-alkaline granites, and alkalic granites of the Devonian-Carboniferous age. These granites have typical equivalent uranium (eU) values between 2.5 and 4.5 ppm and in places have eU greater than 5.5 ppm on the aeroradioactivity map (fig. 8). Two-mica granites are most abundant in the southwestern part of the State. The Sebago Lake pluton, northwest of Portland, and smaller

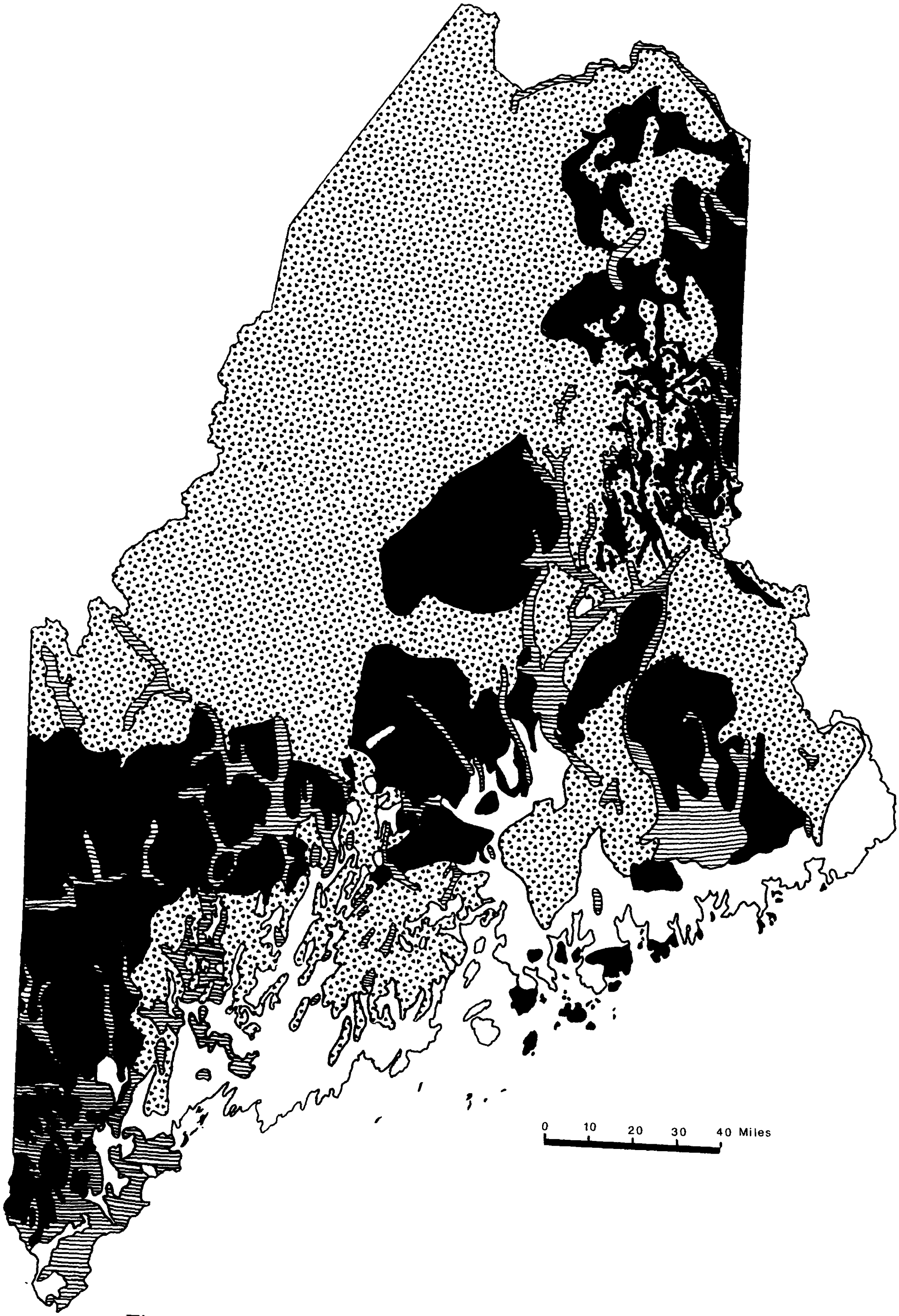


Figure 7. Generalized soil map of Maine (modified from Rourke and others, 1978).

GENERALIZED SOIL MAP OF MAINE
EXPLANATION

Areas dominated by loamy soils with friable substrata developed on glacial till—shallow to deep, silty, sandy, and gravelly loams with moderate permeability

Areas dominated by loamy soils with firm, compact substrata developed on glacial till—shallow to deep, silty, sandy, and gravelly loams with low permeability

Areas dominated by sandy and gravelly soils on glacial outwash plains, deltas, kame terraces, eskers, and Recent alluvium—shallow to deep sands and gravels with high permeability; also includes wet, organic soils in kettles and other low-lying areas

Areas dominated by silty and clayey soils developed on lacustrine and marine sediments—deep clays and silts with low permeability; also includes small areas of shallow to deep, silty and sandy loams with moderate permeability developed on till and bedrock

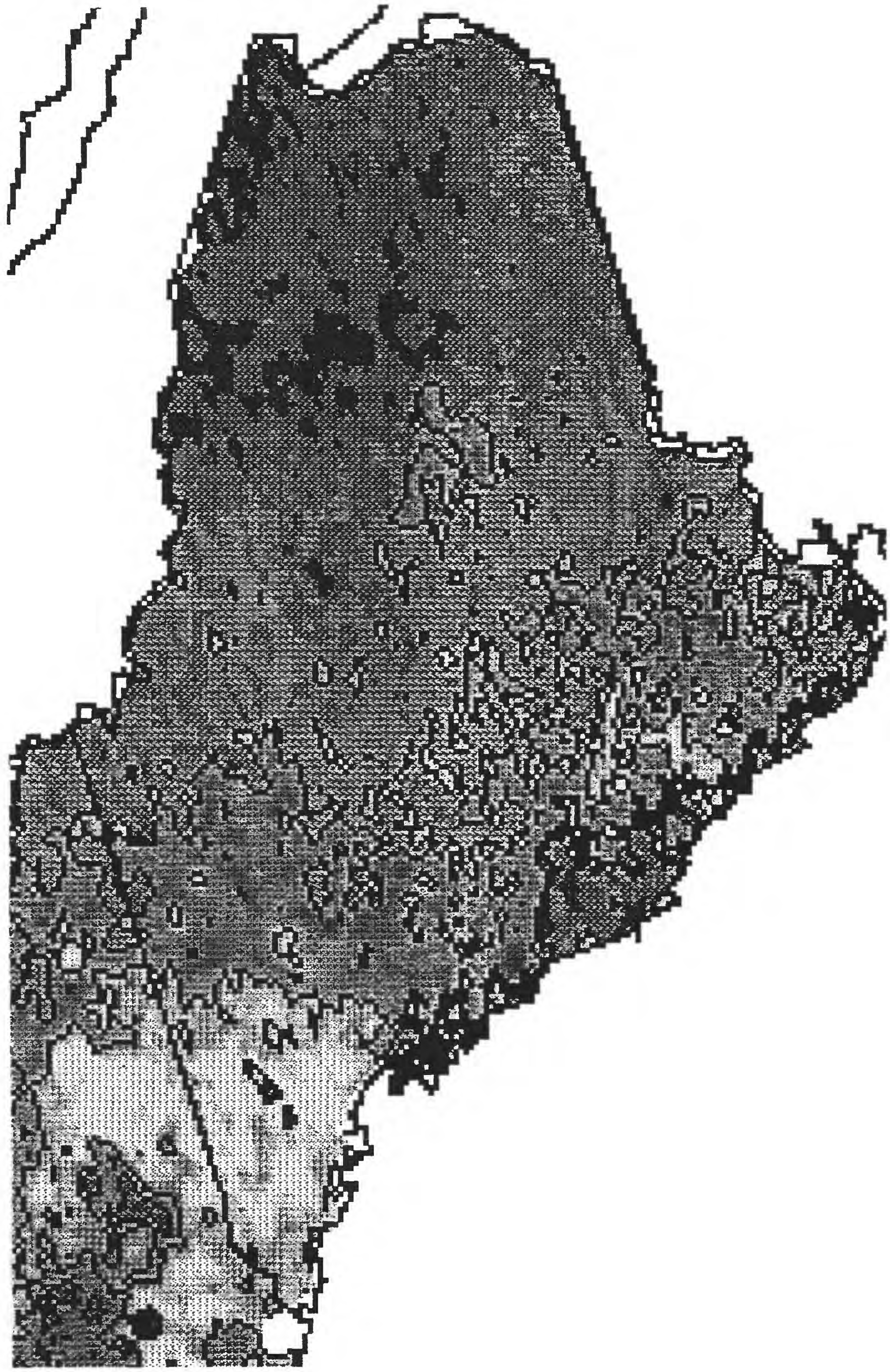


Figure 8. Aerial radiometric map of Maine (after Duval and others, 1989). Contour lines at 1.5 and 2.5 ppm equivalent uranium (eU). Pixels shaded at 0.5 ppm eU increments; darker pixels have lower eU values; white indicates no data.

bodies to the south and east of Portland have U_3O_8 concentrations between 20 and 100 ppm and as high as 280 ppm (Chiasma Consultants, Inc., 1982). North of the Sebago Lake pluton, however, the two-mica granites have generally lower uranium concentrations (average less than 5 ppm and upper values of 9-16 ppm as reported by Bendix Field Engineering (1982)). Alkalic granites are more abundant in the eastern part of the State, particularly in the area northeast of Penobscot Bay and a large body in east-central Piscataquis County. These granites have typical uranium concentrations between 10 and 20 ppm (Bendix Field Engineering, 1982). High radioactivity on the aeroradioactivity map (fig. 8) is also associated with several small areas in the southeastern part of the State underlain by Conway Granite of the White Mountain plutonic series and two small syenite sills of the New Hampshire series, one northeast of Waldboro and the other incorporated in a series of faults in northern Hancock County. Chiasma Consultants, Inc. (1982) reports a U_3O_8 concentration of 26 ppm from Conway Granite in Maine and values ranging 3-75 ppm in associated trachyte dikes. Bendix Field Engineering (1982) reports uranium concentrations of 10 to 35 ppm in the syenite sills. Tonalite and monzonite intrusive rocks of the New Hampshire series underlie several small areas in the east-central part of the State and a large area near the northernmost part of Hancock County. These intrusive rocks have moderate eU (1.5-2.5 ppm) on the aeroradioactivity map (fig. 8). Diorite and mafic intrusive rocks of the New Hampshire series have low eU (0.5-1.5 ppm) on the aeroradioactivity map and comprise two northeast-trending belts along the southern coast and from southern Oxford County to central Picataquis County.

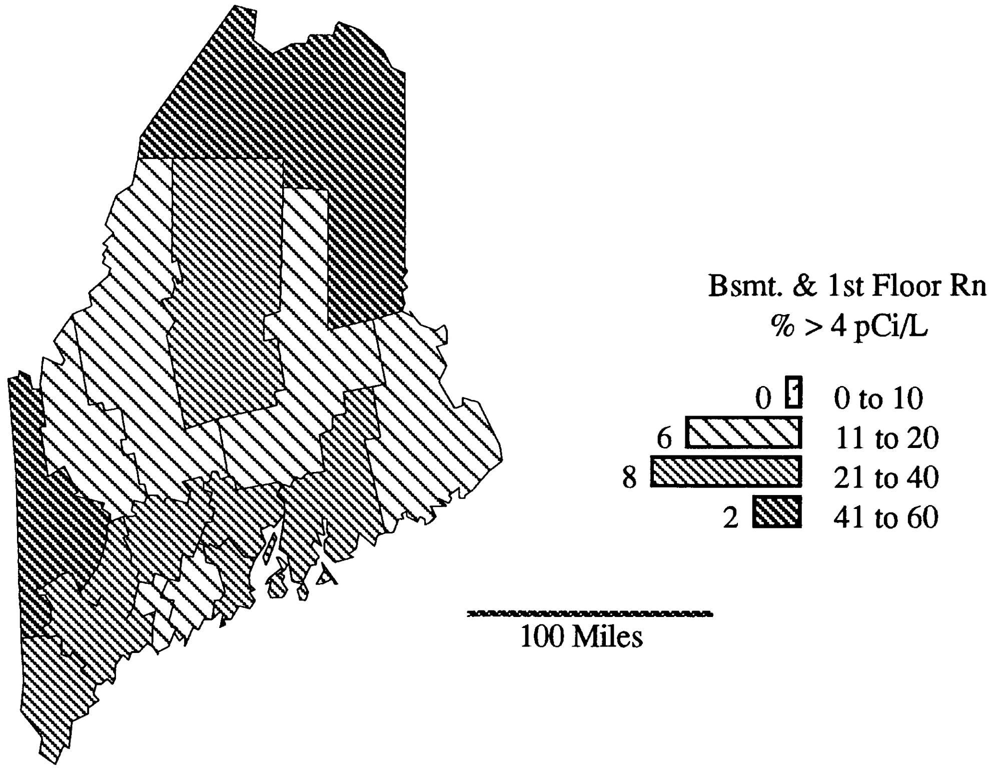
In the southern part of the State, most of the metasedimentary and metavolcanic units have moderate to high eU (2-4 ppm) on the aeroradioactivity map (fig. 8). The individual units are difficult to distinguish due to the overprint of adjacent granites. Chiasma Consultants, Inc. (1982) indicate that some uranium anomalies in the Cambro-Ordovician Cushing Formation and the Silurian Berwick Formation are related to pegmatite dikes from two-mica granites with U_3O_8 values typically between 30 and 60 ppm and as high as 394 ppm. An increase in uranium with metamorphic grade resulting from recrystallization and partial melting at progressively high pressures and temperatures has been suggested by a number of authors (Hess and others 1980; Olszewski and Boudette, 1986). A comparison of figure 5a with figure 8 shows a broad correlation of radioactivity anomalies with either igneous plutons or high metamorphic grade. Several aeroradioactivity anomalies, however, are directly associated with graphitic and sulfidic slate and schist of Cambrian to Silurian age that crop out in a zone parallel to the southern coast. These rocks include the Cambro-Ordovician Scarboro, Diamond Island, and Cushing Formations, the Ordovician Penobscot, Quimby, and Beauceville Formations and the Silurian Berwick, Digdegaush, and Quoddy Formations. Graphitic slates in the vicinity of Portland have U_3O_8 concentrations of 8 ppm (Chiasma Consultants, Inc., 1982). North of this belt is a belt of Silurian-Devonian metamorphosed calcareous sandstone and limestone of the Bucksport and Vassalboro Formations. Bendix Field Engineering (1982) noted several anomalous radioactivity highs in these units, but the Vassalboro stands out as an area of moderate eU (2.0-2.5 ppm) on the radiometric map (fig.8).

Another belt of mostly Silurian graphitic and sulfidic slate and schist with moderate to high eU on the aeroradioactivity map (fig. 8) extends northeast from the northern edge of the Sebago Lake pluton. This belt includes the Silurian Sangerville, Small Falls, Waterville, and Rangeley Formations. North of this belt the only metasedimentary rocks that stand out with low to moderate eU (1-2.5 ppm) on the aeroradioactivity map (fig. 8) are black metapelites of the Devonian Carrabasset, Seboomook, and Tarratine Formations, and the Cambrian Grand Pitch, Dead River, and Hurricane Formations. The Carrabasset Formation forms a northeast-trending belt, mostly in southern Piscataquis County. It intertongues to the northeast with the Devonian Flume Ridge Formation, a metamorphosed calcareous sandstone in which Bendix Field Engineering (1982) found a few areas of anomalously high surface radioactivity, and to the southwest into faulted and folded Seboomook Formation and Silurian metapelites, all of which are heavily intruded by New Hampshire series igneous rocks. The Cambrian metapelites form a belt of low to moderate eU (fig. 8) north of the Devonian rocks. They are highly faulted and intruded by Devonian igneous rocks. North of the belt of Cambrian-age rocks, the metamorphic grade is lower and the radiometric signature on the aeroradiometric map is low. In this area, the Tarratine Formation has elevated eU on the aeroradioactivity map (fig.8), as does a small fault-bounded belt of the Cambrian Hurricane Mountain Formation. Bendix Field Engineering (1982) notes several radioactivity anomalies in the Seboomook Formation, which they argue may be due to fertilizer use in that heavily agricultural region. They also note anomalies associated with the Ordovician Carys Mill Formation gray slate and argillaceous limestone, and the Silurian Allsbury Formation slate and sandstone, which comprise a north-south trending belt in easternmost Aroostook County, and with Ordovician quartz monzonite and Precambrian gneiss in northern Franklin and western Somerset Counties. None of these have corresponding anomalies on the radiometric map (fig. 8), although they are slightly elevated relative to surrounding rocks.

Most of the Ordovician to Devonian rocks in the northern part of the State have low eU values (0-1.5 ppm) on the radiometric map (fig.8). The lowest values (0-0.5 ppm eU) are associated with the Cambro-Ordovician Saint Daniel Formation quartzites in western Aroostook County, Ordovician mafic volcanics of the Winterville Formation in eastern Aroostook County, and most of the area underlain by the Seboomook Formation. In the south, the metamorphosed quartzite and mafic volcanics of the Cambro-Ordovician Cushing and Cape Elizabeth Formations are notably low in radioactivity (0.5-2.0 ppm) on the aeroradiometric map (fig. 8).

INDOOR RADON/RADON IN WATER

Indoor radon data from 839 homes sampled in the State/EPA Residential Radon Survey conducted in Maine during the winter of 1988-89 are shown in figure 9 and listed in Table 1. A map of counties is included for reference (fig. 10). Data is presented by both county and zip code. Because of the large size of the symbols compared to the small scale of the zip code map, some of the symbols representing relatively small and(or) irregularly shaped zip code areas that are near to each other appear to overlap. Indoor radon was measured by charcoal canister and data are shown only for those counties with 5 or more data values. The maximum value recorded in the survey was 103.2 pCi/L in Franklin County. The average for the State was 4.0 pCi/L and 29.9 percent of the homes tested had indoor radon levels exceeding 4 pCi/L. Counties with average indoor radon values exceeding 4 pCi/L include Aroostook, Cumberland, Franklin, Oxford, and York. The remaining counties all had average indoor radon levels between 2 and 4 pCi/L. Counties with average radon levels greater than 4 pCi/L occur in the northern and western parts of the State, whereas counties in the southern and central parts of Maine have moderate (2-4 pCi/L) indoor radon averages. The percent of homes in each county with indoor radon levels exceeding 4 pCi/L follows the same trend as the average values (fig. 9). In Oxford County, 52 percent of the homes tested had indoor radon levels exceeding 4 pCi/L. In Aroostook, Cumberland, Hancock, Kennebec, Piscataquis, and York Counties, between 25 and 50 percent of the homes tested had indoor radon levels exceeding 4 pCi/L (fig. 9). The highest county average, 6.8 pCi/L for



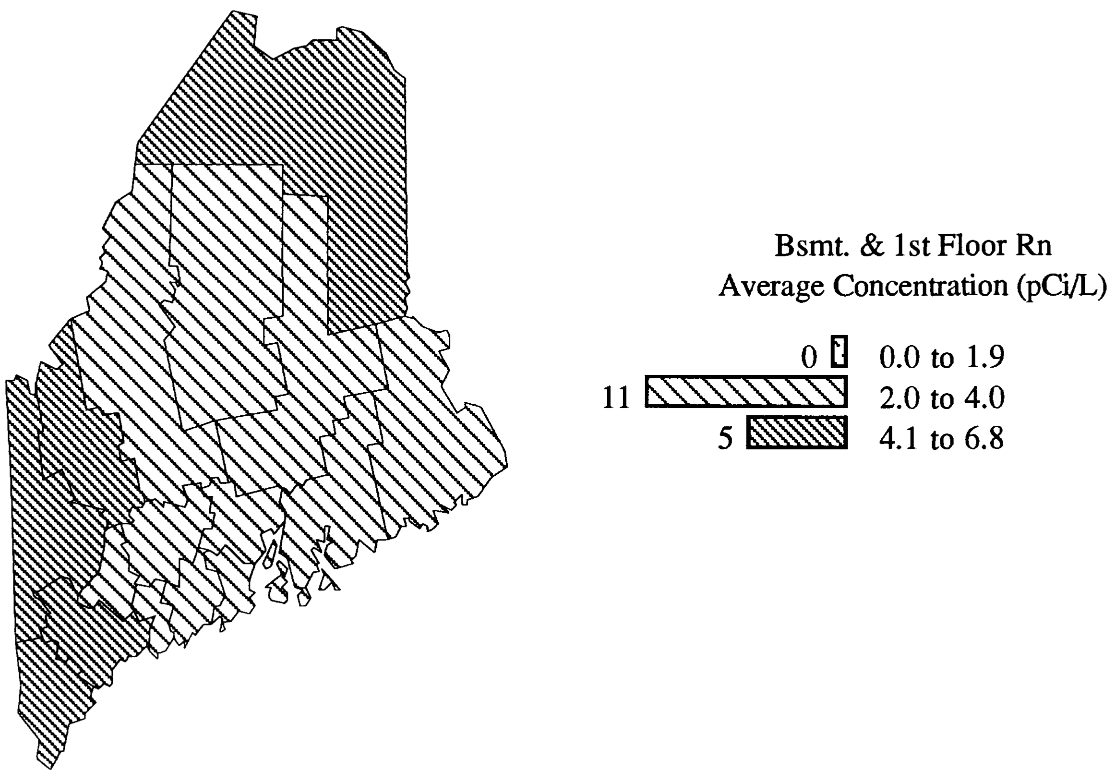


Figure 9. Screening indoor radon data from the EPA/State Residential Radon Survey of Maine, 1988-89. Data are from 2-7 day charcoal canister tests. Histograms in map legends show the number of counties in each category. The number of samples in each county (See Table 1) may not be sufficient to statistically characterize the radon levels of the counties, but they do suggest general trends. Unequal category intervals were chosen to provide reference to decision and action levels.

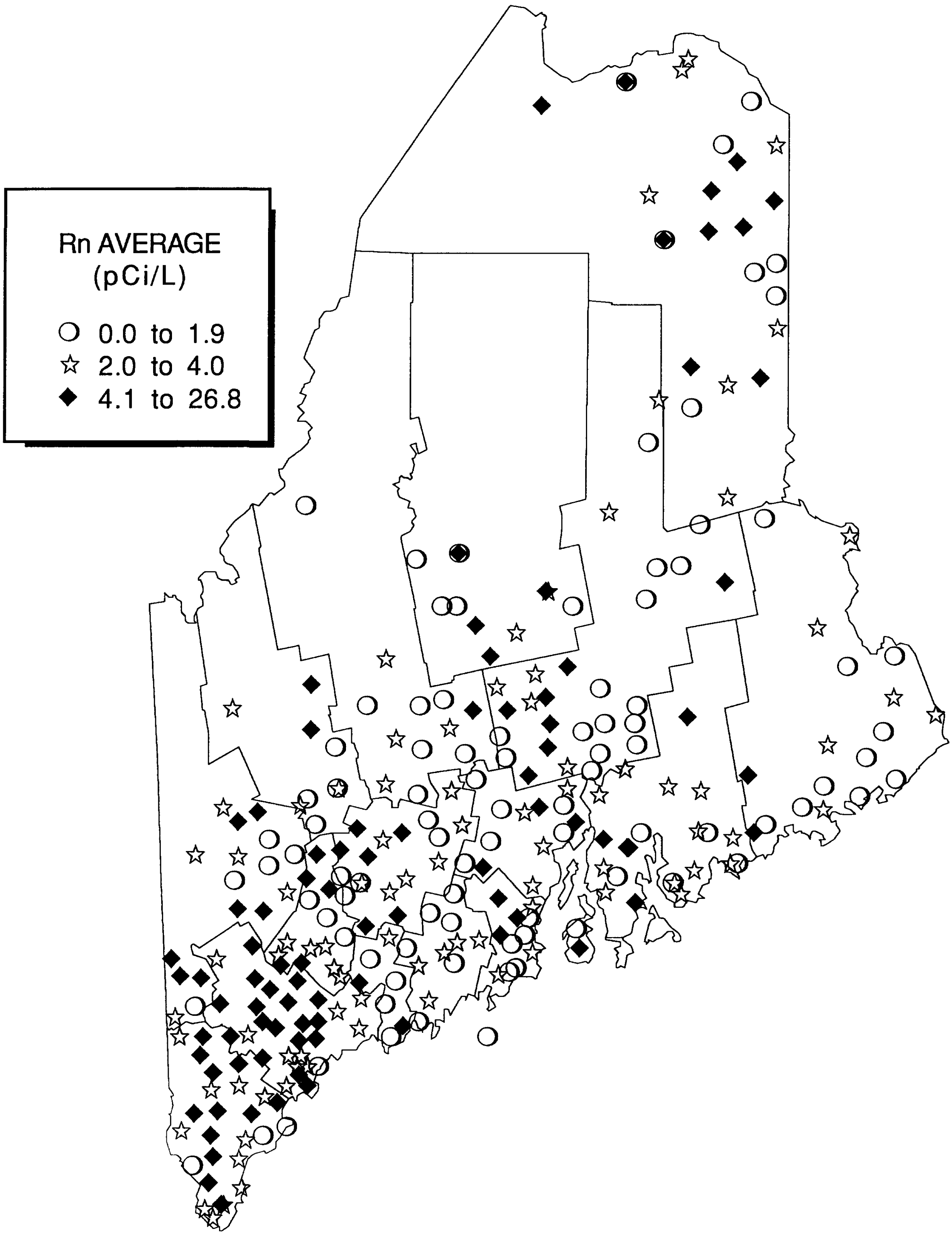


Figure 9 (continued). Average basement and first-floor radon by ZIP code. Each point located in center of ZIP code area (centroid).

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

COUNTY	NO. OF MEAS.	MEAN	GEOM. MEAN	MEDIAN	STD. DEV.	MAXIMUM	%>4 pCi/L	%>20 pCi/L
ANDROSCOGGIN	47	3.1	2.2	2.4	2.7	11.4	23	0
AROOSTOOK	102	4.9	3.0	3.6	5.1	25.2	41	5
CUMBERLAND	132	5.6	3.2	3.2	8.5	82.7	39	3
FRANKLIN	22	6.8	1.8	1.7	21.7	103.2	18	5
HANCOCK	53	3.5	1.8	2.2	3.8	19.4	28	0
KENNEBEC	61	3.5	1.9	2.0	4.2	19.4	28	0
KNOX	30	2.8	1.6	1.6	2.9	9.7	23	0
LINCOLN	18	2.2	1.7	1.7	1.7	6.9	11	0
OXFORD	42	5.6	3.2	4.2	5.9	30.2	52	5
PENOBSCOT	79	2.1	1.4	1.7	1.8	7.5	15	0
PISCATAQUIS	42	3.8	2.1	1.9	4.8	22.5	26	2
SAGADAHOC	34	2.2	1.4	1.6	2.1	8.0	18	0
SOMERSET	31	2.1	1.6	1.6	1.5	5.8	19	0
WALDO	27	3.1	2.0	2.1	3.3	13.0	22	0
WASHINGTON	40	2.5	1.5	1.6	2.7	12.2	15	0
YORK	79	5.6	3.1	2.9	6.7	33.0	41	4

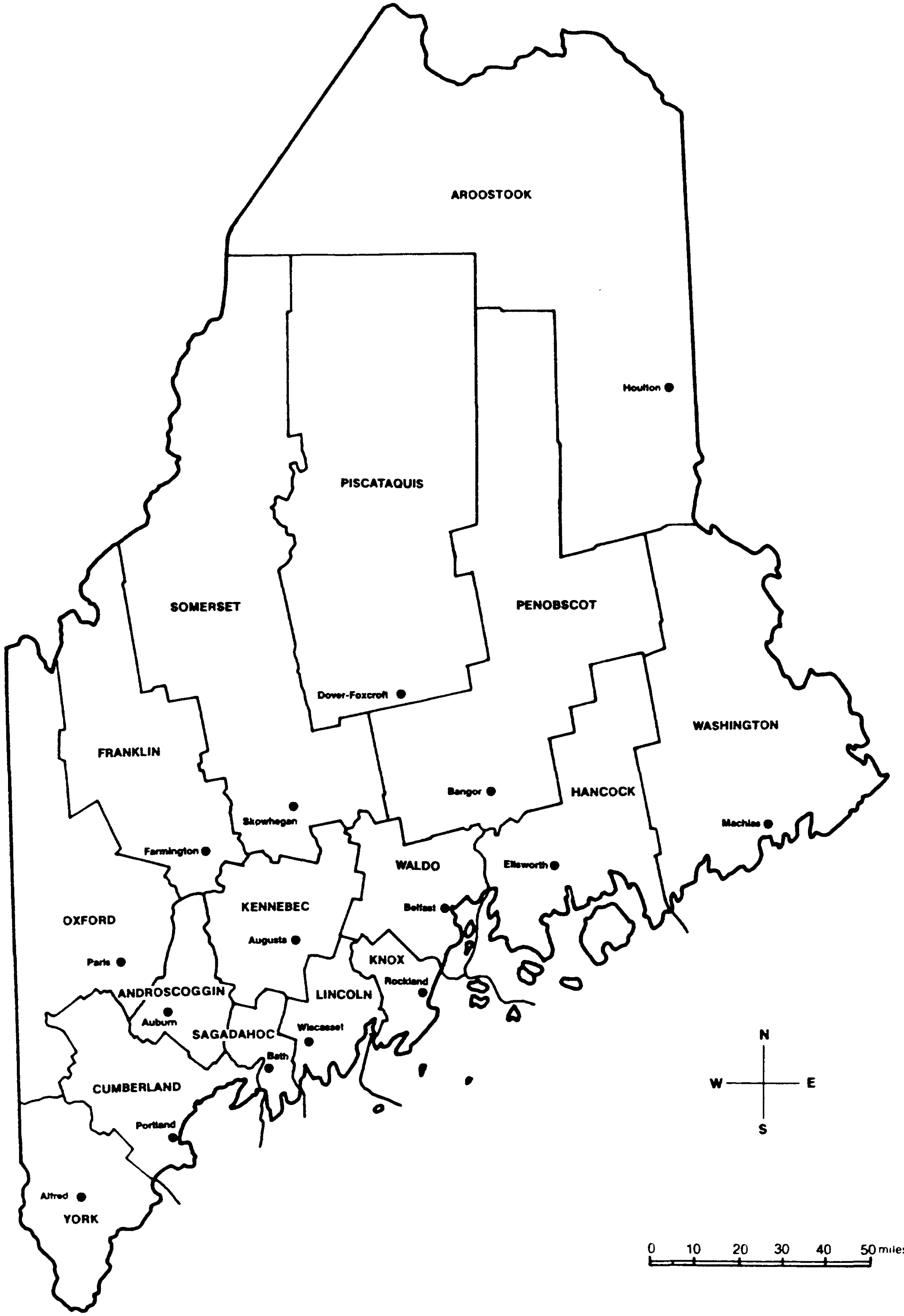


Figure 10. Maine counties (from Facts on File, 1984).

22 measurements in Franklin County, may be somewhat misleading because of the influence of the single 103.2 pCi/L value on the arithmetic mean. With this value excluded, the average for the remaining 21 measurements in Franklin County is 2.2 pCi/L. However, it is important to keep in mind that this high value indicates that elevated indoor radon levels can occur locally within Franklin County.

A study was also made of radon in 13,353 school rooms in 653 schools across the State of Maine (Grodzins and others, 1991). Indoor radon measurements were made with liquid scintillation charcoal detectors, in rooms at or below grade, from a Friday afternoon to the following Monday morning. The results indicated that 32 percent of the schools had at least one room with a radon concentration exceeding 4 pCi/L. Grodzins and others (1991) also noted a strong correlation between the geographic distribution of radon levels in the school study and those of the State/EPA indoor radon survey of homes. In the school survey, they report that school buildings in Aroostook, York, Cumberland, Androscoggin, and Oxford Counties have uniformly high mean radon values; Kennebec, Waldo, Hancock and Washington Counties have moderate values; and Sagadahoc, Lincoln, and Knox Counties have low radon averages.

Radon contributed from domestic well water may also constitute a significant indoor-air radon problem in Maine. There is considerable debate over the amount of indoor radon contributed to the air from water use. Several studies indicate that degassing of radon from water can cause spikes in indoor air concentrations, especially during peak water-use periods (Hess and others, 1986; Nazaroff and Nero, 1988). The amount of radon that is contributed to indoor air from water varies substantially and is related to the volume of air in the house and the volume of water used over a given period of time. The problem of radon in water in Maine has been studied by a number of authors and part of these data are summarized in Norton and others (1989). They examined data from 350 wells in Maine and found that the distribution of radon in ground water is primarily controlled by bedrock geology. Low-grade metamorphic rocks had mean waterborne radon concentrations between 1,000 and 5,000 pCi/L. Water from medium- to high-grade metamorphic rocks yielded average radon concentrations in the 10,000 to 15,000 pCi/L range. Granites consistently yielded water with the highest radon concentrations, averaging 22,000 pCi/L, with values commonly exceeding 50,000 pCi/L. Radon values were variable within single granite bodies. Wells developed in surficial materials had significantly lower waterborne radon concentrations than wells drilled into bedrock. Using these data and the distribution of rock types within each county, Norton and others (1989) estimated average waterborne radon concentrations by county. A map showing the estimated average water radon concentrations for each county is shown in figure 11.

Clausen (1990) examined water data from Hess and others (1980) and from the Maine Department of Human Services. Data from his thesis for 1533 wells, grouped by lithology, are presented in Table 2. Generally, the median value for most wells was below 5000 pCi/L, excluding granite and the general category of igneous rocks. Average values were much higher than the medians for all rock categories due to the fact that all categories had at least one well with a radon concentration greater than 10,000 pCi/L. Clausen concluded that, for the metamorphic rocks, there is a weak positive correlation with increasing metamorphic grade, and that ground water from granites seems to be the most highly variable in radon concentration as well as yielding the highest radon concentrations overall.

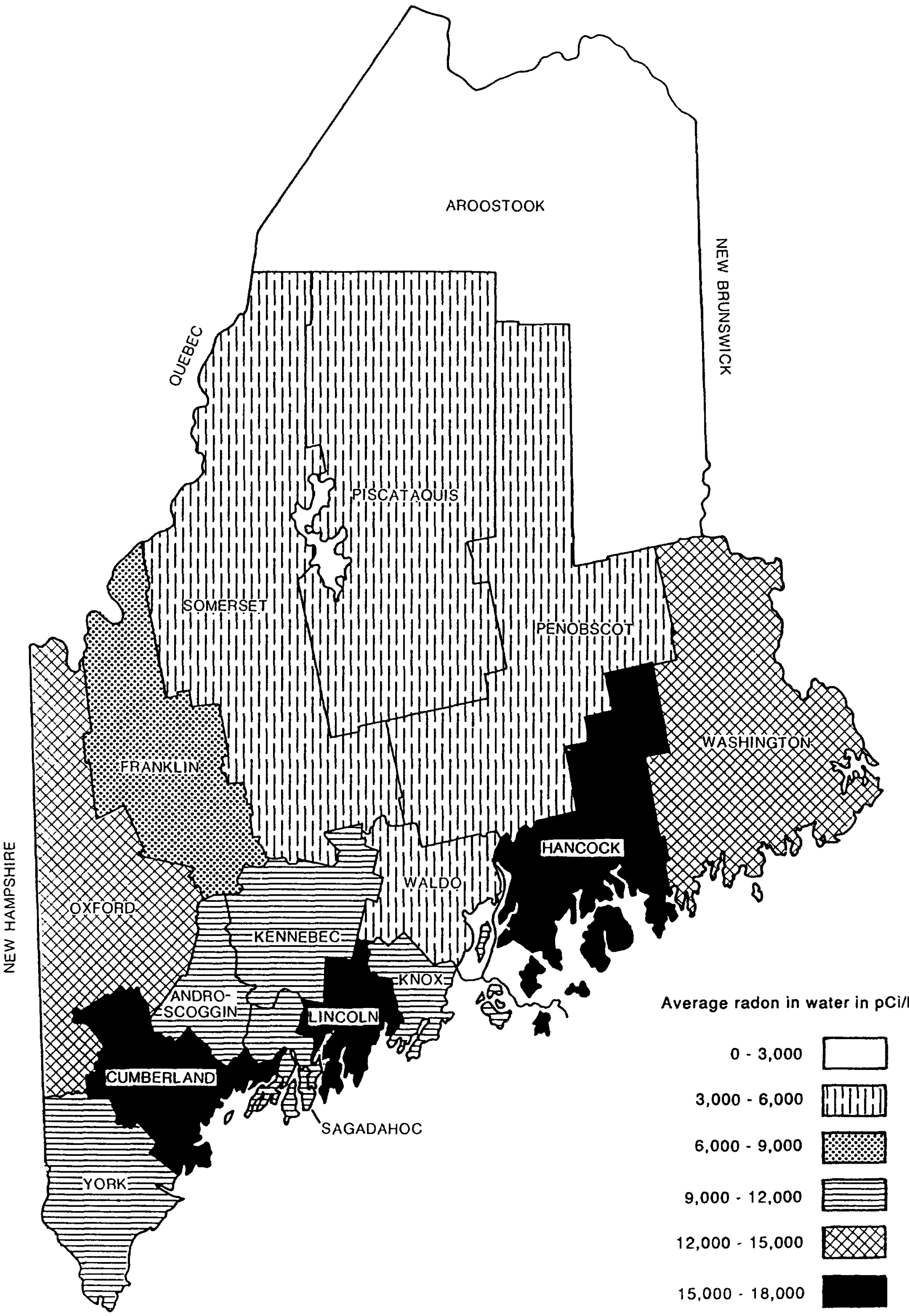


Figure 11. Map showing average radon in water for Maine counties (from Norton and others, 1989).

TABLE 2. RADON ACTIVITIES FOR VARIOUS BEDROCK LITHOLOGIES
(from Clausen, 1990)

		Radon activitities (pCi l^{-1})			
Lithology	n	mean	std. dev.	med.	max.
Calcareous Pelite	13	3,858	4,349	2,300	14,800
Sulfidic Calcareous Pelite	3	4,691	4,039	3,838	15,809
Feldspathic Sandstone	62	3,809	11,186	1,800	88,600
Calcareous Feldspathic Sandstone	62	3,810	11,186	1,800	88,800
Calcareous Quartz Sandstone	22	9,185	14,489	2,677	48,890
Limestone	34	5,916	7,846	3,750	43,620
Interbedded Sandstone and Shale	196	8,744	16,093	2,714	104,000
Interbedded Limestone and Shale	132	15,231	116,570	2,363	1,341,800
Interbedded Limestone, Sandstone and Shale	191	6,380	11,852	2,302	103,700
Mixed Volcanic Rocks	58	5,072	6,056	2,600	30,400
Undetermined Volcanic Rocks	4	3,338	4,705	1,426	10,300
Igneous Rocks	418	18,430	41,817	5,300	363,320
Schist	4	3,228	3,254	2,294	15,900
Granite	334	30,231	87,440	12,450	363,320

GEOLOGIC RADON POTENTIAL

The following discussion examines indoor radon, radioactivity, soil properties, and geology to assess the geologic radon potential for areas in the State. A numeric ranking is given in Table 3 and geologic radon potential areas are illustrated in figure 12. Previous studies on the geologic radon potential of Maine include Olszewski and Boudette (1986), who compiled a generalized geologic map of New England with emphasis on uranium endowment and radon production. This analysis corresponds well with their uranium endowment map for the State of Maine and we have followed some of their groupings for rock units. Because of the variability of the geology of Maine with respect to the distribution of indoor radon data it is difficult to identify definitive correlations between the indoor radon data and specific geologic formations.

In figure 2, the rocks of Maine have been subdivided into major lithologic groups. Of these groups, the rocks, surficial deposits, and geologic structures most likely to cause high (>4 pCi/L) indoor radon concentrations include: two-mica granite, alkaline and calc-alkalic granite, and granodiorite; pegmatites, faults and shear zones; and carbonaceous schist, slate, and phyllite. Deposits and rocks likely to cause moderate (2-4 pCi/L) to high (>4 pCi/L) indoor radon include soils developed on carbonate rocks, especially the interbedded slates and dolostones in south-central and northeastern Maine; glacial gravels, especially outwash, kames, and eskers; melange; granitic gneiss; high- to medium-grade metamorphic rocks, and contact metamorphosed rocks in the vicinity of plutons. Rocks and deposits with moderate to variable radon potential include felsic metavolcanic rocks, intermediate composition plutonic rocks, and glacial till. Rocks likely to cause low indoor radon (< 2 pCi/L) include metamorphosed coarse-grained clastic sedimentary rocks, mafic metavolcanic rocks, marine clays, and mafic plutonic rocks.

Stratified metamorphic rocks of igneous or sedimentary origin

Most of Maine is underlain by Cambrian-Devonian stratified metamorphic rocks of igneous or sedimentary origin that we have ranked from low to high in geologic radon potential. Olszewski and Boudette (1986) classified these Paleozoic metasedimentary and metavolcanic rocks as having variable uranium endowment. Uranium concentration generally increases with metamorphic grade and local uranium concentrations may be present in fractures and faults. Uranium analyses for most of the metasedimentary and metavolcanic rocks in central and northern Maine (previously discussed in the radioactivity section of this report) indicate uranium concentrations of less than 3 ppm in general. Areas in northern Maine underlain by coarse-grained clastic metasedimentary rocks and tills derived from these rocks generally have low equivalent uranium on the NURE map (fig. 8) and have soils with low permeability. Many of the rocks in this area belong to the Seboomook Formation (Area 1, fig. 12). Indoor radon data are sparse for northern Maine except in the northeast, where most of the underlying rocks and tills are composed of carbonate and slate or shale (Area 2, fig. 12). In central and southern Maine, indoor radon is low to moderate in areas underlain by coarse-grained clastic metasedimentary rocks. Formations such as the Vasselboro, which has interbedded carbonate and clastic metasedimentary rocks and tends to be more calcareous in general, appears to be associated with high indoor radon in southern Penobscot County (Area 3, fig. 12). Area 3 on figure 12 is a highly variable area–radon potential varies from moderate to locally high or low. Locally high areas may be associated with granites, kames, eskers, carbonates, graphitic or carbonaceous schist, phyllite, and slate. Locally low areas may be associated with mafic plutonic rocks and clastic metasedimentary rocks. Indoor radon is highly variable in this area and the geology is variable over short distances.

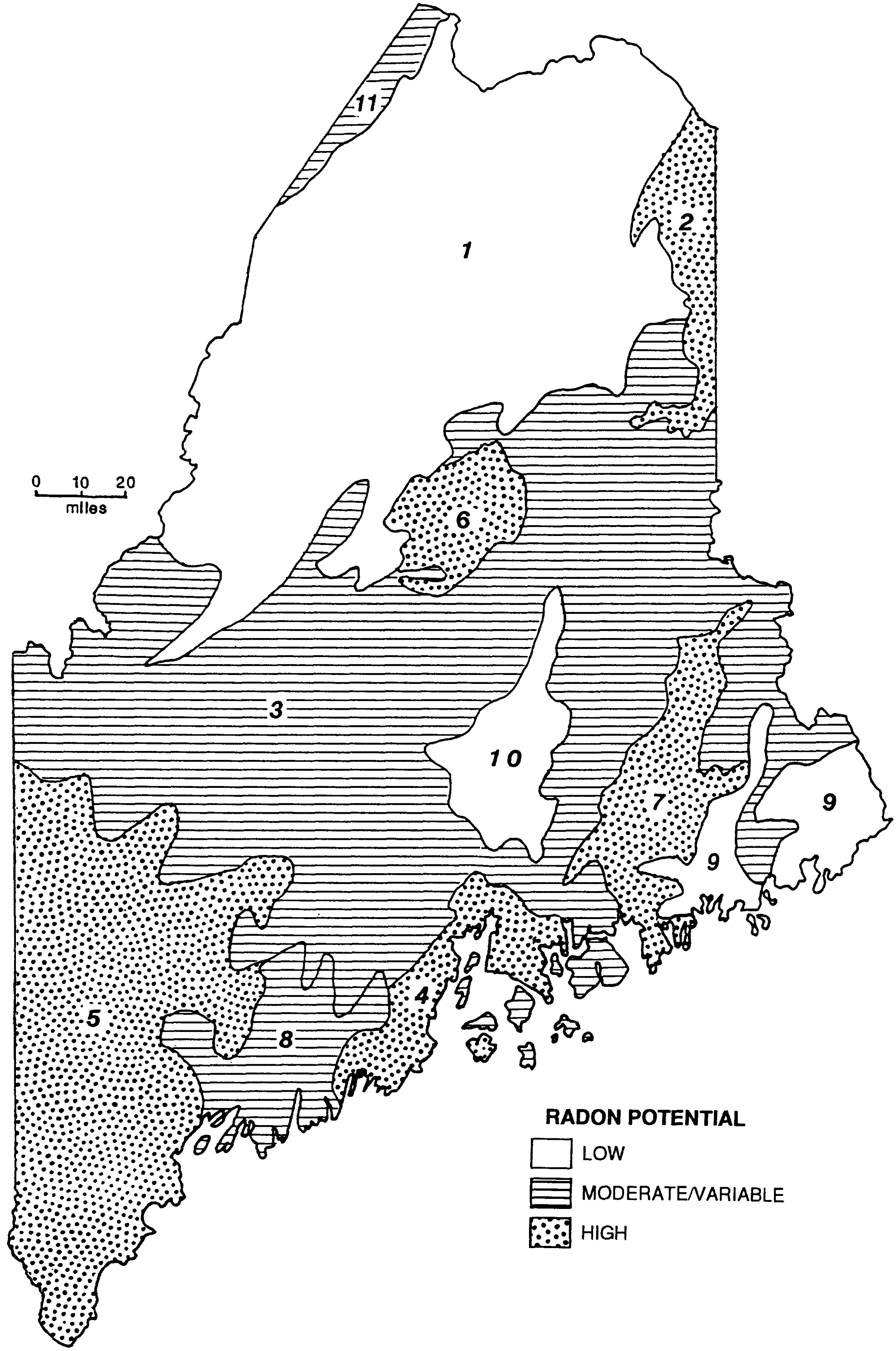


Figure 12. Geologic radon potential areas of Maine. See text for discussion of numbered areas.

Soils and glacial deposits derived from interbedded carbonates and slates in the northeastern portion of the State and in the south-central portion of the State (Areas 2 and 3, fig. 12) are associated with moderate and high indoor radon levels. Equivalent uranium is variable over these deposits (fig. 8) but is higher than in the dominantly clastic metasedimentary rocks. Soils, tills, eskers, and kames derived from these rocks generally have moderate to locally high permeability. Carbonate rocks are usually low in radionuclide elements but the soils developed from carbonate rocks are often elevated in uranium and radium. Carbonate soils are derived from the dissolution of the $CaCO_3$ that makes up the majority of the rock. When the $CaCO_3$ has been dissolved away, the soils are enriched in the remaining impurities, predominantly base metals, including radionuclides.

Graphitic or carbonaceous slates, phyllites, and schists are known to be uranium and radon sources in several areas of the Appalachians (Ratté and Vanacek, 1980; Gundersen and others, 1988) and this may be the case in Maine. Most of the carbonaceous or graphitic rock units in Maine have corresponding moderate to high equivalent uranium in figure 8. Some high indoor radon levels may be associated with carbonaceous rocks of the Penobscot Formation in Knox County (Area 4, fig. 12). Soils formed on carbonaceous and graphitic rocks in Maine have low to moderate permeability.

Igneous plutonic rocks

Intermediate to mafic plutonic rocks generally have low or variable radon potential. Diorite and mafic intrusive rocks of the New Hampshire series have low equivalent uranium (0.5-1.5 ppm) and comprise two northeast-trending belts along the southern coast and from southern Oxford County to central Picataquis County. Two-mica granites, calc-alkaline granites, and alkalic plutonic rocks in Maine have been ranked high in radon potential (in Areas 3, 5, 6, 7, fig. 12). Uranium concentrations in these types of granites are commonly more than 3 ppm and are as high as several hundred ppm in Maine. Uranium occurs as primary uranium oxides such as uraninite or in abundant accessory minerals. Olszewski and Boudette (1986) classified these rocks as moderate to high in uranium endowment. Two-mica granites are most abundant in the southwestern part of the State and include the rocks of the Sebago Pluton. Calc-alkaline to alkaline granites are more abundant in the southern and central part of the State, particularly in the area northeast of Penobscot Bay and in the Katadhin pluton in central Maine (Area 6, fig. 12). Indoor radon is high in the southwestern counties of Maine and in many of the zipcode areas, and may correlate with the abundance of igneous plutons and high grade metamorphic rocks in this area (Area 5, fig. 12). Most of the areas underlain by igneous plutonic rocks and associated glacial deposits have moderate to locally high permeability.

Although there is no obvious anomalous radioactivity associated with the major fault and shear zones in Maine, evidence from other areas of the Appalachians (Gundersen, 1991) suggests that shear zones can create isolated occurrences of severe indoor radon, especially when they deform uranium-bearing rocks. The radon potential of melange (Area 11 and a small part of Area 3, fig. 12) is not well known; however, gray to black phyllitic rocks and deformed zones have the potential to produce at least moderate amounts of radon. We have tentatively ranked these rocks as moderate or variable in radon potential.

Glacial deposits

The effect of glacial deposits is difficult to assess in Maine because most till is locally derived and primarily reflects a collection of clasts of the surrounding bedrock. The areas of coarse-grained glacial deposits in southwestern Maine and the kame and esker deposits scattered throughout the State enhance the geologic radon potential due to their very high permeability. Coarser glacial deposits appear to be associated with igneous plutonic rocks and belts of calcareous and carbonate metasedimentary rocks. Along the coast, areas of slowly permeable marine clay probably reduce the radon potential (Areas 8, 9, fig. 12). Glacial lake sediments with low permeability in Penobscot County (Area 10, fig. 12) appear to be associated with low indoor radon on the zip code radon map. Sagadahoc, Lincoln, Knox, and Washington Counties have average indoor radon less than 3 pCi/L and are underlain by extensive marine clay deposits. Equivalent uranium is low to moderate (fig. 8). Metavolcanic and metasedimentary rocks with probable low uranium concentrations also underlie these counties. Till with compact, low-permeability substrata is dominant in much of central and northern Maine and the rocks underlying these areas are metasedimentary and metavolcanic rocks that are generally low in uranium. As can be seen from the zip code centroid plot of indoor radon in the State (fig. 9), few towns are present in northern Maine and indoor radon data are sparse.

SUMMARY

For the purpose of this assessment, Maine has been divided into eleven geologic radon potential groupings and each area assigned a Radon Index (RI) and a Confidence Index (CI) score (Table 3). The RI is a semi-quantitative measure of radon potential based on geology, soils, radioactivity, architecture, and indoor radon. The CI is a measure of the relative confidence of the RI assessment based on the quality and quantity of the data used to assess geologic radon potential (see the introduction chapter to this booklet for more information).

The rocks, deposits, and geologic structures most likely to cause high (>4 pCi/L) indoor radon levels in Maine include: two-mica granite, alkaline and calc-alkalic granite and granodiorite; pegmatites; faults and shear zones; and carbonaceous schist, slate, and phyllite. Deposits and rocks likely to cause moderate (2-4 pCi/L) to high (>4 pCi/L) indoor radon include soils developed on carbonate rocks, especially the interbedded slates and dolostones in south-central and northeastern Maine; glacial gravels, kames, and eskers; melange; granitic gneiss; medium- to high-grade metamorphic rocks; and contact-metamorphosed rocks in the vicinity of igneous plutons. Rocks and deposits with moderate to variable radon potential include felsic metavolcanic rocks, intermediate composition plutonic rocks, and glacial till. Rocks likely to cause low indoor radon include metamorphosed, coarse-grained, clastic sedimentary rocks; mafic metavolcanic rocks; marine and glaciomarine clays; and mafic plutonic rocks. Radon escaping into indoor air from domestic well water may be a significant factor in the indoor radon concentrations seen in Maine. High radon concentrations in well water correlate positively with granite plutons, pegmatites, faults, and high-grade metamorphic rocks.

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

TABLE 3. RI and CI scores for geologic radon potential areas of Maine. See figure 12 for locations of areas.

FACTOR	Area 1 Seboomook Fm. RI	Area 1 Seboomook Fm. CI	Area 2 metasedimentary predominantly carbonate RI	Area 2 metasedimentary predominantly carbonate CI	Areas 3 and 11 Heterogeneous metamorphic & igneous rocks RI	Areas 3 and 11 Heterogeneous metamorphic & igneous rocks CI
INDOOR RADON	1	1	3	2	2	2
RADIOACTIVITY	1	2	2	2	2	2
GEOLOGY	2	2	2	2	2	3
SOIL PERM.	1	2	2	2	2	2
ARCHITECTURE	3	-	3	-	3	-
GFE POINTS	0	-	0	-	0	-
TOTAL	8	7	12	8	11	9
RANKING	Low	Low	High	Mod	Mod	Mod

FACTOR	Areas 4 and 7 Penobscot Fm., granites and minor metamorphic rocks RI	Areas 4 and 7 Penobscot Fm., granites and minor metamorphic rocks CI	Areas 5 and 6 Granite and high grade metamorphic RI	Areas 5 and 6 Granite and high grade metamorphic CI	Areas 8, 9, and 10 glacial lake clay marine clay RI	Areas 8, 9, and 10 glacial lake clay marine clay CI
INDOOR RADON	2	2	3	2	2	2
RADIOACTIVITY	3	2	3	2	1	2
GEOLOGY	3	3	3	2	1	3
SOIL PERM.	2	2	2	2	1	2
ARCHITECTURE	3	-	3	-	3	-
GFE POINTS	0	-	0	-	0	-
TOTAL	13	9	14	8	8	9
RANKING	High	Mod	High	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

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 MASSACHUSETTS

by R. Randall Schumann and Linda C.S. Gundersen
U.S. Geological Survey

INTRODUCTION

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

PHYSIOGRAPHIC AND GEOGRAPHIC SETTING

The physiography of Massachusetts (fig. 1) is a reflection of the underlying bedrock geology (fig. 2) and subsequent modification by Pleistocene glaciation and postglacial erosional processes. The State's elevation ranges from sea level to 3,491 feet at Mount Greylock, in the Taconic Mountains in northwestern Massachusetts. Massachusetts is divided into six major physiographic regions. From west to east they are the Taconic Mountains, Berkshire Valley, Western New England Upland, Connecticut Valley Lowland, Eastern New England Upland, and the Coastal Lowlands (fig. 1).

The Taconic Mountains are an area of low mountains and hills along the Massachusetts-New York border which extend northward, increasing in height, into Vermont. In Massachusetts, several peaks are greater than 2500 ft in altitude (Denny, 1982). The Taconic Mountains roughly coincide with the Taconic allochthon, a series of schists, phyllites, and metagraywackes that produce steep-sided mountains bordered by a relatively broad valley called the Berkshire Valley (fig. 1). The Berkshire Valley section, consisting of the Stockbridge Valley and several smaller valleys, is a group of roughly linear, flat-floored valleys underlain largely by carbonate rocks that were eroded by the Hoosic and Housatonic Rivers. The Western New England Upland is an area of rolling hills and low mountains ranging from about 1300 to 2500 ft in altitude, known as the Berkshire Mountains and Hoosac Mountains, and underlain primarily by Proterozoic gneisses and quartzite, and Paleozoic schist and quartzite.

The Western New England Upland is separated from the Eastern New England Upland by the Connecticut Valley Lowland, a broad, relatively flat-floored valley carved by the Connecticut River and by glacial erosion. The Connecticut Valley ranges from about 5 to 15 miles wide and the valley floor has a maximum altitude of about 300 ft in its northern part. Ridges of volcanic rock that border the west side of the valley locally rise to elevations of more than 500 ft. The Connecticut Valley is underlain by Triassic and Jurassic sedimentary and volcanic rocks. To the east of the Connecticut Valley Lowland lies the Eastern New England Upland, an area of low

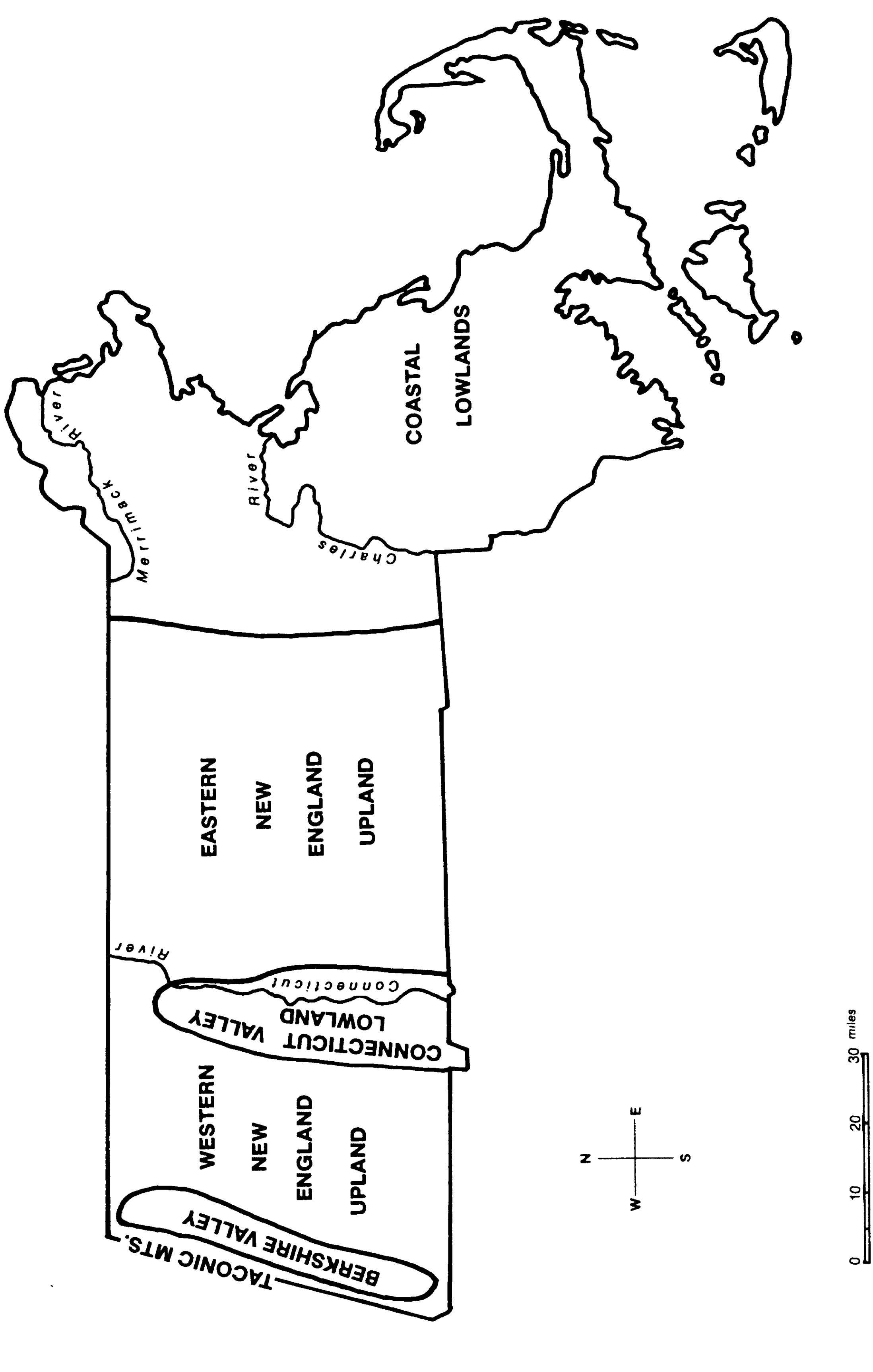


Figure 1. Physiographic areas of Massachusetts (from Facts on File, 1984).

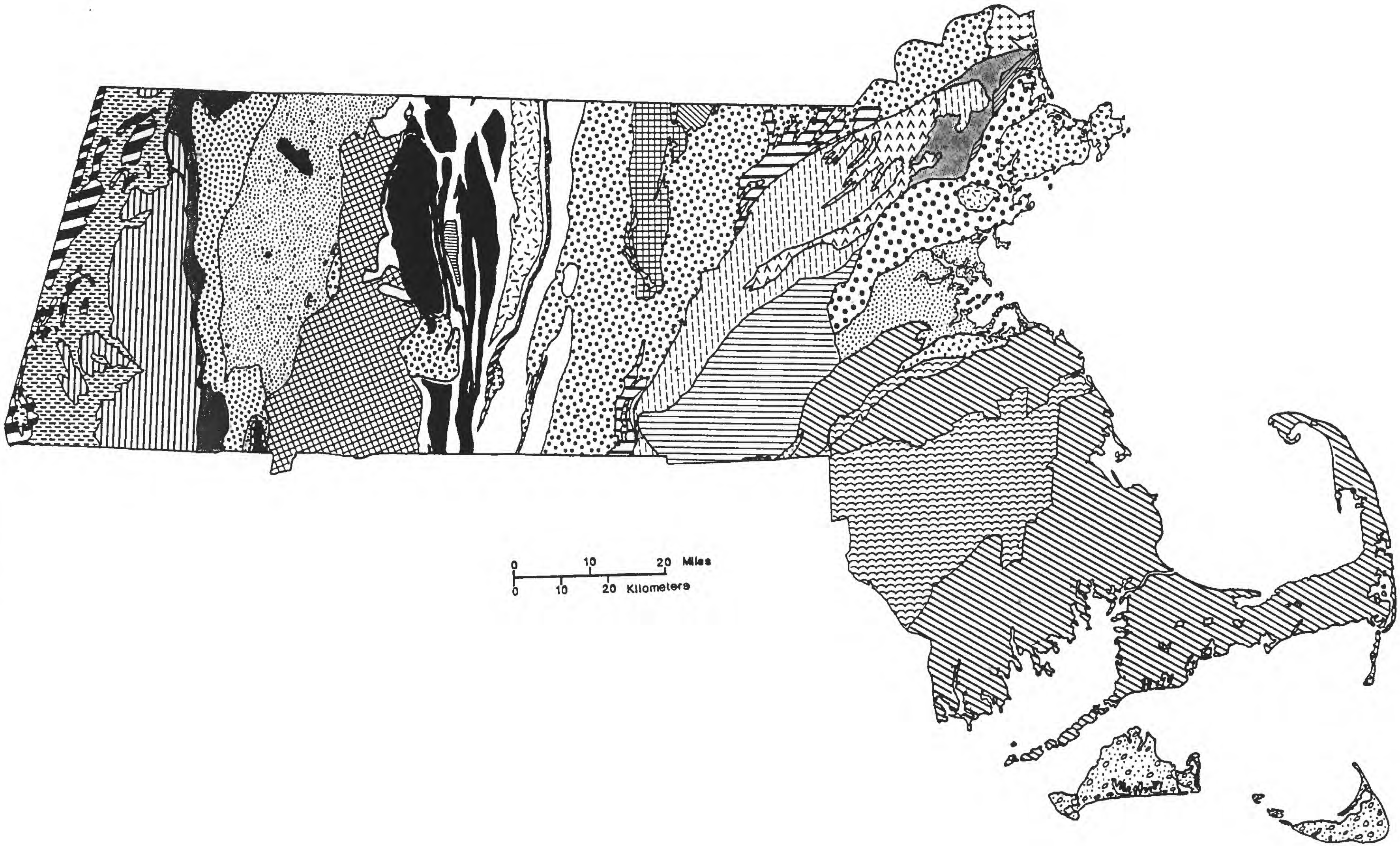


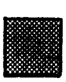
Figure 2. Generalized bedrock geologic map of Massachusetts (after Zen, 1983).

EXPLANATION FOR GENERALIZED BEDROCK GEOLOGIC MAP OF MASSACHUSETTS

TACONIC-BERKSHIRE ZONE (ORDOVICIAN AND OLDER ROCKS)

Walloomsac Formation (Middle Ordovician)—Graphitic quartz phyllite and schist containing minor lenses of limestone; quartzite and calcareous quartzite previously mapped as Bellowspipe Quartzite; graphitic and calcitic marble and schistose marble with interbedded black phyllite; crystalline limestone lenses near base of the Walloomsac locally yielding fragments of pelmatozoa, bryozoa and cup coral
Stockbridge Formation (Lower Ordovician to Lower Cambrian)—Limestone and calcite marble and beds of beige dolostone; local layers of quartzose limestone near base; layered calcite marble; quartzose calcite and dolomite marble, locally containing interbeds of phyllite and quartzite; quartzite; dolostone with quartz and tremolite in higher-grade areas.

Cheshire Quartzite (Lower Cambrian)—White, massive vitreous quartzite
Dalton Formation (Lower Cambrian and Proterozoic Z)—Muscovite-microcline quartzite and feldspathic quartzite with tourmaline, locally includes thin beds of: carbonaceous quartz schist; quartzite; feldspathic, biotite-muscovite gneiss and granofels; muscovite-quartz schist and interlayered feldspathic quartzite and quartz conglomerate with minor beds of rusty schist; quartz and gneiss cobble and pebble conglomerate, and muscovite quartz schist.
Hoosac Formation (Lower Cambrian and Proterozoic Z)—Muscovite-biotite schist or gneiss, with interlayered garnet-biotite schist near base, that interfingers with Dalton Formation; conglomerate
Canaan Mountain Formation (Lower Ordovician and Proterozoic Z)—Rusty-weathering, coarse garnet schist and feldspathic schist
Biotite-plagioclase-quartzite, and calc-silicate gneiss (Proterozoic Y)
Calc-silicate granofels and gneiss (Proterozoic Y)—Including calcitic or dolomitic marble, coarse hornblende-plagioclase-diopside and diopside rock, locally containing beds of schist
Lee Gneiss (Proterozoic Y)—Mafic gneiss and granofels
Well-layered hornblende-biotite gneiss (Proterozoic Y)
Pinkish-gray, fine-grained, well-laminated felsic biotite-microcline-plagioclase-quartz gneiss (Proterozoic Y)—Probably metamorphosed rhyolite
Black and white, well-layered hornblende-biotite-plagioclase gneiss and amphibolite (Proterozoic Y)—Contains irregular pods of diopside or cummingtonite-talc rock or amphibole calc-silicate, epidote-layered quartz-plagioclase gneiss near Hinsdale
Massive amphibolite of uncertain age (Proterozoic Y?)—Near South Sandisfield
Washington Gneiss (Proterozoic Y)—Rusty-weathering, muscovite-biotite-sillimanite and/or kyanite-garnet schist; conglomerate, interlayered metadacite; well-layered, rusty-tan weathering, quartz granofels containing layers of rusty, sulfidic, calc-silicate rocks; coarse- to medium-grained mafic gneiss and metabasalt; rusty-weathering diopside and sulfide-rich calcite marble and calc-silicate rock
Intrusive rocks:
White, magnetite-bearing alaskite and trondhjemite (Ordovician)—Associated with blastomylonite.
White to gray and black-spotted muscovite-biotite granite and granodiorite (Ordovician)—Intruded near or along thrust faults.
Serpentinized peridotite stocks (Ordovician to Proterozoic Z) and **Biotite-hornblende mafic dikes (Proterozoic Z)** Intrudes Washington Gneiss and Proterozoic Y granitiod gneiss
Tyringham Gneiss (Proterozoic Y)—Gray biotite granodioritic to quartz monzonitic gneiss, coarsely porphyritic, locally having fine-grained aplitic border.
Stamford Granite Gneiss (Proterozoic Y)—White to gray biotite granite gneiss containing blue quartz
Granitoid Gneiss (Proterozoic Y)—Biotite granodioritic and granitic gneiss with large schlieren of biotite, locally contains garnet and muscovite



Hoosac Formation (Lower Cambrian and Proterozoic Z)—Phyllite; interbeds of schist and minor quartzite; rusty gray schist and gneiss, locally conglomeratic; greenish-gray schist with garnets; rusty-weathering kyanite schist with distinctive quartz lenses and minor thin beds of calc-silicate rocks; green, tan, and gray schist; granofels; amphibolite
Sherman Marble (Proterozoic Y)—White, coarse-grained graphite dolomite-calcite marble at Sherman Reservoir at the Sate line
Intrusive rocks:
Diorite at Goff Ledges (Ordovician)—Coarse-grained to pegmatitic, hornblende-plagioclase diorite, minor hornblende pyroxenite
White to gray and black-spotted muscovite-biotite granite and granodiorite (Ordovician)—Intruded near or along thrust faults, intrudes Hoosac Fm. and Proterozoic gneisses

Tectonic breccia (Ordovician)—Zones of mixed inclusions of Stockbridge Formation, Walloomsac Formation, and phyllites of the Taconic allochthon, or complexly mixed phyllites of Walloomsac Formation and Taconic allochthon
Nassau Formation (Lower Cambrian and Proterozoic Z)—Siliceous phyllite, quartzite, metasiltstone, and subgraywacke (includes Bomoseen Graywacke Member and Zion Hill Quartzite Member); chloritoid-rich phyllite; albitic phyllite; chloritoid-chlorite phyllite (Mettawee Member); plagioclase-rich, blue quartz pebble metagraywacke and minor gneiss-cobble conglomerate (Rensselaer Graywacke Member); metabasalt and basaltic tuff
Greylock Schist (Lower Cambrian and Proterozoic Z)—Phyllite with minor beds of green quartzite, resembles Hoosac and Nassau Formations; phyllite and interbedded metagraywacke, dolostone, and conglomerate.
Everett Formation (Lower Cambrian and Proterozoic Z)—Phyllite, metagraywacke and quartzite; predominantly chloritoid-rich schist in Lenox Mountain

CONNECTICUT VALLEY BELT (SILURIAN AND DEVONIAN ROCKS)

Belchertown Complex (Devonian)—Quartz monzodiorite, quartz monzodiorite gneiss, hornblende peridotite, hornblendite, intrusive breccia, mafic and ultramafic fragments in quartz diorite; biotite tonalite of marginal stocks; inclusions of amphibolite, granofels and dacite porphyry.

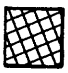
Prescott Complex: Cooleyville Granitic Gneiss (Devonian)—Biotite tonalite to granite in composition; contains inclusions of hornblende gabbro (formerly Prescott Diorite of Emerson, 1917) and intrusions of Littleton Formaion

Putney Volcanics (Devonian)—Greenish-gray plagioclase-quartz-muscovite phyllite and granofels.
Gile Mountain formation (Devonian)—Gray, slightly rusty phyllite and schist interbedded with quartzite, local calcareous granofels or quartzose marble, pods and stringers of vein quartz, amphibolite, and hornblende schist.
Waits River Formation (Devonian)—Interbedded gray, rusty-weathering, schist and calcareous granofels or quartzose marble, pods and stringers of vein quartz; amphibolite or hornblende schist with calcareous granofels.
Goshen Formation (Devonian)—Quartzite or quartz schist grading upward into gray, carbonaceous schist; local calcareous granofels; micaceous quartzite and schist. Calc-silicate granofels; carbonaceous schist and quartz schist.
Erving Formation (Devonian)—Biotite-plagioclase granofels, minor mica schist and calc-silicate granofels, layers of epidote amphibolite; mixed mica schist and amphibolite.
Littleton Formation (Devonian)—Black to gray aluminous mica schist, quartzose schist, and aluminous phyllite; locally intruded by hornblende-olivine gabbro of uncertain age.
Russell Mountain Formation (Silurian)—Quartzite, calc-silicate granofels, and calc-silicate marble.
Fitch Formation (Silurian)—Calc-silicate granofels, biotite granofels, sulfidic schist and marble.
Clough Quartzite (Silurian)—Quartz conglomerate, quartzite, mica schist and calc-silicate rocks.
Intrusive rocks:
Williamsburg Granodiorite (Devonian)—Biotite-muscovite granodiorite.
Feldspar-quartz-muscovite pegmatite (Devonian)—Partly associated with the Williamsburg Granodiorite

Hawley Formation (Middle Ordovician)—Interbedded amphibolite, greenstone, feldspathic schist and granofels. Sparse coticule (Emerson, 1971, p. 43); black, rusty-weathering schist and thin dark quartzite; interlayers of amphibolite; light-colored plagioclase gneiss; medium-gray mafic schist containing megacrysts of plagioclase and angular fragments of feldspar granofels, epidote-plagioclase granofels; dark-gray amphibolite; lioght-colored plagioclase granofels; garnetiferous mafic gneiss
Cobble Mountain Formation (Middle Ordovician)—Rusty-weathering feldspathic gneiss and mica schist; nonrusty-weathering silvery-gray schist and aluminous schist; serpentinite and/or talc rock; thin beds of gneiss, amphibolite, pelitic schist and granofels; feldspar gneiss, coticule and cummingtonite schist; calc-silicate rocks
Moretown Formation (Middle Ordovician or older)—Light-colored, pinstriped granofels and schist; nubble garnet schist and fine-grained amphibolite; rusty, carbonaceous quartz-muscovite schist; green to dark-green greenstone or amphibolite
Rowe Schist (Lower Ordovician and Cambrian)—Light-colored schist with quartz, kyanite and staurolite typical at higher grades; gray to black, slightly rusty, moderately carbonaceous schist; minor quartzite; well-layered and foliated amphibolite, includes its type Chester Amphibolite Member at Chester, Massachusetts
Intrusive rocks:
Middlefield Granite (Devonian)—Moderately foliated granite
Gneiss at Hallockville Pond (Ordovician)—Light-gray foliated quartz biotite gneiss
Serpentinite and/or talc rock (age uncertain)—Interpreted as tectonic slivers

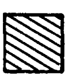
Collinsville Formation (Middle Ordovician or older)—Brown to rusty-brown schist containing coticule and locally massive amphibolite at base; amphibolite and plagioclase gneiss; felsic gneiss; local calc-silicate beds; quartzite; garnetiferous biotite gneiss; rusty-weathering, massive granofels; some rusty-stained gneiss
Monson Gneiss (Ordovician, Cambrian, or Proterozoic Z)—Layered to massive biotite-plagioclase gneiss, amphibolite, microcline augen gneiss; lenses of peridotite, variously altered
Fourmile Gneiss (Ordovician, Cambrian, or Proterozoic Z)—Layered to massive biotite-feldspar gneiss and amphibolite; ultramafic hornblendite; muscovite quartzite
Poplar Mountain Gneiss (Proterozoic Z) (Probably correlates with Mount Mineral Formation but is more feldspathic)—Dark biotite gneiss containing white microcline megacrysts and beds of quartzite; basal quartzite, commonly feldspathic
Mount Mineral Formation (Proterozoic Z) (Probably correlates with Poplar Mountain Gneiss but is more aluminous)—Aluminous schist, amphibolite, and quartzite, undifferentiated; locally rich in garnet and kyanite, and with relict sillimanite and orthoclase
Dry Hill Gneiss (Proterozoic Z)—Pink microcline-hornblende gneiss, biotite-tourmaline schist, minor quartzite; white to buff quartzite and feldspathic quartzite, commonly with biotite and/or actinolite (Pelham Quartzite Member)
Intrusive rocks:
Glastonbury Gneiss (Ordovician)—Massive granitic gneiss in core of Glastonbury dome and in adjacent areas
Pauchaug Gneiss (Ordovician)—Massive granitic gneiss in core of Warwick dome

MESOZOIC BASINS (JURASSIC AND TRIASSIC ROCKS)



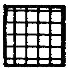
Portland Formation (Lower Jurassic)—Red arkose and siltstone, gray sandstone and siltstone, black shale, red conglomerate and arkose.
Granby Basaltic Tuff (Lower Jurassic)—Dark tuff, with sediment fragments.
Hampden Basalt (Lower Jurassic)—Thin quartz tholeiite, locally associated with Granby Basaltic Tuff.
East Berlin Formation (Lower Jurassic)—Red arkosic sandstone and siltstone, gray sandstoneand mudstone, black shale, red conglomerate and arkosic sandstone.
Holyoke Basalt (Lower Jurassic)—Thick quartz tholeiite containing local gabbroic segregations.
Shuttle Meadow Formation (Lower Jurassic)—Red arkosic sandstone and siltstone, gray sandstoneand mudstone, black shale, red conglomerate and arkosic sandstone.
Hitchcock Volcanics (Lower Jurassic)—Basaltic breccia containing abundant fragments of New Haven Arkose, locally intrusive into arkose near base.
New Haven Arkose (Lower Jurassic and Upper Triassic)—Red, pink, and gray coarse-grained, locally conglomeratic arkose interbedded with brick-red shaley siltstone and fine-grained arkosic sandstone; continuous with and lithically similar to the Sugarloaf Formation near Northampton.
Intrusive and Cataclastic Rocks—Silicified fault-breccia or strongly silicified metamorphic rocks. Mylonite along Connecticut Valley border fault. Diabase dikes and sills.
Mount Toby Formation (Lower Jurassic)—Red arkosic sandstone, gray sandstone and siltstone, black shale, red conglomerate and arkosic sandstone, coarsens eastward; breccia of granitic gneiss at Taylor Hill and breccia of amphibolite at Whitmore Ferry.
Turner Falls Sandstone (Lower Jurassic)—Red arkosic sandstone, gray sandstone and siltstone, black shale, red conglomerate and arkosic sandstone.
Deerfield Basalt (Lower Jurassic)—Quartz tholeiite.
Sugarloaf Formation (Lower Jurassic and Upper Triassic)—Red arkose, gray sandstone and siltstone, black shale, red conglomerate and arkosic sandstone, coarsens eastward; continuous with and lithically similar to the New Haven Arkose near Northampton.
Fine-grained hornblende diorite (age uncertain)—In Connecticut River bed, near French King Rock

MERRIMACK BELT (SILURIAN, DEVONIAN, AND PENNSYLVANIAN ROCKS)



Massive to weakly foliated, pink and gray, fine- to medium-grained biotite granite (Pennsylvanian)—commonly contains pink magnetite-bearing pegmatite
Massabesic Gneiss Complex—Biotite-feldspar paragneiss of Proterozoic Z age intruded by potassium-feldspar-rich gneiss of Ordovician age.

Biotite-muscovite granite (Devonian)
Hardwick Tonalite (Devonian)—Gray biotite tonalite to granodiorite gneiss; intruded by porphyritic microcline-biotite granite gneiss in sills

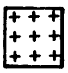


Fitchburg Complex (Devonian)—Gray to white muscovite-biotite granite; commonly contains white pegmatite; may include granite of late Paleozoic age; gray biotite-muscovite granite to granodiorite gneiss; common inclusions of Littleton Formation; gray, biotite granodiorite to tonalite gneiss; contains zones of foliated biotite-muscovite granite gneiss and inclusions of mica schist and feldspathic granulite, inclusions of massive coarse-grained biotite-hornblende tonalite

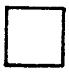
Biotite-hornblende diorite, quartz-bearing diorite, metadiorite and norite (Devonian)

Coys Hill Porphyritic Granite Gneiss (Devonian)—Microcline granite gneiss, commonly containing garnet, sillimanite, and muscovite; contains hornblende gneiss inclusions.

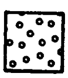
Chelmsford Granite (Devonian)—Gray muscovite-biotite granite.
Diorite and tonalite (Devonian and Silurian)—Includes Dracut Diorite, tonalite near the Ayer Granite, and equivalents of the Exeter Diorite of New Hampshire
Ayer Granite (Lower Silurian and Upper Ordovician?)—Biotite granite to tonalite, locally gneissic, locally with muscovite, may include rocks older than Silurian.



Newburyport complex (Silurian and Ordovician)—Gray granite, tonalite, and granodiorite



Erving Formation (Lower Devonian)—Biotite-plagioclase granofels, minor mica schist and calc-silicate granofels, layers of epidote amphibolite; mica schist and amphibolite
Littleton Formation (Lower Devonian)—Black to gray aluminous mica schist, quartzose schist, aluminous phyllite; biotite gneiss, quartz-feldspar-garnet gneiss, and calcitic marble
Fitch Formation (Upper Silurian)—Sulfidic calc-silicate and minor sulfidic schist
Partridge Formation (Middle Ordovician) (includes Brimfield Schist of Emerson, 1917)—Sulfidic mica schist, amphibolite, calc-silicate rock; mafic and felsic gneisses and biotite gneiss of volcanic derivation; minor amphibolite and sulfidic schist; sillimanite-feldspar augen gneiss; lenses of ultramafic rock; layered felsic gneiss and schist
Ammonoosuc Volcanics (Middle Ordovician)—Amphibolite, felsic gneiss, garnet-amphibole quartzite, and marble; ultramafic rock; basal quartzite and conglomerate
Intrusive rocks:
Granodiorite (Devonian)
Biotite-muscovite granite (Devonian)
Includes intrusive rocks of uncertain age: Biotite granitic gneiss, Granodiorite, Quartz diorite, Granite, Hornblende-plagioclase gneiss, Biotite granitic gneiss—Mainly small lenses, **Hornblende-olivine gabbro**—Intrudes the Littleton Formation, **Biotite-garnet-feldspar gneiss of Ragged Hill**



Coal Mine Brook Formation (Middle Pennsylvanian)—Fossiliferous, carbonaceous slate and garnet phyllite with a lens of meta-anthracite; conglomerate and arkose
Harvard Conglomerate (Pennsylvanian)—Conglomerate and chloritoid-hematite phyllite
Worcester Formation (Lower Devonian and Silurian)—Carbonaceous slate and phyllite with minor metagraywacke
Paxton Formation (Silurian)—Biotite and calc-silicate granofels, sulfidic schist, amphibolite, cordierite schist, and sillimanite quartzite; rusty-weathering sulfidic quartzite and schist, calc-silicate granofels; **Bigelow Brook Member**—Biotite granofels, sulfidic schist, and calc-silicate granofels; **Southbridge Member**—Biotite and calc-silicate granofels
Oakdale Formation (Silurian)—Metamorphosed, pelitic to calcareous siltstone and muscovite schist.
Berwick Formation (Silurian)—Metamorphosed calcareous sandstone, siltstone, and mica schist.
Eliot Formation (Silurian)—Phyllite and calcareous phyllite
Tower Hill Quartzite (Silurian)—Quartzite and phyllite
Vaughn Hills Quartzite (Silurian or Ordovician)—Quartzite, phyllite, conglomerate, and chlorite schist
Reubens Hill Formation (Silurian or Ordovician)—Amphibolite, hornblende-chlorite schist, and feldspathic schist. Includes metamorphosed diorite
Boylston Schist (Silurian or Ordovician)—Carbonaceous phyllite and schist, locally sulfidic; quartzite; calc-silicate beds
Intrusive rocks:
Muscovite-biotite granite (Devonian)—At Millstone Hill

ESMOND-DEDHAM ZONE (TERTIARY AND OLDER ROCKS)

Cretaceous and Tertiary sediments—Clay, silt, sand, and gravel, mostly of non-marine and nearshore marine origin; contains Tertiary fossils

Red arkosic conglomerate, sandstone, and siltstone (Upper Triassic)—In Essex County
Lynn Volcanic Complex (Lower Devonian, Silurian, or Proterozoic Z)—Rhyolite, agglomerate, and tuff
Green Lodge Formation of Rhodes and Graves (1931) (Upper Cambrian?)—Quartzite and slate
Westboro Formation (Proterozoic Z)—Quartzite, schist, calc-silicate quartzite, and amphibolite. Consists of quartzite and argillite in Saugus and Lyunnfield areas
Metamorphosed mafic to felsic flow, and volcaniclastic and hypabyssal intrusive rocks (Proterozoic Z)—Includes some diorite and gabbro north and northwest of Boston
Intrusive rocks:
Nahant Gabbro and gabbro at Salem Neck (Ordovician)—Labradorite-pyroxene gabbro, hornblende gabbro and hornblende diorite
Topsfield Granodiorite (Proterozoic Z)—Grayish, porphyritic granodiorite containing blue quartz; usually cataclastically foliated and altered
Diorite at Rowley (Proterozoic Z)—Dark green-gray, medium-grained hornblende diorite
Diorite and gabbro (Proterozoic Z)—Complex of diorite and gabbro, subordinate metavolcanic rocks and intrusive granite and granodiorite
Serpentinite (age uncertain)

Dighton Conglomerate (Upper Pennsylvanian)—Coarse conglomerate having sandy matrix; minor sandstone
Rhode Island Formation (Upper and Middle Pennsylvanian)—Sandstone, graywacke, shale, and conglomerate; minor beds of meta-anthracite. Fossil plants
Wamsutta Formation (Middle and Lower Pennsylvanian)—Red to pink, well-sorted conglomerate, graywacke, sandstone, and shale; fossil plants; rhyolite and mafic volcanic rocks
Pondville Conglomerate (Lower Pennsylvanian)—Quartz conglomerate having abundant sandy matrix; boulder conglomerate, arkose; fossil plants
Hoppin Formation (Middle and Lower Cambrian)—Quartzite, argillite, and minor limestone

Peabody Granite (Middle Devonian)—Alkalic granite containing ferro-hornblende

Newbury Volcanic Complex (Lower Devonian and Upper Silurian)—Micrographic rhyolite; undivided sedimentary and volcanic rocks; calcareous mudstone, red mudstone, and siliceous siltstone; porphyritic andesite, includes tuffaceous mudstone beds; basalt, andesite, rhyolite, and tuff

Orange-pink, rusty-weathering, medium- to coarse-grained biotite granite to granodiorite (Silurian)—Locally porphyritic
Sharpners Pond Diorite (Silurian)—Non-foliated, medium-grained equigranular biotite-hornblende tonalite and diorite

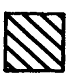
Braintree Argillite and Weymouth Formation (Middle and Lower Cambrian)—Argillite, some with rare limestone
Intrusive rocks:
Wenham Monzonite (Middle Devonian)—Monzonite containing ferro-hornblende
Cherry Hill Granite (Devonian)—Alaskitic granite containing ferro-hornblende
Blue Hill Granite Porphyry (Lower Silurian and Upper Ordovician)—Microperthite-quartz porphyry
Cape Ann Complex (Lower Silurian or Upper Ordovician)—Alkalic granite to quartz syenite containing ferro-hornblende; **Squam Granite**—Fine- to medium-grained monzodiorite; **Beverly Syenite**—Quartz-poor facies
Quincy Granite (Lower Silurian or Upper Ordovician)—Alkalic granite

Bellingham Conglomerate (Pennsylvanian, Cambrian or Proterozoic Z)—Red and gray metamorphosed conglomerate, sandstone, graywacke, and shale
Cambridge Argillite (Proterozoic Z to earliest Paleozoic)—Gray argillite and minor quartzite; rare sandstone and conglomerate
Roxbury Conglomerate (Proterozoic Z to earliest Paleozoic)—Conglomerate, sandstone, siltstone, argillite, and melaphyre. Consists of Brookline, Dorchester, and Squantum Members
Mattapan Volcanic Complex (Proterozoic Z or younger)—Rhyolite, melaphyre, agglomerate, and tuff

Andover Granite (Silurian or Ordovician)—Gray, foliated, muscovite-biotite granite; pegmatite masses common. Includes Acton Granite (Silurian or Ordovician)

Tadmuck Brook Schist (Silurian?, Ordovician, or Proterozoic Z)—Andalusite phyllite and sillimanite schist, partly sulfidic; local quartzite in upper part
Tatnic Hill Formation (Ordovician or Proterozoic Z)—Sulfidic sillimanite schist, sillimanite schist and gneiss, biotite gneiss; minor amphibolite, calc-silicate gneiss and marble; gray mica schist (Yantic Member); calc-silicate gneiss and marble (Fly Pond Member)
Nashoba Formation (Ordovician or Proterozoic Z)—Sillimanite schist and gneiss, partly sulfidic, amphibolite, biotite gneiss, calc-silicate gneiss
Fish Brook Gneiss (Ordovician or Proterozoic Z)—Light-gray, biotite-plagioclase quartz gneiss
Shawsheen Gneiss (Ordovician or Proterozoic Z)—Sillimanite gneiss, sulfidic at base; minor amphibolite
Quinebaug Formation (Ordovician, Cambrian, or Proterozoic Z)—Amphibolite, biotite and hornblende gneiss, felsic gneiss, and calc-silicate gneiss
Marlboro Formation (Ordovician, Cambrian, or Proterozoic Z)—Thinly layered amphibolite, biotite schist and gneiss, minor calc-silicate granofels and felsic granofels; homogeneous light-gray feldspathic gneiss
Intrusive rocks:
Straw Hollow Diorite and Assabet Quartz Diorite, undifferentiated (Silurian)—Gray, medium-grained, slightly-foliated biotite-hornblende diorite and quartz diorite
Granodiorite of the Indian Head pluton (age uncertain)—Biotite granodiorite & hornblende-biotite tonalite
Light-gray muscovite granite (age uncertain)

Plainfield Formation (Proterozoic Z)—Quartzite, pelitic schist, minor calc-silicate rock and amphibolite
Blackstone Group (Proterozoic Z)—Quartzite, schist, phyllite, marble, and metavolcanic rocks
Metamorphosed felsic metavolcanic rocks (Proterozoic Z)
Intrusive rocks:
Milford Granite (Proterozoic Z)—Light-colored biotite granite, locally gneissic; granodiorite, with clots of mafic minerals, locally gneissic (mafic phase)
Biotite granite (Proterozoic Z)—Light-colored biotite granite, locally foliated. Mafic minerals less prominent than in Milford Granite but granular quartz common. Includes mafic-poor granite similar to the Hope Valley Alaskite Gneiss
Hope Valley Alaskite Gneiss (Proterozoic Z)—Mafic-poor gneissic granite, locally muscovitic. Gradational with Scituate Granite Gneiss
Scituate Granite Gneiss (Proterozoic Z)—Gneissic granite with biotite in small clots. Equivalent to part of former Northbridge Granite Gneiss (usage now abandoned). Gradational with Hope Valley Alaskite Gneiss
Ponaganset Gneiss (Proterozoic Z)—Gneissic biotite granite containing microcline and biotite. Equivalent to part of former Northbridge Granite Gneiss (usage now abandoned)
Gabbro (Proterozoic Z)—Hornblende gabbro and hornblende-pyroxene gabbro metamorphosed in part to hornblende gneiss and amphibolite



Felsic and mafic volcanic rocks (Proterozoic Z)—Southwest of Boston Basin
Gneiss and schist near New Bedford (Proterozoic Z)—Hornblende and biotite schist and gneiss, amphibolite
Biotite gneiss near New Bedford (Proterozoic Z)—Layered feldspathic gneiss
Intrusive rocks:
Granite of Rattlesnake Hill pluton (Devonian)—Coarse-grained biotite granite and fine-grained riebeckite granite
Alkalic granite in Franklin (Devonian to Ordovician)
Alaskite (Proterozoic Z)—Light-gray, pinkish-gray to tan, mafic-poor, muscovite gneissic granite
Dedham Granite (Proterozoic Z)—Light grayish, equigranular to slightly porphyritic, variably altered, granite south and west of Boston. Includes dioritic rock near Scituate and Cohasset and Barefoot Hills Quartz Monzonite of Lyons (1969) and Lyons and Wolfe (1971). Gray granite to granodiorite, more mafic than the main body of Dedham Granite, crops out north of Boston
Westwood Granite (Proterozoic Z)—Light-grayish, fine- to medium-grained granite
Fine-grained granite and granite porphyry (age uncertain)
Granite of the Fall River pluton (Proterozoic Z)—Light-gray, medium-grained, biotite granite, in part mafic-poor. Gneissic in New Bedford area. Includes **Bulgarmarsh Granite (Proterozoic Z)**
Porphyritic granite (Proterozoic Z)—Gray, seriate to porphyritic biotite granite containing biotite, epidote, and sphene. Mafic inclusions common. Gneissic in New Bedford area
Granite, gneiss, and schist, undivided (Proterozoic Z)—Plutonic and metamorphic rocks of probable Proterozoic Z age. May include plutonic and volcanic rocks of Paleozoic or younger age
Diorite (Proterozoic Z)—Medium-grained hornblende diorite, metamorphosed in part
Sharon Syenite (Proterozoic Z)—Gray to dark-gray syenite, mixed with ferro-gabbro

mountains and hills underlain primarily by Paleozoic gneiss, schist, and phyllites of sedimentary origin that are intruded by Paleozoic plutonic (granitic) rocks. Relief on the plutonic rocks is generally less than 1000 ft (Denny, 1982).

The Coastal Lowlands occupy approximately the eastern one-third of Massachusetts (fig. 1) and consist of flat to gently rolling lowlands ranging from sea level to about 400 ft. The border between the Coastal Lowlands and the Eastern New England Upland is distinct and abrupt. In the northern part of the State it is defined by an east-facing scarp as much as 300 ft high running from Worcester to the New Hampshire border along the west side of the Nashua River valley (Denny, 1982). The Coastal Lowland is underlain primarily by Proterozoic through Tertiary-age sedimentary rocks intruded by Proterozoic and Paleozoic granites and granite gneisses.

In 1990 the population of Massachusetts was 6,016,425, including 84 percent urban population (fig. 3). Average population density is approximately 700 per square mile. The climate of Massachusetts is temperate, although it is colder and drier in the western region. Average annual precipitation ranges from 40 to 48 in (fig. 4).

BEDROCK GEOLOGY

Massachusetts has been divided into major geologic belts and zones (fig. 5) that will be described from west to east across the State. For simplicity the groupings shown in figure 5 are modified from those presented in Zen (1983). The geologic descriptions that follow are derived from several sources including Zen (1983), Rankin and others (1989), and Page (1976). A generalized bedrock geologic map is given for reference in figure 2. It is suggested, however, that the reader refer to the published State Geologic Map of Massachusetts (Zen, 1983), large-scale, local geologic maps and reports, and other references for more detail.

The *Taconic-Berkshire Zone* (figs. 2, 5) consists of sedimentary, metasedimentary, and metavolcanic rocks of the Taconic Mountains, Stockbridge Valley, and Berkshire Mountains, that are locally intruded by granitic rocks. The Taconics in Massachusetts consist of all or parts of the Everett, Berlin Mountain, and Greylock thrust slices (fig. 5). The southern part of the Everett slice is underlain almost entirely by the Everett Formation, consisting of phyllite, metagraywacke, and quartzite. The northern part of the Everett slice is underlain by the Everett and Nassau Formations. The Nassau formation consists of phyllite, quartzite, metasiltstone, subgraywacke, and local conglomerate and volcanic rocks. The Berlin Mountain slice, which lies to the north of the Everett slice, is underlain almost entirely by Nassau Formation. The Greylock slice, to the east of the main body of the Taconics, is underlain primarily by the Greylock Schist, which consists of phyllite with interbedded quartzite, metagraywacke, dolostone, and conglomerate. To the east of the Taconic Mountains lies the Vermont-Stockbridge Valley Autochthon, which is underlain by the Stockbridge Formation, comprising limestone, dolostone, quartzite, and marble, locally containing interbeds of phyllite and quartzite; and the Walloomsac Formation, consisting of graphitic phyllite and schist, quartzite, calcareous quartzite, calcareous marble, and limestone. The Berkshire massif and the southern tip of the Green Mountain anticlinorium underlie most of the Berkshire Mountains. The Berkshire massif consists of a complex thrust-faulted group of thrust slices made up of Middle Proterozoic metamorphic rocks of sedimentary and volcanic origin (Rankin and others, 1989), including biotite gneiss, quartzite, amphibolite, biotite-quartz-feldspar gneiss, mafic gneiss, granofels, schistose gneiss, granulite, and bedded magnetite rock. Rocks of the Berkshire massif are intruded by biotite granite, granodiorite, and granitic gneiss, including the Stamford Granite Gneiss and the Tyringham Gneiss; and locally by peridotite stocks, mafic dikes, magnetite-

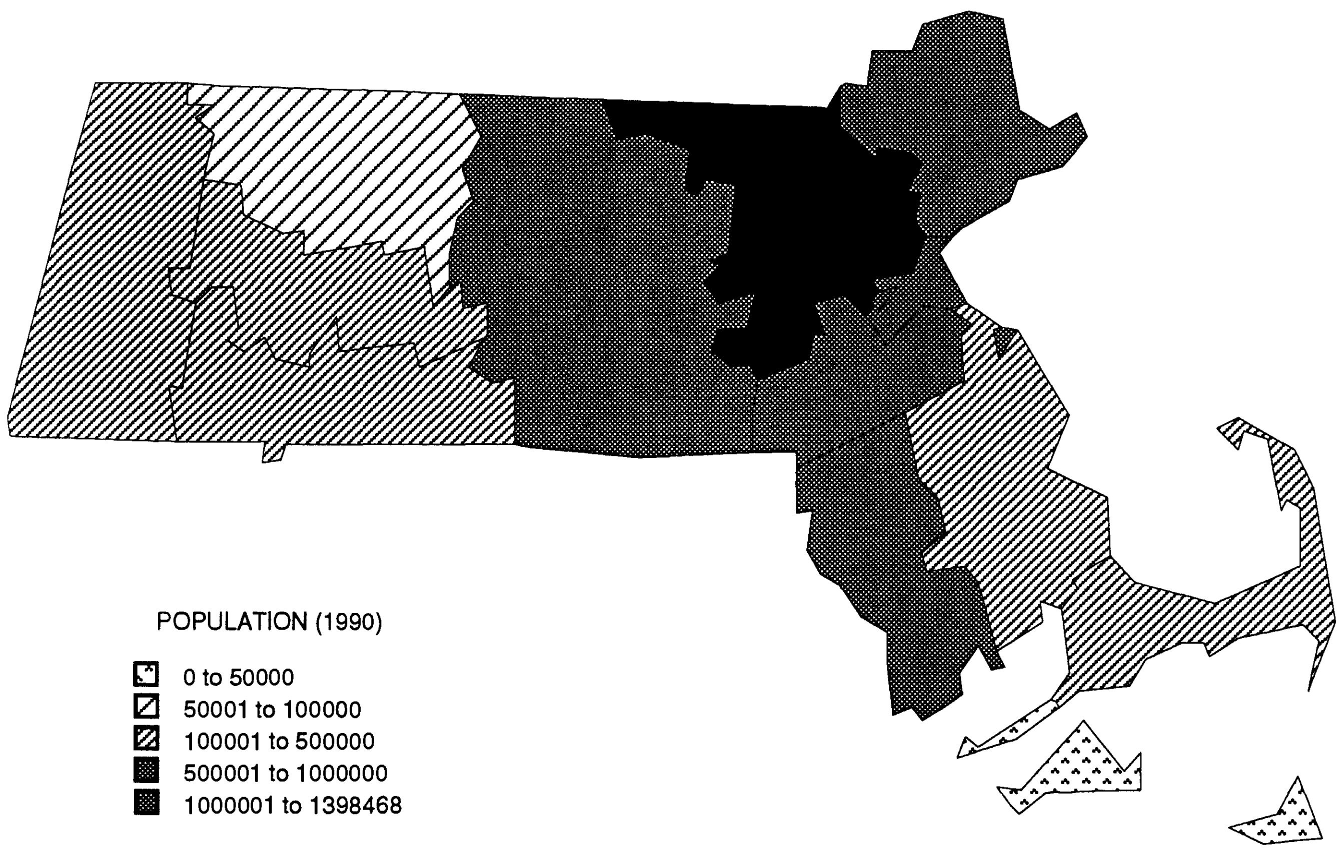


Figure 3. Population of counties in Massachusetts (1990 U.S. Census data).

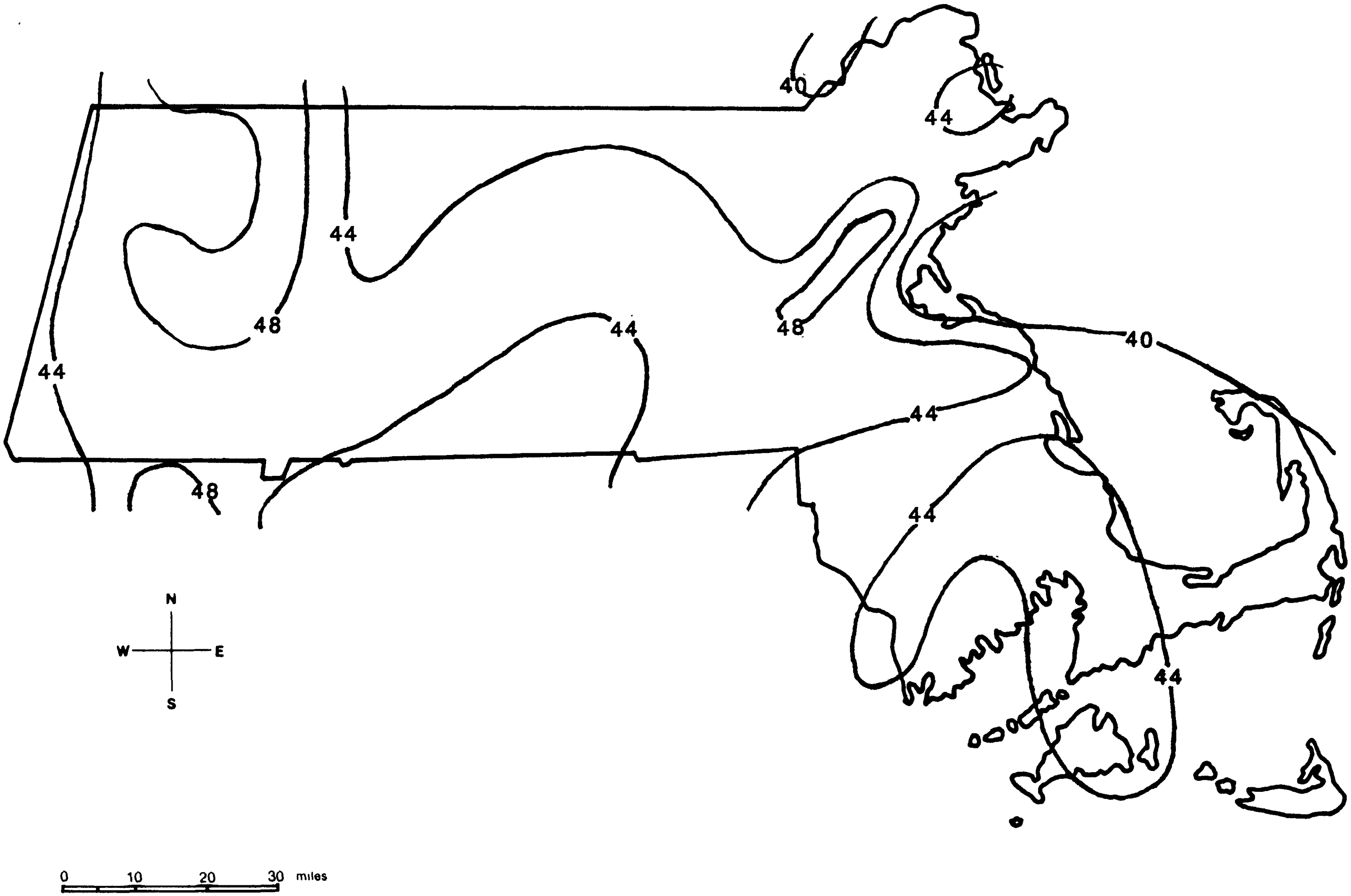
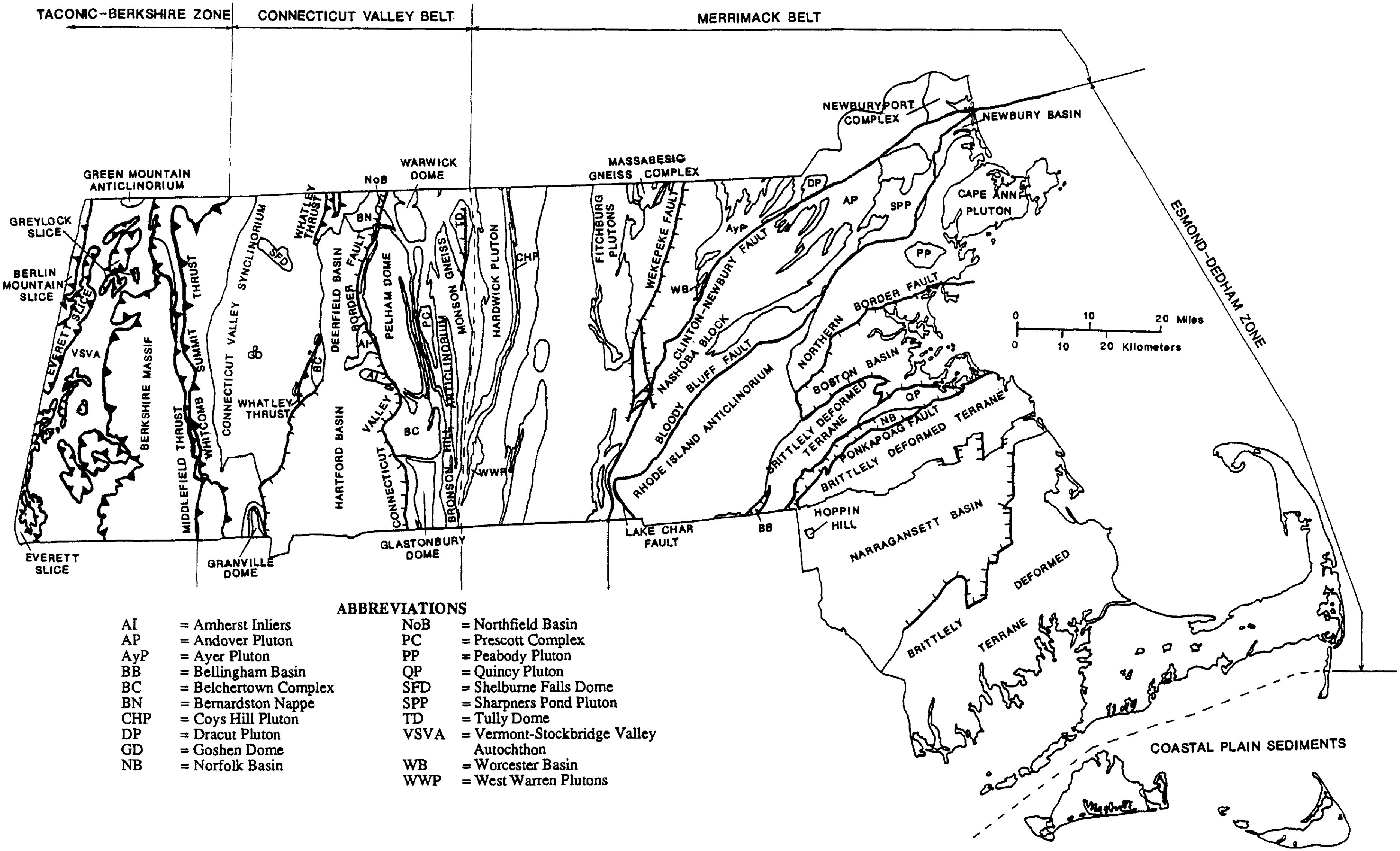


Figure 4. Average annual precipitation in Massachusetts (data from National Oceanic and Atmospheric Administration, 1974).



ABBREVIATIONS

AI	= Amherst Inliers	NoB	= Northfield Basin
AP	= Andover Pluton	PC	= Prescott Complex
AyP	= Ayer Pluton	PP	= Peabody Pluton
BB	= Bellingham Basin	QP	= Quincy Pluton
BC	= Belchertown Complex	SFD	= Shelburne Falls Dome
BN	= Bernardston Nappe	SPP	= Sharpners Pond Pluton
CHP	= Coys Hill Pluton	TD	= Tully Dome
DP	= Dracut Pluton	VSVA	= Vermont-Stockbridge Valley Autochthon
GD	= Goshen Dome	WB	= Worcester Basin
NB	= Norfolk Basin	WWP	= West Warren Plutons

Figure 5. Map showing tectonic/geologic terranes of Massachusetts (after Zen, 1983).

bearing alaskite, and trondhjemite (Zen, 1983). Included in the Taconic-Berkshire Zone for this discussion are rocks of the Middlefield thrust comprising the Sherman Marble, a coarse-grained graphite-dolomite-calcite marble exposed at Sherman Reservoir at the Vermont border, and the Hoosac Formation, consisting of phyllite, schist, gneiss, quartzite, calc-silicate rocks, granofels, and amphibolite. These rocks are locally intruded by granite, granodiorite, and diorite.

The Connecticut Valley Belt consists of metasedimentary rocks of the Connecticut Valley Synclinorium and Bronson Hill Anticlinorium (fig. 5), which are separated by sedimentary rocks of the Mesozoic basins (discussed separately) and intruded by various granitic plutons. To the west of the Connecticut Valley Synclinorium are rocks of the Whitcomb Summit thrust, included in this belt for the purposes of this discussion and comprising the Rowe Schist; the Moretown Formation, consisting of light-colored granofels and schist, and dark-colored amphibolite and greenstone; the Cobble Mountain Formation, comprising feldspathic gneiss, mica schist, aluminous schist, pelitic schist, serpentinite, and calc-silicate rock; and the Hawley Formation, consisting of interbedded amphibolite, greenstone, feldspathic schist, granofels, and mafic gneiss and schist. These rocks are intruded locally by the Middlefield Granite, a biotite gneiss at Hallockville Pond, and by serpentinite and/or talc rock. Rocks of the Connecticut Valley Synclinorium include the Clough Quartzite; Fitch Formation, consisting of granofels, schist, and marble; the Russell Mountain Formation, comprising quartzite, granofels, and marble; the Littleton Formation, consisting of schist and phyllite, which underlies the northern part of this map unit; Erving Formation, including granofels, mica schist, and amphibolite; Goshen Formation, consisting of quartzite and quartz schist grading upward into carbonaceous schist; the Waits River Formation, consisting of interbedded schist, calcareous granofels, and marble, and amphibolite and hornblende schist; Gile Mountain Formation, comprising phyllite and schist interbedded with calcareous granofels and marble; the Putney Volcanics, consisting of plagioclase-quartz-muscovite phyllite and granofels. The Williamsburg Granodiorite underlies the eastern edge of the synclinorium near Northampton. The Shelburne Falls, Goshen, and Granville Domes are underlain by the Collinsville Formation, consisting primarily of schist, mafic and felsic gneiss, granofels, and amphibolite.

The eastern part of the Connecticut Valley Belt consists of several domes underlain by mafic gneisses (black unit on fig. 2), surrounded by younger schists and amphibolites (white unit on fig. 2) and intruded by several granitic complexes. The Pelham dome comprises the Dry Hill Gneiss, consisting of microcline-hornblende gneiss, schist, and quartzite; Mount Mineral Formation, which consists of schist, amphibolite, and quartzite; and the Poplar Mountain Gneiss, consisting of biotite gneiss and quartzite. The Monson Gneiss, comprising biotite-plagioclase gneiss, amphibolite, and microcline augen gneiss, underlies the main part of the Bronson Hill Anticlinorium and the Tully dome (fig. 5). The Glastonbury Gneiss is a granitic gneiss that forms the core of the Glastonbury dome. The Pauchaug Gneiss is a granitic gneiss forming the core of the Warwick dome. The Fourmile Gneiss, consisting of biotite-feldspar gneiss and amphibolite, surrounds the east and south sides of the Pelham dome and the northwestern flank of the Glastonbury dome. Other granitic complexes include the Belchertown Complex, which lies mainly to the east of the Hartford basin, but underlies a small area to the west of the basin; and the Prescott Complex. The Belchertown Complex consists of quartz monzodiorite and monzodiorite gneiss, hornblende peridotite and hornblendite, and inclusions of mafic and ultramafic rocks, dacite, and tonalite. The Prescott Complex consists of biotite to tonalite granite with intrusions of hornblende gabbro and schist and phyllite of the Littleton Formation.

The Mesozoic Basins consist of late Triassic-early Jurassic continental sedimentary and igneous rocks of the Newark Supergroup occurring in three half-graben basins extending north-south in the west-central part of the State. Each basin has eastward dipping rocks which are folded into a broad syncline along the faulted eastern margin. The Hartford basin is the largest of the three, extending northward from Connecticut. The basal Triassic New Haven Arkose consists of fluvial arkosic sandstone and conglomerate forming a wide band on the western side of the basin. The New Haven Arkose is overlain by a narrow belt of Jurassic volcanic and sedimentary rocks that include the Shuttle Meadow Formation, Holyoke Basalt, East Berlin Formation, and the Hampden Basalt. The Shuttle Meadow and East Berlin Formations comprise a mixture of sandstone and conglomerate, and red and black lacustrine shales. The Holyoke and Hampden Basalts (and the Hampden Basalt equivalent called the Granby Basaltic Tuff) are tholeiitic basalt flows. The eastern part of the Hartford basin is a wide belt of sedimentary rocks of the Jurassic Portland Formation. The lower part of the Portland consists of lacustrine black shales and red siltstones and the upper part consists of fluvial sandstones and conglomerates. Along the eastern margin of the basin all of the formations intertongue with conglomerates made up of clasts of the older rocks immediately outside of the basin. The Deerfield basin is a much smaller half graben north of the Hartford basin that is connected to it by a narrow band of New Haven Arkose. The basal Triassic Sugarloaf Arkose, which is similar to the New Haven Arkose, forms a broad band on the eastern side of the basin. The uppermost part of this formation contains a thin belt of Jurassic lacustrine black shales and red siltstones. The Sugarloaf Arkose is overlain by the thin Jurassic Deerfield Basalt, which is overlain by the Jurassic Turners Falls Formation, then the Mount Toby Formation, each forming moderately thick bands within the syncline. Both of these units contain a mixture of sandstone and conglomerate and red and black lacustrine shales, but the Mount Toby is more conglomeratic. As in the Hartford basin, all formations intertongue with alluvial fan conglomerates along the eastern border fault. The Northfield basin is a small half graben north of the Deerfield basin and connected to it by a narrow belt of Sugarloaf Formation. It is filled entirely with Sugarloaf conglomeratic sandstone. Jurassic diabase dikes and sills intrude the sedimentary rocks of all of the basins.

The Merrimack Belt consists of metavolcanic and metasedimentary rocks intruded by a number of granitic plutons. Metavolcanic rocks dominate the western part of the Merrimack belt and include the Ammonoosuc Volcanics, consisting of amphibolite, quartzite, ultramafic rocks, felsic gneiss, and marble, with quartzite and conglomerate at the base; the Partridge Formation, comprising mica schist, amphibolite, calc-silicate rock, and mafic and felsic gneisses of volcanic origin; the Fitch Formation, consisting of sulfidic calc-silicate and sulfidic schist; and the Littleton Formation, consisting of aluminous mica schist and phyllite, and quartzose schist, gneiss, and marble; and the Erving Formation, which consists primarily of biotite-plagioclase granofels. These rocks are locally intruded by lenses and dikes of granite, granodiorite, and granitic gneiss. The eastern part of the Merrimack belt is primarily underlain by metasedimentary rocks, including the Boylston Schist; Reubens Hill Formation, including amphibolite and schist; the Vaughn Hills Quartzite; Tower Hill Quartzite; phyllite of the Eliot Formation; Berwick Formation, consisting of metamorphosed sandstone and siltstone, and mica schist; the Oakdale Formation, consisting of metasiltstone and muscovite schist; the Paxton Formation, comprising granofels, schist, amphibolite, and quartzite; and slate and phyllite of the Worcester Formation. The Harvard Conglomerate and the Coal Mine Brook Formation, consisting of slate, phyllite, thin meta-anthricite, conglomerate and arkose, underlie the Worcester basin (fig. 5), located at the eastern edge of the Merrimack belt, to the east and northeast of Worcester.

A number of granitic intrusions occur in the Merrimack belt; they will be discussed in order roughly from west to east (refer to fig. 5). The Hardwick Pluton consists of the Hardwick Tonalite, a biotite tonalite to granodiorite gneiss, and biotite-muscovite granite. The Coys Hill Pluton, which forms a thin band directly to the east of the Hardwick, contains porphyritic microcline granite gneiss with hornblende gneiss inclusions. The West Warren Plutons are located at the southern tip of the Coys Hill Pluton and consist of biotite-hornblende diorite, quartzose diorite, metadiorite, and norite. The Fitchburg Pluton consists of muscovite-biotite granite, granodiorite, granodiorite gneiss, and pegmatite; biotite granodiorite to tonalite gneiss; and zones and inclusions of granite gneiss, mica schist, and biotite-hornblende tonalite. The southern tip of the Massabesic Gneiss Complex extends into Massachusetts just to the east of the Fitchburg Complex (fig. 5). The Massabesic Gneiss Complex consists of biotite-feldspar gneiss intruded by potassium feldspar gneiss and biotite granite containing magnetite-bearing pegmatites. The Ayer Pluton consists of the Ayer Granite, a biotite granite to tonalite; and the Chelmsford Granite, a muscovite-biotite granite. Southwest of the Ayer Pluton is a small body of muscovite-biotite granite at Millstone Hill that is not shown separately on the generalized geologic map (fig. 2). To the east of the Ayer Pluton lies the Dracut Pluton, comprising the Dracut Diorite. The Newburyport Complex is an intrusion of gray granite, tonalite, and granodiorite located in the northeasternmost corner of Massachusetts (figs. 2, 5).

The Esmond-Dedham Zone consists of metasedimentary rocks of the Nashoba terrane, and a series of brittley deformed terranes, gneissic terranes, and granitic plutons (the Milford-Dedham zone of Zen (1983)). The Nashoba terrane is separated from the low-grade metamorphic rocks of the Merrimack synclinorium by the Clinton-Newberry Fault system (fig. 5). Eastward across the fault the metamorphic grade increases abruptly, then abruptly decreases across the Bloody Bluff Fault, which marks the eastern margin of the Nashoba terrane. Major rock units in the Nashoba terrane include the Marlboro Formation, characterized by amphibolite with lesser amounts of metasedimentary or metavolcanic gneisses; Quinebaug Formation, consisting of amphibolite and mafic, felsic, and calc-silicate gneiss; the Fish Brook Gneiss, a biotite-feldspar quartz gneiss; Shawsheen Gneiss, a sillimanite gneiss with minor amphibolite; and the Nashoba Formation, consisting primarily of feldspathic to aluminous schists and other metasedimentary or metavolcanic gneisses. Overlying this sequence is the Tadmuck Brook Schist, which is equivalent in age to the Andover Granite (Andover pluton on fig. 5). The youngest rocks in this sequence are the Sharpners Pond Diorite and related calc-alkalic igneous rocks (Rankin and others, 1989). Precambrian granitic suites can be divided into two groups, the Milford-Ponaganset Plutonic Suite and the Esmond-Dedham Plutonic Suite. Both groups contain areas of metasedimentary rocks but they consist primarily of granite, with lesser amounts of granodiorite and tonalite. The Milford-Ponaganset Plutonic Suite occupies the Rhode Island Anticlinorium (fig. 5) and includes the Hope Valley Alaskite, a mafic-poor granite gneiss; Scituate Granite Gneiss; Ponaganset Gneiss, a gneissic biotite granite; and the Milford Granite, dominantly a light-colored biotite granite and granodiorite. To the northeast of this area, between the Bloody Bluff Fault and the Northern Border Fault, lies an area of brittley-deformed terrane consisting of granitic, volcanic, and metavolcanic rocks including diorite, granodiorite, gabbro, and serpentinite; the Lynn Volcanic complex, on the northern edge of the Boston Basin, consisting of rhyolite, agglomerate, and tuff; and metasedimentary rocks of the Westboro Formation. The Newbury basin, underlain by the Newbury Volcanic Complex, consisting of rhyolite, andesite, and sedimentary rocks, lies at the northern end of this zone. South of the Newbury basin, The Cape Ann and Peabody Plutons, and the Quincy Pluton to the south of the Boston basin, consist of alkalic granites, monzonites, monzodiorites, and alaskitic granites of the Cape Ann Complex, Quincy Granite, Blue Hill Granite Porphyry, Cherry Hill Granite, Wenham Monzonite, and Peabody Granite. The Esmond-Dedham Plutonic Suite lies to the southeast of the Boston basin and the Milford-Ponaganset Plutonic Suite. The rocks of the Esmond-Dedham suite are similar to those of the Milford-Ponaganset Plutonic Suite except that hornblende is more common whereas biotite is less common (Rankin and others, 1989). The Esmond-Dedham Plutonic Suite includes the Westwood and Dedham Granites, the Sharon Syenite, alaskite, diorite, granites of the Rattlesnake Hill and Fall River Plutons, and a small body of alkalic granite near Franklin. Also included in this map unit are felsic and mafic volcanic rocks southwest of the Boston basin and hornblende and biotite gneiss and schist near New Bedford. Just east of the eastern margin of the Narragansett basin is a granite thought to correlate with the Dedham Granite, along with metasedimentary and metavolcanic rocks also presumed to be late Precambrian in age. Proceeding southeast, the granitic and gabbroic rocks become progressively more intensely deformed, terminating in shear zones. Among the highly deformed granitic rocks occurs a relatively massive alkalic granite, similar to the Scituate granite, the exact age and origin of which is currently not known.

The *Narragansett basin, Boston basin, and Norfolk basin* are underlain by late Precambrian to Pennsylvanian sedimentary, metasedimentary, and volcanic rocks. In the Boston basin, the oldest rocks are felsic volcanic rocks of the Lynn and Mattapan Volcanic Complexes. Overlying the volcanic rocks is a sequence of coarse-grained clastic sedimentary rocks belonging to the Boston Bay Group, which contains two formations, the Roxbury Conglomerate and the Cambridge Argillite. This map unit also includes the Bellingham Conglomerate. The Narragansett basin is underlain Primarily by the Rhode Island Formation, consisting of sandstone, shale, graywacke, and conglomerate; and the Dighton Conglomerate. The Hoppin Formation, consisting of quartzite, argillite, and minor limestone, underlies Hoppin Hill, in the northwestern part of the Narragansett basin (fig. 5). The Norfolk basin, a narrow, east-west trending basin located between the Narragansett and Boston basins, is underlain by the Pondville quartz conglomerate and the Wamsutta Formation, consisting of conglomerate, graywacke, sandstone, shale, and minor rhyolite and mafic volcanic rocks. Cretaceous and Tertiary sedimentary rocks and unconsolidated sediments underlie Nantucket island and Martha's Vineyard (fig. 2).

GLACIAL GEOLOGY

Deposits of five or possibly six Pleistocene glacial advances in New England have been recognized or inferred from surface or subsurface data (Stone and Borns, 1986); however, two main till units are mapped throughout much of southern New England (Richmond and Fullerton, 1991). Glacial deposits exposed at the surface in Massachusetts are of Late Wisconsin age. Glaciers moved in a dominantly N-S or NW-SE direction across the State, terminating on Long Island, Martha's Vineyard, and Nantucket Island at their maximum extent. In Late Wisconsin time, parts of four glacial lobes advanced across Massachusetts. The Connecticut Valley Lobe covered the western part of the State and carved the Connecticut Valley Lowland. The Charles-Merrimack Lobe covered the northern part of the coastal lowland. The Narragansett-Buzzard's Bay Lobe and the Cape Cod Bay Lobe covered the southern part of the coastal lowland and Cape Cod (fig. 6). The final retreat of Wisconsinan glaciers from Massachusetts occurred about 12,000 years ago (Stone and Borns, 1986).

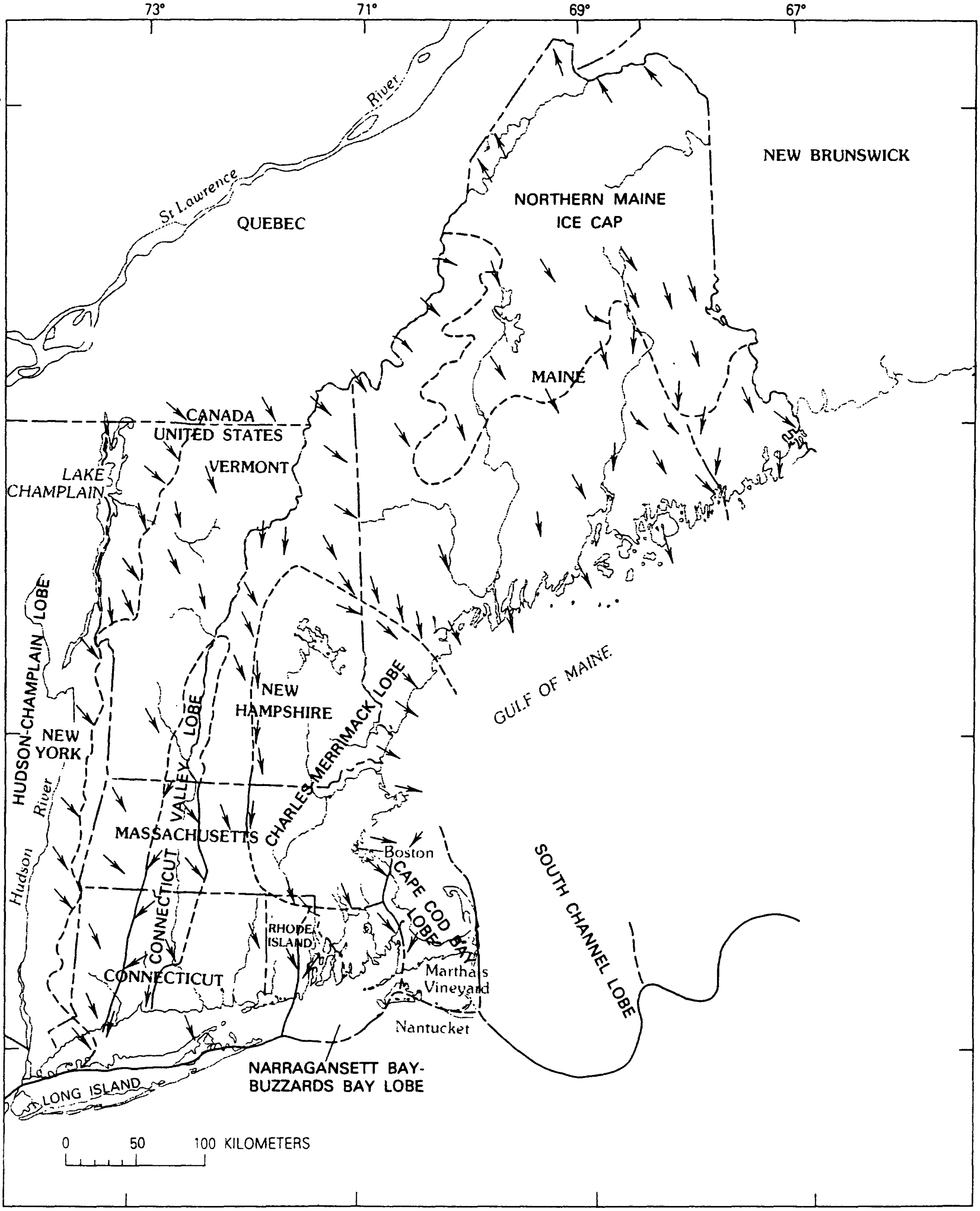


Figure 6. Major late Wisconsin glacial lobes of New England. Arrows indicate major directions of ice advances (from Stone and Borns, 1986).

Figure 7 is a generalized map of glacial deposits in Massachusetts. The glacial deposits are divided into two main categories, till and stratified glacial deposits. Till, sometimes also referred to as drift or ground moraine, is the most widespread glacial deposit (fig. 7), covering about 63 percent of the State (Stone, 1982). Till was deposited directly by glacier ice and it is composed of a nonsorted matrix of sand, silt, and clay containing variable amounts of rounded cobbles and boulders. Till composition generally reflects the local bedrock. The "upper till", which covers most of the surface mapped as till on figure 7, is sandy to gravelly and locally calcareous. It typically overlies a "lower till" which is more clayey, more compact, and less bouldery that the upper till (Richmond and Fullerton, 1991). Till thickness averages 3-5 m (Stone, 1982), and is rarely more than 10 m (Richmond and Fullerton, 1991). Glacial landforms typically associated with till include drumlins, kettles, and moraines. The Martha's Vineyard and Nantucket moraines (fig. 7) are part of a larger terminal moraine complex that stretches from Long Island to Nantucket. These moraines were deposited approximately 21,000 years ago (Stone and Borns, 1986). The Sandwich and Buzzard's Bay moraines are also part of a large moraine complex that was deposited approximately 18,000 years ago (Stone and Borns, 1986). Remnants of smaller, younger moraines, such as the Monk's Hill Moraine (fig. 7), are found in the southern coastal lowland.

Glacial meltwater deposits were laid down in streams and lakes in front of the retreating ice margin. They are characterized by layers of poorly-sorted to well-sorted gravel and sand with minor beds of silt and clay. Thickness of these deposits ranges from 5-40 m (Richmond and Fullerton, 1991). Meltwater deposits are subdivided into two categories on figure 7. Glaciofluvial deposits consist primarily of outwash (layered sand and gravel deposited by glacial meltwater streams), but also include deposits of kames and eskers, kame terraces, and collapsed stratified drift. Outwash is generally the coarsest-grained class of glacial deposits because most of the silt and clay was removed by the rapidly-moving water. The other types of deposits, referred to as ice-contact stratified drift, range from poorly sorted to well sorted and consist of sand, gravel, cobbles, and boulders, with varying amounts of silt and clay, though they generally contain considerably less fine-grained material than till. Glaciofluvial deposits cover about 7 percent of the State (Stone, 1982).

Glaciolacustrine deposits, the second category of glacial meltwater deposits, were deposited in or adjacent to glacial lakes that formed at the edge of the retreating glacier and occupied topographic basins. Glaciolacustrine deposits cover about 28 percent of the State and include lake-bottom sand, silt, and clay, and lacustrine delta silt, sand, and gravel (Stone, 1982). Silt and clay are the dominant grain sizes in lake bottom sediments (Zoino and Campagna, 1982). Coarse-grained glaciofluvial valley fill deposits, which supplied sediment to the glacial lake deltas, are also included in this map unit (fig. 7). Large glacial lakes in Massachusetts include lakes Hitchcock and Westfield, in the Connecticut River basin; the Taunton basin lake in southeastern Massachusetts; and lakes Nashua and Charles in northeastern Massachusetts (fig. 7).

Glaciomarine deposits form a separate category of glacial deposits shown on figure 7. These deposits consist of silt and clay marine bottom sediments and silt, sand, and gravel delta sediments, which were deposited in ocean water. Glaciomarine deposits cover about 2 percent of Massachusetts (Stone, 1982).

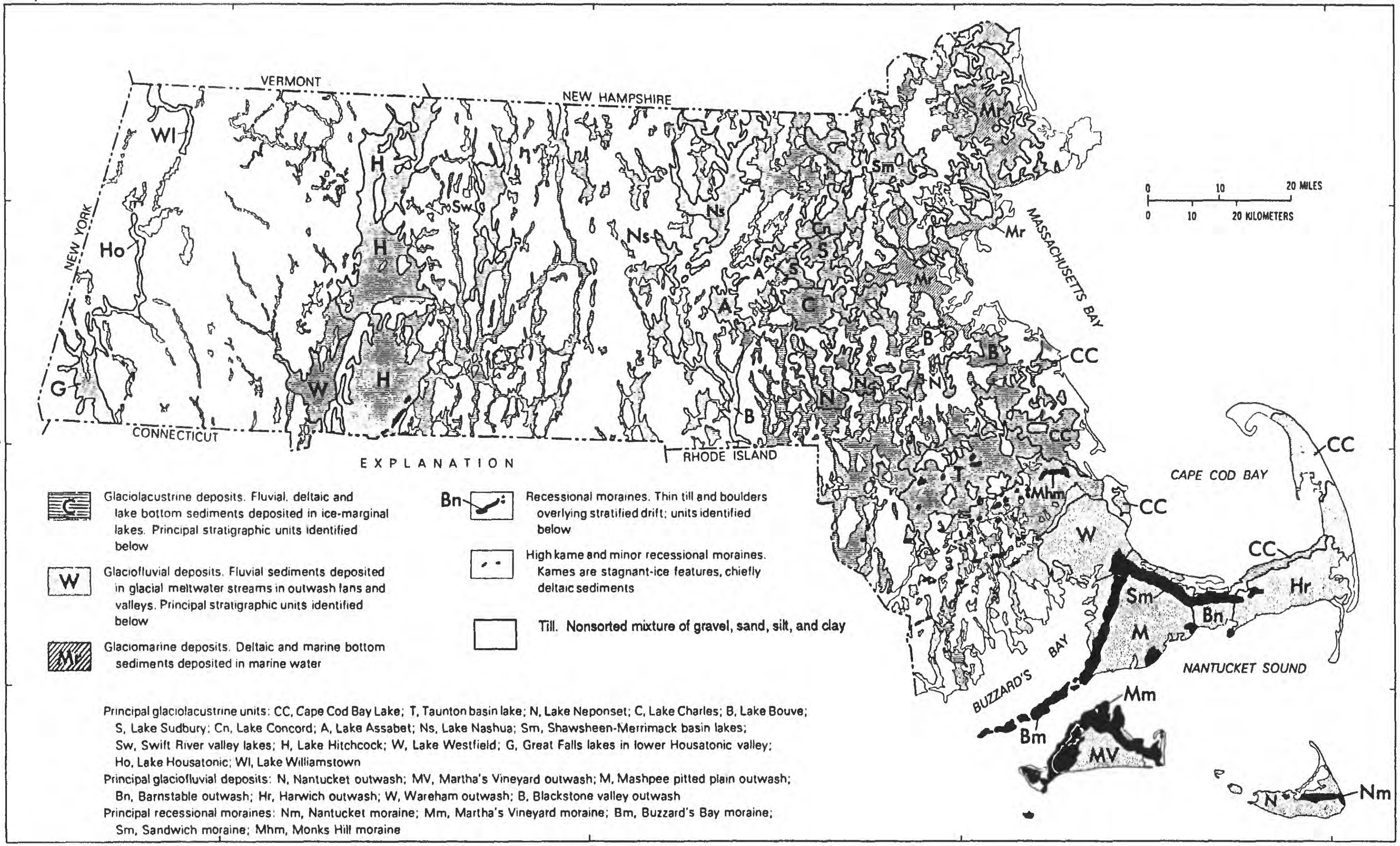


Figure 7. Generalized glacial geologic map of Massachusetts (modified from Stone, 1982).

SOILS

Soils in Massachusetts include Inceptisols, mineral soils with horizons of alteration or accumulation of metal oxides such as iron, aluminum, or manganese; Entisols, mineral soils with no discernible horizons because their parent material is inert (such as quartz sand) or because the soils are very young; and Histosols, organic soils such as peats or mucks which occur along coastlines or in river valleys. Figure 8 is a generalized soil map of Massachusetts (U.S. Department of Agriculture, 1989). The following discussion is condensed from the general soils map of Massachusetts (U.S. Department of Agriculture, 1989) and from U.S. Soil Conservation Service county soil surveys. State- and county-scale soil survey reports should be consulted for more detailed descriptions and information.

Very deep, loamy and sandy soils formed in glacial till derived from granite, schist and gneiss on upland till plains and moraines cover about 45 percent of Massachusetts (fig. 8). The till is a stony and bouldery, unsorted and unstratified material consisting of a heterogeneous mixture of sand, silt, clay, gravel, stones, and boulders. These soils are moderately well- to well drained and have a loamy or sandy surface layer and a firm (typically clayey) to friable (loosely packed, easily separated, and permeable) substratum. Soils with friable subsurface layers have moderate permeability, whereas those with firm substrata have low permeability. This map unit consists of gently sloping to very steep soils on hilltops and hillsides throughout the State. Most areas underlain by the soils of this unit are forested.

Very deep, loamy soils formed in glacial till derived from limestone and crystalline rocks on upland till plains occur in the extreme western part of the State (fig. 8). This map unit consists of nearly level to very steep soils, mainly in the central valley region of Berkshire County. These soils are moderately drained to well drained, typically have a friable substratum, and have moderate permeability. Areas underlain by these soils are extensively farmed. This map unit makes up about 5 percent of the State.

Very deep, loamy and sandy soils formed in glacial outwash, lacustrine, and alluvial sediments, on outwash plains and in stream valleys are found in the Connecticut Valley and eastern Massachusetts (fig. 8). This map unit consists of nearly level to moderately steep soils. Soils formed from glacial outwash are well drained to excessively drained and have high permeability. Soils formed from alluvial deposits include poorly-drained soils in valley bottoms and moderately drained to well-drained soils on terraces and floodplains. Alluvial soils have moderate to high permeability. Glaciolacustrine sediments formed from postglacial lakes. Fine particles (silt and clay) that were held in suspension within these lakes settled out and formed alternating layers of silt and clay. This map unit also includes soils formed on glaciomarine sediments, primarily silt and clay that were deposited by glaciers in ocean water. Soils formed on glaciolacustrine and glaciomarine sediments have low to moderate permeability. Alluvial, glaciolacustrine, and glaciomarine soils in low-lying areas may be subject to high water tables and flooding. Most areas underlain by soils of this unit are cleared and are used for agricultural and commercial uses. This map unit makes up about 30 percent of the State.

Moderately deep to shallow, loamy soils formed in glacial till on bedrock-controlled uplands cover about 15 percent of the State (fig. 8). Generally in Massachusetts, areas of shallow soils are a complex of rock outcrop, shallow-to-bedrock soils (10-20 inches of soil over bedrock), moderately deep soils (20-40 inches of soil over bedrock), and very deep soils (greater than 60 inches of soil over bedrock). These soils are well- to excessively drained and have moderate permeability. This map unit consists of gently sloping to very steep soils on hilltops and hillsides,

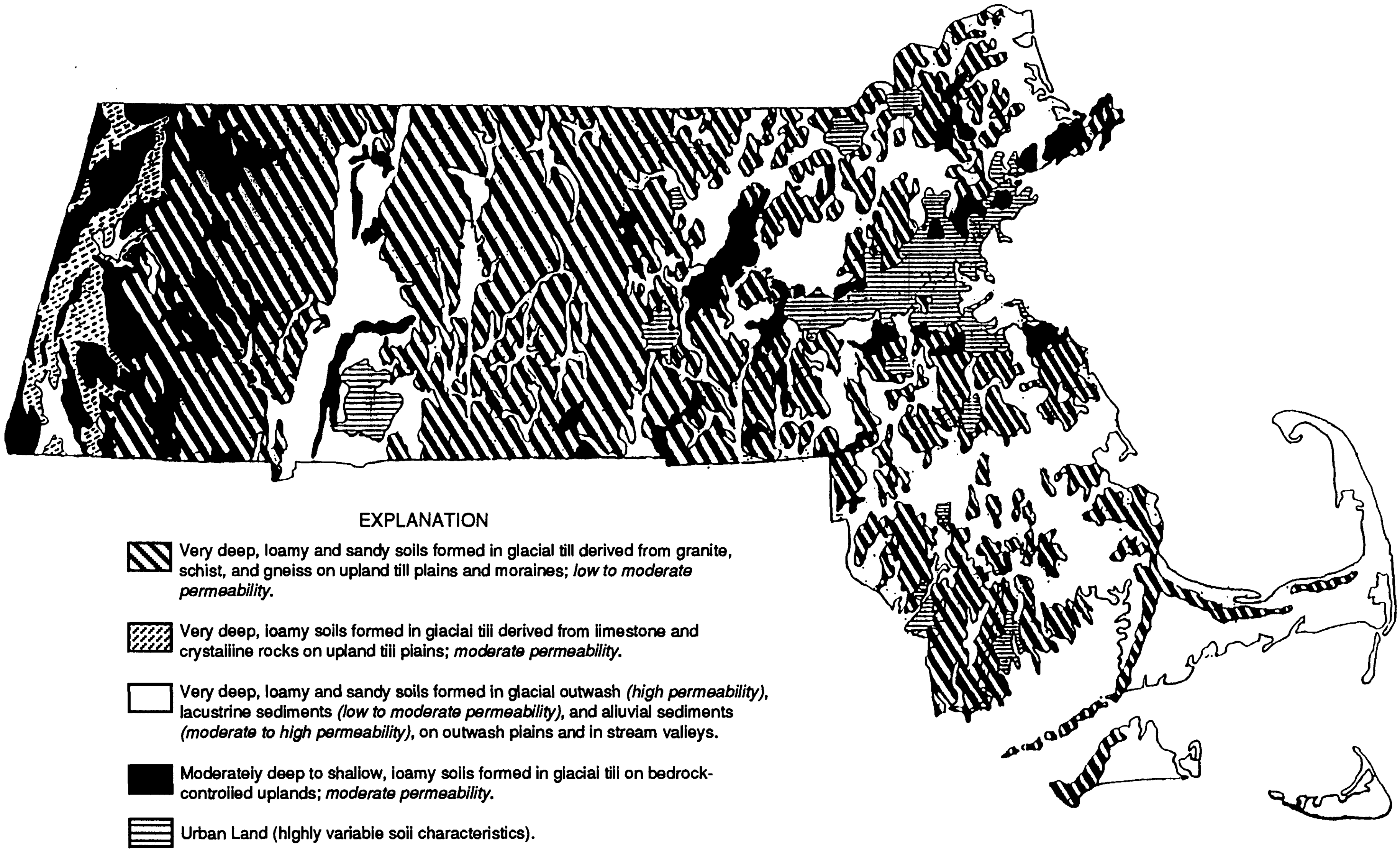


Figure 8. Generalized soil map of Massachusetts (modified from U.S. Department of Agriculture, 1989).

mainly in the western and eastern parts of the State. Most areas underlain by this soil unit are forested.

Areas mapped as urban land (fig. 8) consist of nearly level to moderately steep areas where the soils have been altered or obscured by urban works and structures. Buildings, industrial areas, and paved areas cover more than 75 percent of the surface. The properties and characteristics of this map unit are highly variable.

RADIOACTIVITY

An aeroradiometric map of Massachusetts (fig. 9) compiled from National Uranium Resource Evaluation (NURE) flightline data (Duval and others, 1989) shows several high radioactivity areas in the State. Low radioactivity (<1.5 ppm eU) is associated with the gneisses and amphibolites of the Berkshire massif; the Waits River Formation in the northern Connecticut Valley Synclinorium; with mafic and ultramafic rocks of the gneissic domes in the eastern Connecticut Valley Belt; with volcanic rocks in and south of the Newbury basin; and with mostly mafic granites and gneisses, including the Ponaganset Gneiss, south and southwest of Boston. Low to moderate radioactivity is associated with sedimentary rocks of the Narragansett basin. A prominent radiometric low in the eastern Connecticut Valley Belt is associated with Quabbin Reservoir. Moderate radioactivity (1.5-2.5 ppm) covers the southern and central Taconic Mountains, the Mesozoic basins and southern part of the Connecticut Valley Synclinorium, and scattered areas throughout the Merrimack Belt, associated mainly with Paleozoic-age metamorphic rocks. High radioactivity (>2.5 ppm) is associated with black phyllitic schist of the Walloomsac Formation in the northern Taconics; with granite gneiss in the southern part of the Warwick Dome; with the Hardwick Tonalite in north-central Massachusetts; and with granitic plutons and glacial deposits containing significant amounts of granitic rock as source material in the Merrimack Belt. A group of small high (>2.5 ppm eU) radioactivity areas occurs in a roughly arcuate pattern extending from the center of the Hartford basin north of Springfield into the southern part of the Connecticut Valley synclinorium just north of the Granville Dome.

Conglomerate beds of the Dalton Formation, on the west side of the Berkshire Mountains, have radioactivity 3-7 times background, which, although caused mostly by thorium (Field and Truesdell, 1982), may also contain elevated uranium concentrations. The Tyringham Gneiss locally contains up to 11 ppm uranium on the west side of the Berkshire Mountains southeast of Stockbridge. Other parts of the Tyringham Gneiss have normal radioactivity (Field and Truesdell, 1982). Precambrian gneiss south of Adams contains 5-10 ppm uranium, and locally as much as 80 ppm in a small pegmatite. There are no reported uranium occurrences in the Newark Supergroup of Massachusetts but there are some units likely to have elevated uranium concentrations. Carbonaceous debris in fluvial crossbeds in the uppermost New Haven Arkose and Sugarloaf Formation and in the middle portion of the Portland Formation are similar to reported uranium-bearing units in the Triassic of Connecticut (Robinson and Sears, 1988). Black shales and deltaic gray sandstones in the Shuttle Meadow, East Berlin, lower Portland, Turners Falls, and lower Mount Toby formations may also have elevated uranium. The basalts and diabases, the lower portions of the New Haven Arkose and Sugarloaf Formations, and the upper portions of the Portland and Mount Toby Formations are not likely to have significant uranium concentrations, except possibly along fractures.

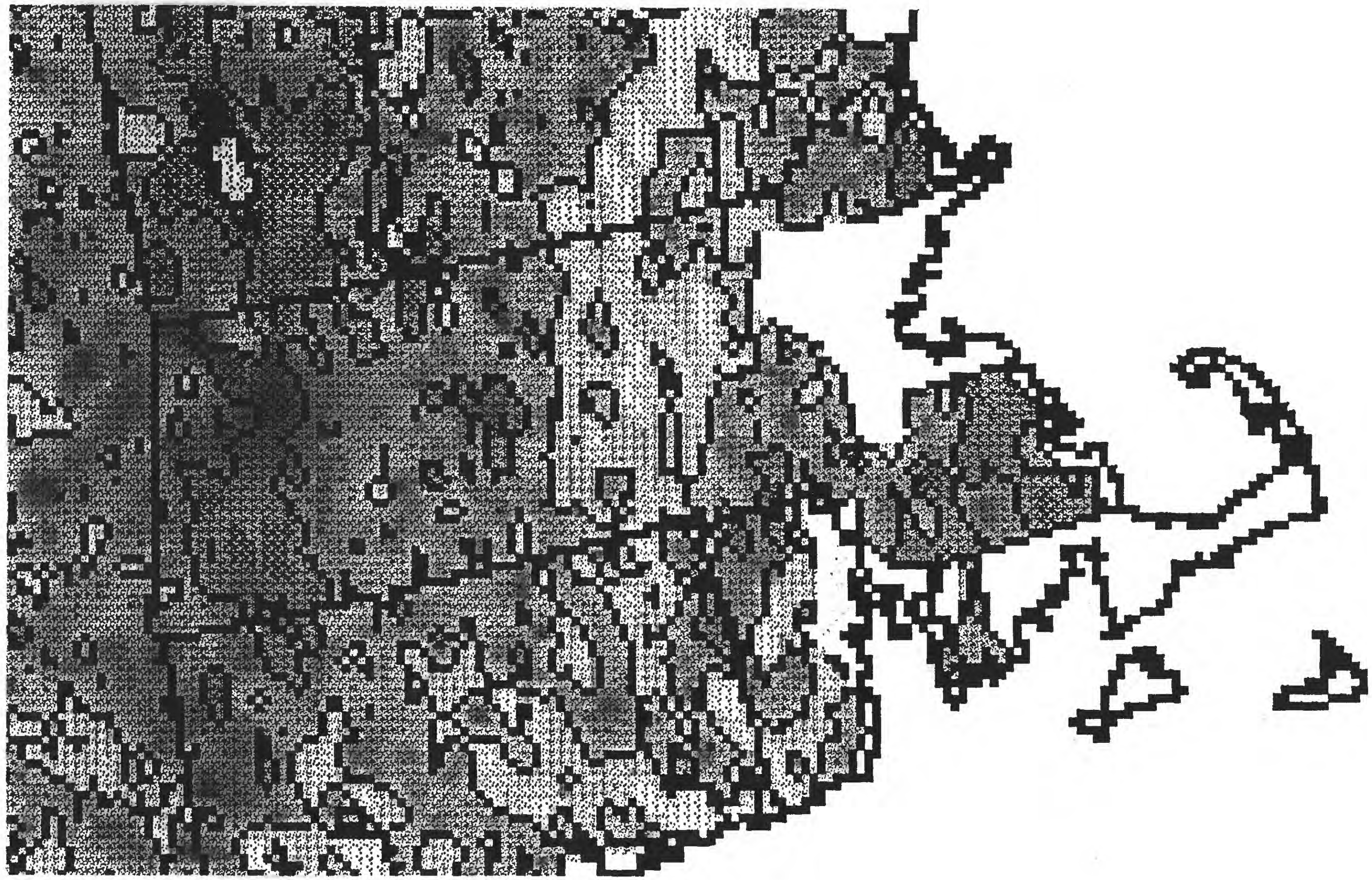


Figure 9. Aerial radiometric map of Massachusetts (after Duval and others, 1989). Contour lines at 1.5 and 2.5 ppm equivalent uranium (eU). Pixels shaded at 0.5 ppm eU increments; darker pixels have lower eU values; white indicates no data.

The Warwick and Vernon domes have cores of the Pauchaug Gneiss, a massive feldspathic gneiss containing 1-2 ppm uranium on average. However, the south end of the Warwick dome contains an area with 5-33 ppm uranium, which can be easily seen on the aeroradioactivity map (fig. 9). The Hardwick Tonalite was found to contain up to 4 ppm uranium near Athol. Small granite bodies in the North Brookfield area had radioactivity 3-4 times background, possibly due to high potassium-feldspar content (Field and Truesdell, 1982). Radiometric anomalies in the Merrimack Belt and Esmond-Dedham Zone appear to generally correlate with the locations of granitic plutons, including the Hardwick, Coys Hill, Fitchburg, Ayer, Dracut, Newburyport, Andover, Cape Ann, Peabody, and Quincy plutons. The widespread appearance of the radiometric highs probably reflect the overlying glacial till, which incorporates fragments of granitic rock from the various plutons, that has spread over most of northeastern Massachusetts. Chemical analyses of samples of the Quincy Granite yielded as much as 33 ppm uranium (Zollinger and others, 1982). Uranium occurs in pegmatites in the Cape Ann Complex in Essex County; the Loudville Lead Mine and at West Chesterfield in Hampshire County; in the Dedham Granite and in pegmatites at Blueberry Mountain in Middlesex County; and in pegmatites at the foot of Long Hill in Leominster and on Rollstone Hill in Fitchburg, Worcester County (Grauch and Zarinski, 1976).

Only one uranium occurrence has been reported in Pennsylvanian sedimentary rocks of the Narragansett basin. It consists of an iron-stained zone in the Dighton Conglomerate that yielded 14 ppm uranium (Zollinger and others, 1982). Areas along cataclastic and mylonitic fault and shear zones, particularly the Lake Char fault zone (Zollinger and others, 1982), may host significant uranium concentrations and generate locally elevated radon because shear zones tend to concentrate and redistribute uranium to sites of high emanation, and because shear zones typically have enhanced permeability compared to surrounding rocks (Gundersen, 1991).

INDOOR RADON

Indoor radon data from 1664 homes sampled in the State/EPA Residential Radon Survey conducted in Massachusetts during 1988 are shown in figure 10 and listed in Table 1. A map of counties is included for reference (fig. 11). Indoor radon was measured by 2-7 day charcoal-canister screening tests. Data for Berkshire and Dukes Counties, and for Franklin and Hampshire Counties, which each contain fewer than 100 samples, are shown both individually and combined in Table 1. Data for these counties were combined by the Massachusetts Department of Public Health to achieve a statistically representative sample at the county level (the pairs of combined counties were treated as one county). Average (arithmetic mean) values reported here and used in the Radon Index evaluations may be subject to bias by extremely high values, especially if the sample size is relatively small, and thus may not necessarily represent "typical" indoor radon values in each county. A comparison of county averages with the corresponding number of samples, median, geometric mean, and maximum (Table 1) can indicate instances in which the county indoor radon average has been artificially elevated by the influence of one or more high values. Maximum indoor radon levels listed in Table 1 represent the highest screening indoor radon level recorded in the 1988 State/EPA survey, and do not necessarily indicate the highest *possible* indoor radon levels in each county. However, these values may be helpful in giving a general, relative indication of where locally high indoor radon levels are likely to occur.

The statewide indoor radon average for Massachusetts was 3.3 pCi/L and 24 percent of the homes tested in the State had indoor radon levels exceeding 4 pCi/L. Notable counties include Dukes, Essex, Middlesex, and Worcester, in which the average indoor radon for each county

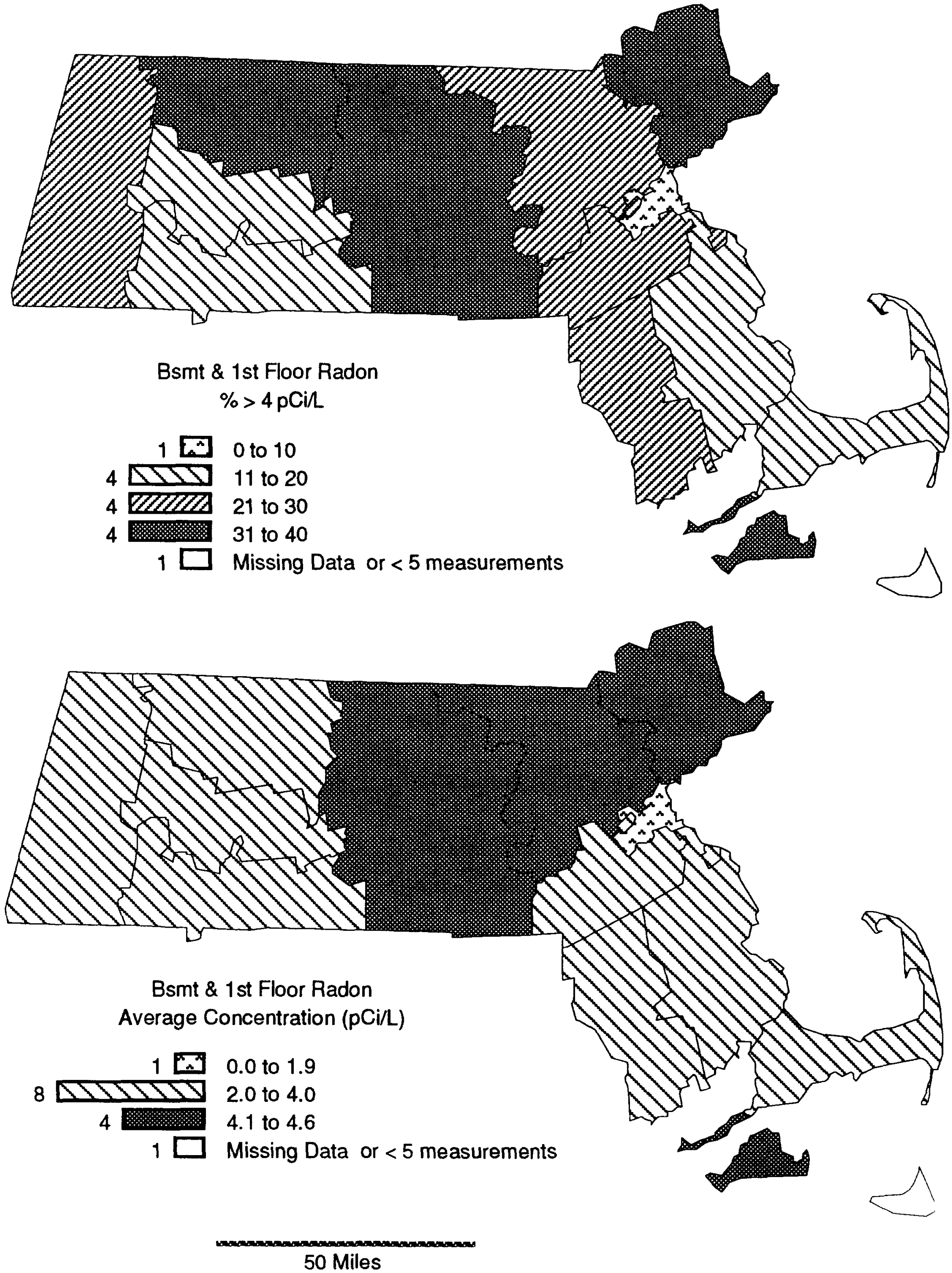


Figure 10. Screening indoor radon data from the EPA/State Residential Radon Survey of Massachusetts, 1988, for counties with 5 or more measurements. Data are from 2-7 day charcoal canister tests. Histograms in map legends show the number of counties in each category. The number of samples in each county (See Table 1) may not be sufficient to statistically characterize the radon levels of the counties, but they do suggest general trends. Unequal category intervals were chosen to provide reference to decision and action levels.

Figure 11. Massachusetts counties.

exceeded 4 pCi/L. Counties with 25 percent or more homes exceeding 4 pCi/L include Dukes, Essex, Franklin, Middlesex, and Worcester. The 4.6 pCi/L average and high percentage of homes exceeding 4 pCi/L for Dukes County may be somewhat misleading, however, as the median indoor radon value was 1.2 pCi/L and only 6 homes were sampled in this county. Although not necessarily representative of the whole county, it does indicate that some homes with indoor radon levels exceeding 4 pCi/L are found on Martha's Vineyard and further testing is warranted. The Martha's Vineyard Moraine has high permeability and incorporates clasts of more radon-rich rocks from north of this area, and may be a source for elevated indoor radon levels on Martha's Vineyard. No homes were sampled on Nantucket Island.

TABLE 1. Screening indoor radon data from the State/EPA Residential Radon Survey of Massachusetts conducted during 1988. Data represent 2-7 day charcoal canister tests.

COUNTY	NUMBER of MEAS.	AVERAGE	STD. DEV.	MEDIAN	GEOM. MEAN	MAX	%≥4 pCi/L	%≥20 pCi/L
BARNSTABLE	99	2.1	2.0	1.6	1.5	12.5	14	0
BARNSTABLE +DUKES	105	2.2	2.6	1.6	1.6	19.5	15	0
BERKSHIRE	47	3.3	3.8	1.9	1.8	15.7	21	0
BRISTOL	115	2.8	3.4	1.8	1.8	28.8	22	1
DUKES	6	4.6	7.4	1.2	1.9	19.5	33	0
ESSEX	203	4.1	5.1	2.8	2.6	52.4	36	1
FRANKLIN	26	3.3	3.4	1.6	2.1	12.6	31	0
FRANKLIN +HAMPSHIRE	80	2.8	2.9	1.6	1.9	14.1	23	0
HAMPDEN	125	2.0	2.4	1.3	1.4	22.9	11	1
HAMPSHIRE	54	2.6	2.6	1.6	1.8	14.1	19	0
MIDDLESEX	400	4.1	7.0	2.2	2.3	61.3	26	3
NORFOLK	171	3.0	3.5	1.9	2.0	30.1	21	1
PLYMOUTH	141	2.0	2.0	1.4	1.4	14.7	12	0
SUFFOLK	61	1.7	1.3	1.2	1.4	8.0	5	0
WORCESTER	216	4.6	5.3	2.8	2.9	41.1	38	3
STATEWIDE	1664	3.3	4.9	1.9	2.0	61.3	24	1

GEOLOGIC RADON POTENTIAL

The metamorphic rocks of the Taconic Mountains and carbonate sedimentary and metasedimentary rocks of the Vermont-Stockbridge Valley have been ranked moderate in geologic radon potential. Soil permeability is generally moderate. Radioactivity is moderate with one distinctive anomaly. Graphitic phyllites and schist of the Walloomsac Formation have moderate to high radioactivity associated with them and may produce locally elevated indoor radon levels. Elevated radon may also be associated with fault and shear zones, especially in the Taconics.

The Berkshire Mountains have been ranked moderate overall in radon potential. The granitic to dioritic gneiss and schist have generally low equivalent uranium associated with them. Shear zones, pegmatites, and local accumulations of monazite in biotite schist and gneiss may be sources of locally high indoor radon levels. Soil permeability is low to moderate. Hall and others (1985) classified these rocks as having variable low to high uranium enrichment.

Metamorphic rocks of the Connecticut Valley Belt, on the eastern and western sides of the Mesozoic basins, have been ranked moderate in geologic radon potential. Metasedimentary and metavolcanic gneisses and schists have generally low to moderate radioactivity associated with them. Soils have generally moderate permeability. The Pauchaug and Glastonbury granite gneisses, which form the cores of the Warwick and Glastonbury domes, as well as other locally-occurring granitic rocks, may generate locally high indoor radon levels. Locally high radon is likely to be associated with the area of anomalous radioactivity at the south end of the Warwick dome and may be associated with faults and shears throughout the area.

Mesozoic sedimentary and igneous rocks of the Hartford, Deerfield, and Northfield basins in the Connecticut Valley have been ranked moderate or variable overall in radon potential. Most of the sedimentary rocks in the basins have low radon potential but locally high indoor radon may be associated with Jurassic-age black shales and localized uranium deposits in fluvial sandstone and conglomerates. Soil permeability is low to moderate in glacial lake-bottom sediments that cover most of the Hartford basin, and moderate to high in glaciofluvial deposits, including outwash, lacustrine delta deposits, and alluvium in the basins. Radioactivity is generally moderate but contains scattered radiometric highs in the central Hartford basin.

Granitic plutons of the Merrimack Belt have been ranked high in geologic radon potential. The metasedimentary rocks surrounding the plutons are predominantly phyllites and carbonaceous slates and schists with moderate to high radon potential. Mafic metamorphic rocks, which are less common in the Merrimack Belt, have generally low to moderate radon potential. Faults and shear zones may produce locally high radon concentrations. Equivalent uranium (fig. 9) is high over most of the area and the soils have low to moderate permeability. Overall, this area is ranked high in geologic radon potential.

Granitic plutonic rocks and metamorphic rocks of the Nashoba terrane, and granites of the Cape Ann and Peabody plutons, are ranked high in radon potential. They are associated with moderate to high radioactivity and the soils developed on these rocks have moderate to high permeability. Relationships between radon and underlying bedrock in eastern Massachusetts, particularly in the Merrimack zone and in these areas, are less distinct, probably due to the influence of glacial deposits that are made up of a mixture of the rock types underlying eastern Massachusetts and areas to the north. The glacial deposits generally have enhanced permeability and may have enhanced radon emanation due to the redistribution of rock components, mixing, and grain-size reduction effects of the glaciers. Volcanic rocks and soils of the Newbury basin are ranked moderate in radon potential. They are associated with generally low radioactivity, low to moderate soil permeability, and moderate to high indoor radon levels.

The Esmond-Dedham terrane is ranked moderate or variable overall in radon potential. This area includes a number of granite plutons and faulted and brittley sheared zones that may generate high radon levels, as well as mafic metasedimentary and metavolcanic rocks having low to moderate radon potential. Aeroradioactivity is generally low to moderate with one anomaly associated with granite of the Rattlesnake Hill Pluton. Soils in this area have low to moderate permeability. Indoor radon in this area averages between 2 and 4 pCi/L.

Proterozoic to Pennsylvanian sedimentary rocks of the Boston basin have been ranked low in radon potential. Pennsylvanian sedimentary rocks of the Narragansett basin are associated with low to moderate radioactivity and low to moderate soil permeability, and have moderate geologic radon potential. The Norfolk basin is similar to the Narragansett basin and also has moderate radon potential. Information on soil characteristics and radioactivity is unavailable for the Boston basin but radioactivity is assumed to be generally low based on the radioactivity of similar rocks elsewhere in the State. Soil characteristics are highly variable in urban areas due to human disturbance, and thus are considered to be variable for this assessment. Black shales and conglomerates in the Boston basin may have locally high radioactivity and may cause locally elevated indoor radon levels (J. Sinnott, personal communication, 1992).

Sediments of the Coastal Plain are found primarily on Nantucket Island and Martha's Vineyard. Areas underlain by Cretaceous and Tertiary sediments have low radon potential, but areas underlain by the Martha's Vineyard and Nantucket moraines have moderate to locally high radon potential caused by their relatively higher permeability and better drainage characteristics compared to surrounding areas, and the crystalline rock source component of the moraines. This is also true of the Buzzard's Bay and Sandwich moraines on Cape Cod (see fig. 7 for locations and names of moraines). Areas underlain by highly permeable glacial outwash may also generate locally elevated indoor radon levels if the water table is not too high to preclude soil-gas transport.

SUMMARY

For the purpose of this assessment, Massachusetts has been divided into twelve geologic radon potential areas and each area assigned a Radon Index (RI) and a Confidence Index (CI) score (Table 2). The RI is a semi-quantitative measure of radon potential based on geology, soils, radioactivity, architecture, and indoor radon. The CI is a measure of the relative confidence of the RI assessment based on the quality and quantity of the data used to assess geologic radon potential (see the Introduction chapter to this regional booklet for more information). The areas referred to in the radon potential matrix (Table 2) are shown on figure 12.

The Boston basin has low geologic radon potential overall, but a few homes in the area may have locally elevated indoor radon levels. Areas with moderate or variable radon potential include the Narragansett basin, Esmond-Dedham terrane, the Newbury basin, and roughly the western half of Massachusetts. The Coastal Plain, consisting of Martha's Vineyard and Nantucket, are assigned a variable radon potential, based on the variable geology and drainage characteristics of the moraines, outwash, and glacial till on the islands. Although only 6 homes in this area were sampled in the State/EPA Residential Radon Survey, the fact that two of the homes had screening indoor radon levels exceeding 4 pCi/L, including a 19.5 pCi/L reading, indicates that further investigations are warranted in this area.

Areas with high radon potential include the central and eastern parts of the State underlain by granitic rocks and by tills containing granites or other uraniferous rocks, such as graphitic schists and phyllites, as a major source component. Faults and shear zones in many parts of the State, particularly in the Taconics, on the west side of the Berkshire Mountains, and in the Merrimack and Esmond-Dedham terranes, have the potential to generate locally high indoor radon.

This is a generalized assessment of the State's geologic radon potential and there is no substitute for having a home tested. The conclusions about radon potential presented in this report cannot be applied to individual homes or building sites. Indoor radon levels, both high and low, can be quite localized, and within any radon potential area there will likely be areas with higher or lower radon potential 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 State radon program or EPA regional office. More detailed information on state or local geology may be obtained from the state geological survey. Addresses and phone numbers for these agencies are listed in chapter 1 of this booklet.

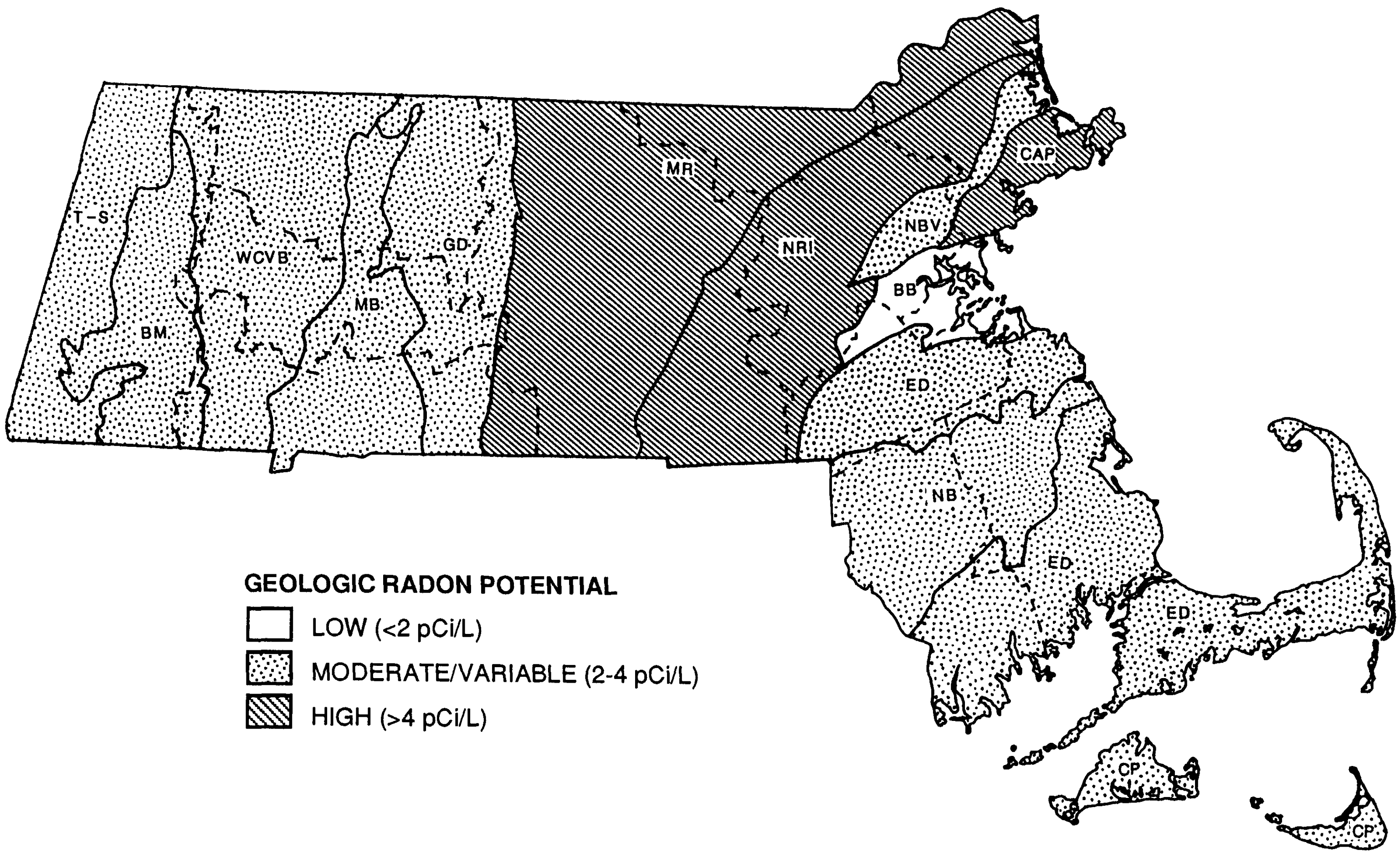


Figure 12. Geologic radon potential areas of Massachusetts. Refer to Table 2 for rankings of areas. Radon values in parentheses indicate predicted average screening indoor radon levels for all homes in the area. Abbreviations of areas: T-S, Taconic Mountains-Stockbridge Valley; BM, Berkshire Mountains; WCVB, western Connecticut Valley Belt; MB, Mesozoic Basins; GD, gneissic domes of the eastern Connecticut Valley Belt; MR, Merrimack Belt; NRI, Nashoba and Rhode Island terranes; CAP, Cape Ann and Peabody plutons; NBV, Newbury basin volcanics and surrounding volcanic rocks; NB, Narragansett Basin; BB, Boston Basin; ED, Esmond-Dedham terrane; CP, Coastal Plain.

TABLE 2. RI and CI scores for geologic radon potential areas of Massachusetts.

FACTOR	Taconics/ Stockbridge Valley RI	Taconics/ Stockbridge Valley CI	Berkshire Mountains RI	Berkshire Mountains CI	Western Connecticut Valley Belt RI	Western Connecticut Valley Belt CI	Mesozoic basins RI	Mesozoic basins CI
INDOOR RADON	2	2	2	2	2	2	2	2
RADIOACTIVITY	2	2	1	2	2	2	2	2
GEOLOGY	2	3	2	3	2	3	2	3
SOIL PERM.	2	3	2	3	2	3	2	3
ARCHITECTURE	3	-	3	-	3	-	3	-
GFE POINTS	0	-	0	-	0	-	0	-
TOTAL	11	10	10	10	11	10	11	10
	MOD	HIGH	MOD	HIGH	MOD	HIGH	MOD	HIGH

FACTOR	Gneissic Domes RI	Gneissic Domes CI	Merrimack Belt RI	Merrimack Belt CI	Nashoba Terrane & Cape Ann/Peabody RI	Nashoba Terrane & Cape Ann/Peabody CI	Newbury & other Volcanics RI	Newbury & other Volcanics CI
INDOOR RADON	2	2	3	3	3	2	2	2
RADIOACTIVITY	1	2	3	2	2	2	2	2
GEOLOGY	2	3	3	3	3	3	1	3
SOIL PERM.	2	3	2	3	2	3	2	3
ARCHITECTURE	3	-	3	-	3	-	3	-
GFE POINTS	0	-	0	-	0	-	0	-
TOTAL	10	10	14	11	13	10	10	10
	MOD	HIGH	HIGH	HIGH	HIGH	HIGH	MOD	HIGH

FACTOR	Boston Basin RI	Boston Basin CI	Esmond-Dedham Terrane RI	Esmond-Dedham Terrane CI	Coastal Plain RI	Coastal Plain CI	Narragansett Basin RI	Narragansett Basin CI
INDOOR RADON	1	3	2	2	3	1	2	2
RADIOACTIVITY	1	1	2	2	1	1	2	1
GEOLOGY	1	3	2	3	2	2	1	3
SOIL PERM.	2	1	2	3	2	3	2	3
ARCHITECTURE	3	-	3	-	3	-	3	-
GFE POINTS	0	-	0	-	0	-	0	-
TOTAL	8	8	11	10	11	7	9	9
	LOW	MOD	MOD	HIGH	MOD	MOD	MOD	MOD

RADON INDEX SCORING:

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

Possible range of points = 3 to 17

CONFIDENCE INDEX SCORING:

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

Possible range of points = 4 to 12

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PRELIMINARY GEOLOGIC RADON POTENTIAL ASSESSMENT OF NEW HAMPSHIRE

by
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INTRODUCTION

This chapter presents a discussion of the bedrock and glacial geology, soils, and radioactivity of New Hampshire in the context of indoor radon. The New Hampshire Division of Public Health Services conducted a survey of 1810 randomly selected homes throughout the state to assess the extent of the indoor radon problem in New Hampshire (Pirie and Hannington, 1989; and 1990 addendum). Testing began in February 1988 and continued through 1990. Of the homes tested, 27.8 percent had screening indoor radon measurements greater than 4 pCi/L and the average indoor radon level was 4.8 pCi/L. Examination of these indoor radon data in the context of geology, soil parameters, and radioactivity suggest that the majority of townships with high (>4 pCi/L) indoor radon levels are underlain by granite and granitic gneiss, particularly in the north-central and eastern portions of the State (fig. 1). Some of these rocks are particularly enriched with uranium or have uranium distributed in mineral phases which may be easily dissolved by ground water. High indoor radon may also be associated with pegmatites, major fault zones, and high-grade metamorphic rocks. High concentrations of radon in domestic water are associated with granite, pegmatite, and faults in some parts of New Hampshire. The radon in these wells may be high enough to contribute significantly to the radon content of the indoor air.

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

PHYSIOGRAPHIC AND GEOGRAPHIC SETTING

The physiography of New Hampshire is in part a reflection of the erodability of the underlying bedrock lithology (fig. 1) and the effects of extensive glaciation. New Hampshire has four major physiographic regions: the Coastal Lowlands, the Eastern New England Upland, the Connecticut River Valley, and the White Mountains (fig. 2). Other physiographic regions include the Whitefield Lowlands, Winnipesaukee, Ossipee, and Conway Lowlands, Ossipee Mountains, Belknap Mountains, and Merrimack Valley. Elevation in the State ranges from sea level in the southeastern part of the State to 6,288 feet at Mt. Washington in the White Mountains.

The Coastal Lowlands, in the southeastern corner of the State, have relatively flat to gently rolling topography with elevations generally less than 200 ft above sea level. The area is covered by glaciomarine silts and clays that blanket bedrock knolls (Chapman, 1976). The Eastern New

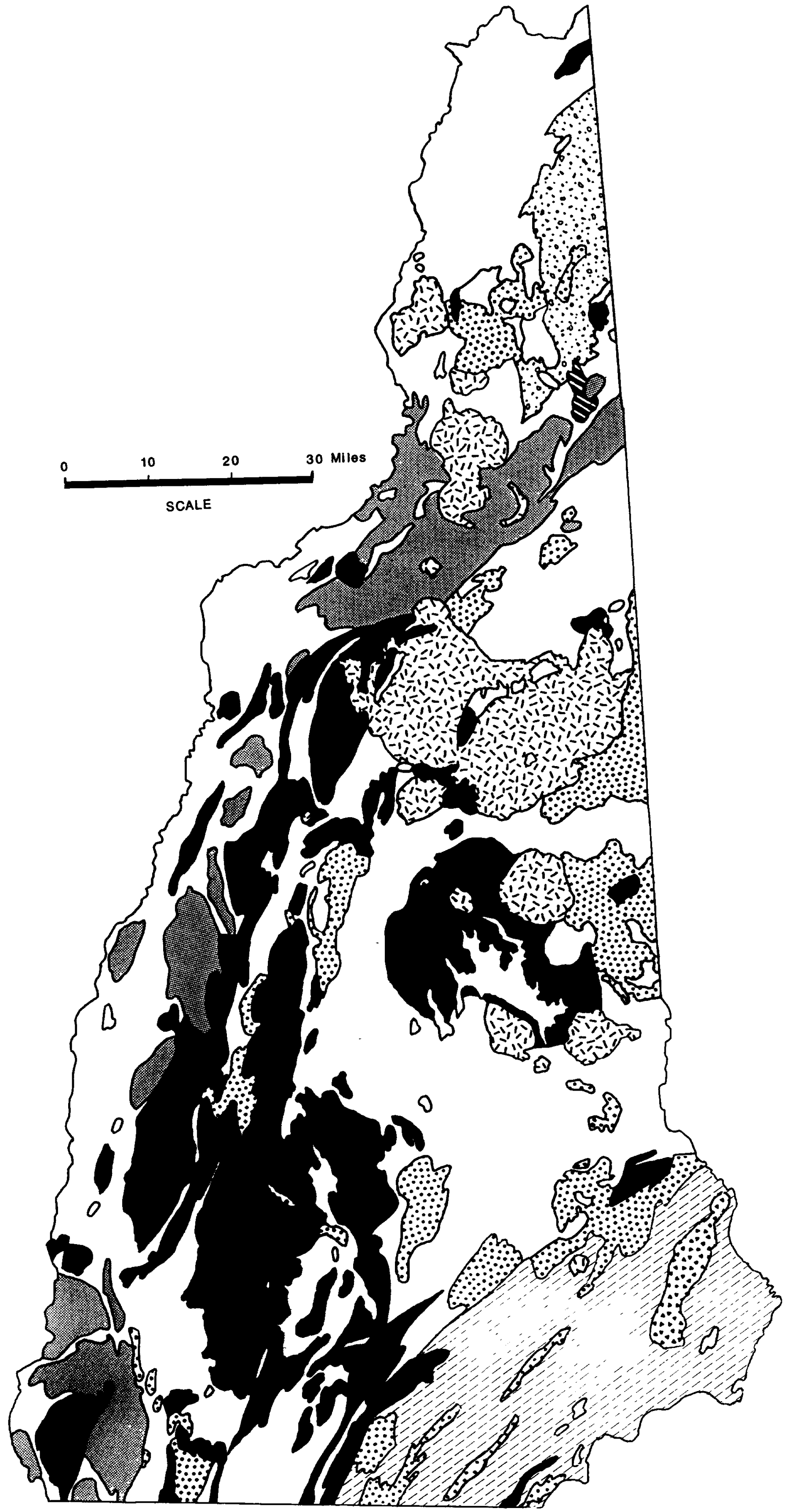

Figure 1. Generalized bedrock geologic map of New Hampshire (redrawn from Boudette, 1990).

GENERALIZED GEOLOGIC MAP OF NEW HAMPSHIRE
EXPLANATION

Jurassic-Cretaceous rocks of the White Mountain and New England-Quebec igneous succession

Devonian-Carboniferous two-mica granite

Silurian-Devonian intrusive rocks ranging from gabbro to granite in composition

Late Cambrian-Early Devonian metamorphic rocks

Late Ordovician sheeted gabbro sequence

Middle to Late Ordovician intrusive rocks ranging from gabbro to syenite in composition

Early Ordovician intrusive rocks ranging from gabbro to granodiorite in composition

Cambrian-Early Ordovician metamorphic rocks

Late Precambrian metamorphic rocks

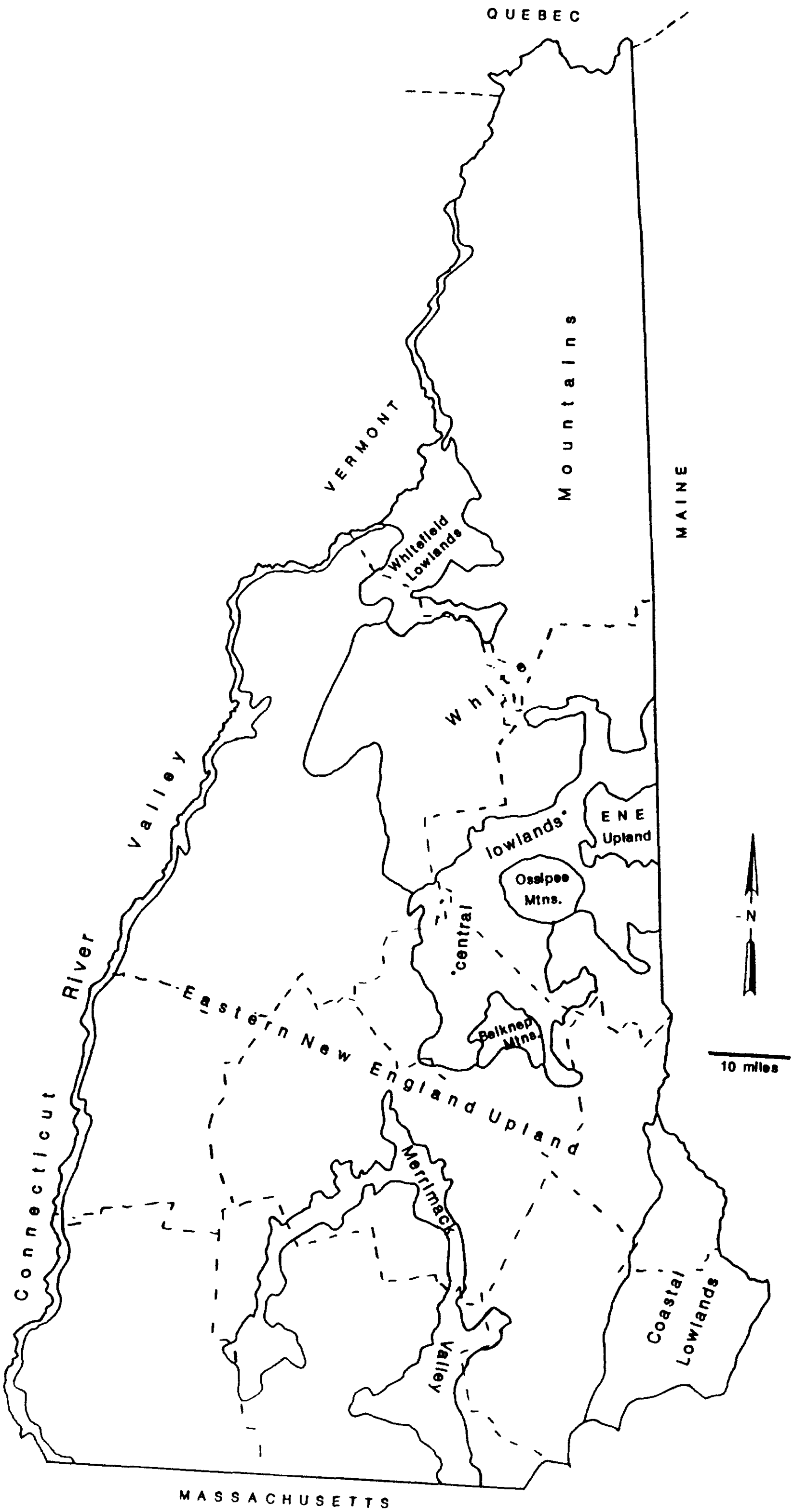

Figure 2. Physiographic regions of New Hampshire (modified from Chapman, 1976).

England Upland covers much of the southern part of the State, and is underlain primarily by metasedimentary and metavolcanic rocks. The eastern part, which is separated from the western part by the Merrimack Valley, consists of rolling hills with smooth, glacially-rounded summits separated by rounded glacial valleys, somewhat resembling a dissected plateau. Elevations range from about 200 to 1500 ft. The western part of the Eastern New England Upland is more mountainous than the eastern part, averaging between 1500 and 2000 ft in elevation. This area is much more dissected than the eastern part, and the area has distinctly rugged topography. This area includes some higher mountains such as Mt. Monadonock and Mt. Kearsarge. The Connecticut Valley runs along nearly the entire western border of the State. It is a wide glacial valley carved from metasedimentary and metavolcanic rocks which was occupied by a glacial lake during the Pleistocene Epoch. The valley floor and terraces are covered by sandy alluvium and glaciolacustrine deposits, with lake-bottom clays underneath.

The White Mountains occupy most of the northern part of the State. They are underlain by metasedimentary, metavolcanic, and plutonic rocks of Mesozoic and Paleozoic age (Denny, 1982). Relief in the White Mountains everywhere exceeds 1000 ft and in places it exceeds 3000 ft. Elevations range from about 2000 ft to more than 6000 ft. Evidence of glacial erosion can be seen on even the highest peaks, and alpine glacial features, such as cirques and tarns, are found in the central White Mountains, called the Presidential Range (Chapman, 1976). The White Mountains are separated from the New England Uplands by the Whitefield Lowlands on the west and by an area of "central lowlands", consisting of the Winnipesaukee, Ossipee, and Conway Lowlands, to the southeast. These lowlands are interrupted by two small mountain ranges, the Ossipee Mountains and the Belknap Mountains, which contain distinct evidence of volcanic activity in the form of ring dikes.

In 1990, the population of New Hampshire was 1,109,252, including 52 percent urban population (fig. 3). The population density is approximately 117 per square mile. The climate is highly variable due to its proximity to high mountains and the Atlantic Ocean. The mean annual temperature is 40 °F and the annual precipitation is 40-44 inches (fig. 4).

GEOLOGIC SETTING

The geology of New Hampshire is complex, and the names of rock formations and the way rocks are grouped have changed with time. All of the New Hampshire bedrock is igneous or metamorphic and has been divided into lithic/age groups at a level sufficient to pertain to the radon problem. Descriptions in this report are derived from the following references: Billings (1955, 1956); Lyons and others (1982, 1986); Hatcher and others (1989); and Boudette (1990). A generalized geologic map is given in figure 1. It is suggested, however, that the reader refer to the most recent state geologic map (Lyons and others, 1986) as well as other detailed geologic maps available from the New Hampshire Department of Environmental Services (1989). A new geologic map of New Hampshire compiled by the State of New Hampshire and the U.S. Geological Survey is in press at the time of this writing. The geology of New Hampshire has been divided into three geologic provinces: the Avalonian Composite Terrane, the Gander Terrane, and the Boundary Mountains Terrane (fig. 5). This terminology will be used throughout this report.

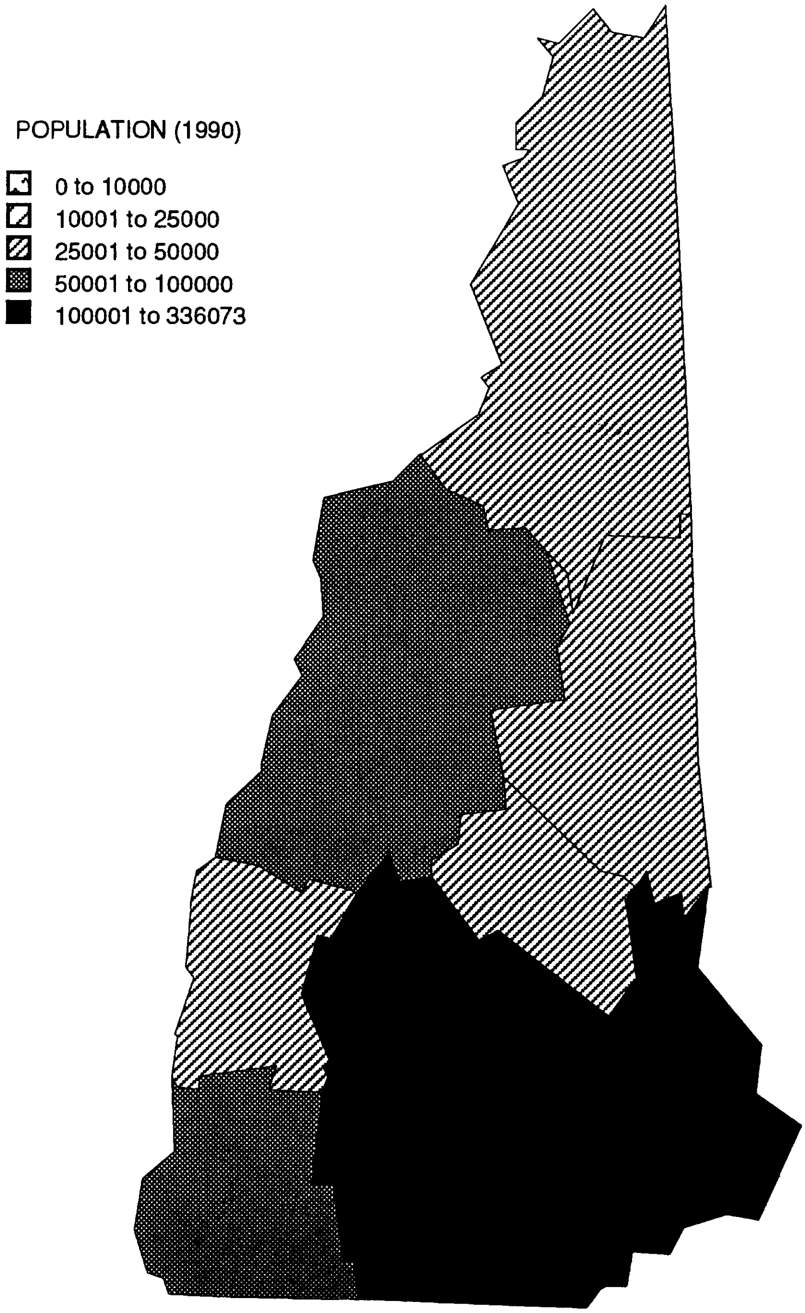

Figure 3. Population of counties in New Hampshire (1990 U.S. Census data).

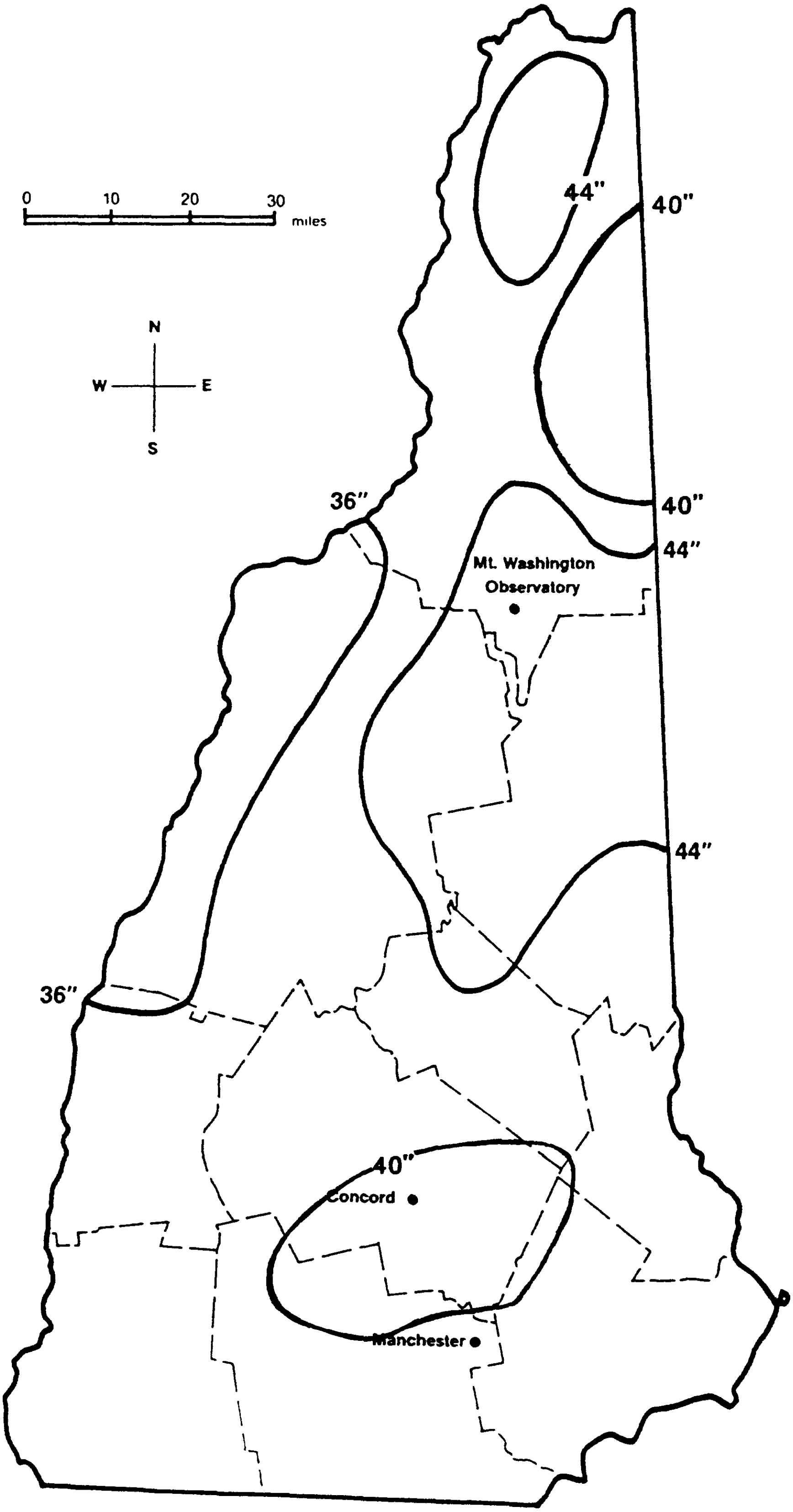

Figure 4. Average annual precipitation in New Hampshire (modified from Facts on File, 1984, and National Oceanic and Atmospheric Administration, 1974).

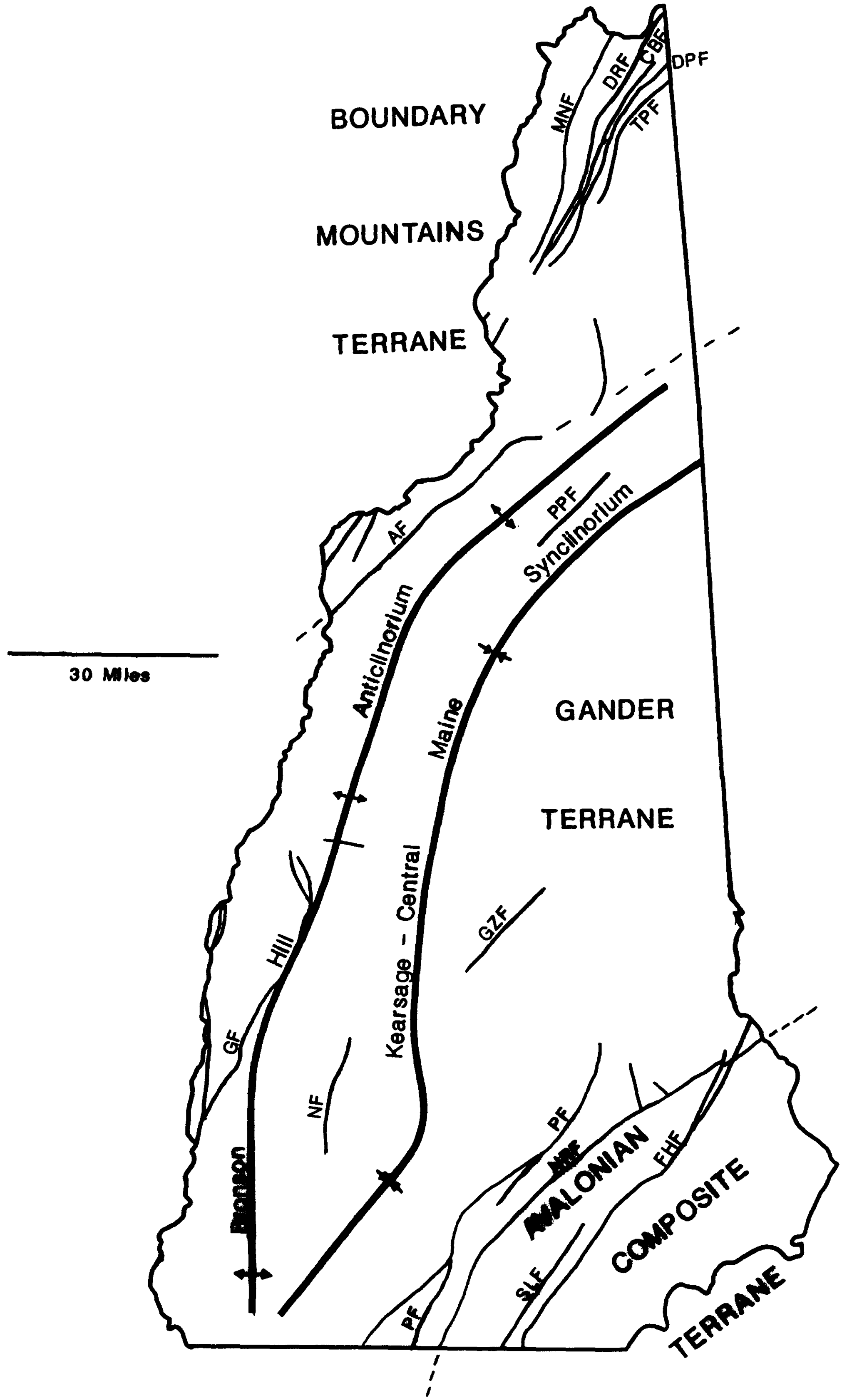

Figure 5. Tectonic map of New Hampshire (after Lyons and others, 1982, 1986). Dashed lines indicate boundaries of geologic terranes. Abbreviations for faults: AF, Ammonoosuc; CBF, Connary Brook; DPF, Deer Pond; DRF, Deadwater Ridge; FHF, Flint Hill; GF, Grantham; GZF, Gaza; MNF, Monroe; NF, Newbury; NRF, Nonesuch River; PF, Pinnacle; PPF, Pine Peak; SLF, Silver Lake; TPF, Thrasher Peaks.

Avalonian Composite Terrane

The Avalonian Composite Terrane is underlain predominantly by Late Precambrian metasedimentary and metavolcanic rocks that are intruded by younger igneous plutons of varying composition and age. These Precambrian metamorphic rocks are the oldest rocks in the State and comprise the Merrimack Group and Rye Formation. The Merrimack Group underlies most of the terrane and consists of micaceous schist, phyllite, slate, and siltstone. In places, the Merrimack Group is divided into the Kittery, Berwick, and Eliot Formations. The Rye Group, which crops out along the coast, consists of micaceous schist of sedimentary origin and amphibolite and biotite gneiss of volcanic origin. The Late Precambrian Massabesic Gneiss lies just to the northwest of the Merrimack Group between the Flint Hill Fault and Nonesuch River Fault. The Massabesic Gneiss consists predominantly of felsic metavolcanic rocks with variable amounts of amphibolite, mica schist, calc-silicate rock, and quartzite. The gneiss is migmatitic (partially melted) and cut by younger gneiss of igneous origin. The Massabesic Gneiss was formerly referred to as the Fitchburg Pluton (Billings, 1956). Two-mica granite of Devonian-Carboniferous age intrudes the Precambrian metamorphic rocks of the Avalonian Terrane, especially near the Nonesuch River Fault and in the southern portion of the terrane. A large diorite body also intrudes the metamorphic rocks in the eastern part of the terrane.

Gander Terrane

The Gander Terrane is underlain in part by Ordovician-Devonian metasedimentary and metavolcanic rocks and by abundant igneous plutons of variable composition and age that form north-trending belts or large sheet-like batholiths. The composition and character of both the metamorphic and igneous rocks changes from west to east across the terrane, as does the metamorphic grade of the rocks. In the west, along the Connecticut River, a broad band of low-grade metasedimentary and metavolcanic rocks of Ordovician-Devonian age extends the length of the terrane. On Lyons and others' (1986) map the rock units that comprise this area are the Ordovician Partridge Formation, Ammonoosuc Volcanics, and Quimby Formation; the Silurian Clough Quartzite, Greenville Cove, Rangely, Perry, Small Falls, Madrid, and Fitch Formations; and the Devonian Littleton and Gile Mountain Formations. Most of these units occur discontinuously along the Connecticut River Valley on the west side of the Bronson Hill Anticlinorium. The Littleton Formation and Ammonoosuc Volcanics are the most extensive units and are found throughout the anticlinorium on the western side. The Ammonoosuc Volcanics are predominantly mafic and felsic metavolcanic and volcaniclastic metasedimentary rocks, and the Littleton Formation consists of metapelite, metagraywacke, and metavolcanic rocks. Graphitic and sulfidic schist and slate make up much of the Partridge and Quimby Formations; however, the Quimby also contains metagraywacke. For the most part, the Silurian-age units occur in two complexly folded and faulted areas in the northern and southern parts of the anticlinorium along the Connecticut Valley. These include the laminated quartzite and metapelite of the Greenville Cove Formation; the metamorphosed clastic sediments, metavolcanic rocks, graphitic-sulfidic schists, calc-silicate rock, iron formation, and metamorphosed volcaniclastic rocks of the Rangely Formation; quartzite and metapelite of the Perry Mountain Formation; sulfidic-graphitic schist and calc-silicate rock of the Small Falls Formation; biotite-feldspar granofels, calc-silicate rock, and sulfidic schist of the of the Madrid Formation; and limestone, calcareous clastic metasedimentary rocks, and pelitic schist of the Fitch Formation. The Gile Mountain Formation is exposed in the Gander Terrane in northwestern Sullivan County and is comprised generally of graywacke, phyllite, schist, and slate of variable composition, with amphibolite or greenstone, and felsic volcaniclastic rocks.

East of the Bronson Hill Anticlinorium and throughout the rest of the Gander Terrane, Silurian-Devonian metasedimentary and metavolcanic rocks dominate the metamorphic rocks. Metamorphic grade increases from west to east. The most extensive units include the metapelite, quartzite, and metaturbidite of the Devonian Littleton Formation; the pelitic schist, metasandstone and minor calc-silicate rock of Silurian Rangely Formation; and the quartzites, metapelites, and metaturbidites of the Silurian Perry Mountain Formations. Sulfidic graphitic schist, calc-silicate rock, and biotite-feldspar granofels of the Small Falls and Madrid Formations occur to a lesser extent, especially in the tightly folded areas just west of the Kinsman Quartz Diorite Plutonic Series (described below).

Gabbroic to granitic plutons of Ordovician age, referred to as the Oliverian Plutonic Series, are emplaced as small domes throughout the Bronson Hill Anticlinorium. A very large body of Oliverian granite and syenite also underlies the northern portion of the terrane at the border between the Gander and Boundary Mountains Terranes. Many of these domes lie along the axis of the Bronson Hill Anticlinorium. On the western side of the anticlinorium is a north-northeast-trending belt of Devonian-age biotite-muscovite granodiorite, tonalite, and granite called the Bethlehem Gneiss Intrusive Suite. A parallel belt of granite, granodiorite, tonalite and quartz diorite called the Kinsman Quartz Monzonite Intrusive Suite lies to the west of the Bethlehem. The Spaulding Quartz Diorite Intrusive Suite is composed of diorite, tonalite, granodiorite, and granite, and lies south and west of the Kinsman. Jurassic and Cretaceous rocks of the White Mountain and New England-Quebec Plutonic Suites form several bodies in the eastern half of the Gander Terrane. The most prominent of these are the calc-alkaline Jurassic Conway Granite and related Jurassic Osceola Granite, granites, syenite, diorite, and moat volcanics that comprise the White Mountains. Cretaceous biotite granite and volcanic rocks also underlie the area of Ossipee and the south end of Lake Winnipesaukee. Quartz-diorite, tonalite, granodiorite, and granite of the Winnipesaukee Quartz Diorite underlie most of the area around the lake. Bodies of Devonian-Carboniferous two-mica granite occur throughout the Gander Terrane west of the Bethlehem Gneiss Intrusive Suite and in parts of the Avalonian and Boundary Mountains Terranes.

The Ordovician-Devonian igneous rocks of the northern Gander Terrane are continuous into the Boundary Mountains Terrane. The Gander Terrane is separated from the Boundary Mountain Terrane by an indistinct boundary, marked in part by the Ammonoosuc Fault.

Boundary Mountains Terrane

The Boundary Mountains Terrane of New Hampshire comprises folded and faulted, north-trending belts of Cambrian-Devonian metasedimentary and metavolcanic rocks in the northern half of the terrane, which are complexly deformed and intruded by igneous plutons in the southern half of the terrane. The Gile Mountain, Frontenac, Perry Mountain, Littleton, and Dead River Formations are the major belts of rock from west to east. The Rangely, Dixville, Ammonoosuc, Fitch, Clough, and Waits River Formations underlie smaller areas in the southern half of the terrane. The Waits River Formation crops out in the southern portion of the belt of Gile Mountain Formation. The Waits River consists of calcareous schist and granofels, with interbedded metapelite and metagraywacke and minor mafic metavolcanic rocks. The eastern portion of the Gile Mountain Formation is composed of the Meetinghouse Slate Member, consisting of gray slate, phyllite, and graywacke and bounded on the east by the Monroe Fault. The Silurian-Ordovician Frontenac Formation lies east of the Monroe fault and comprises feldspathic sandstone, gray slate, phyllite, and quartz-mica schist with layers of greenstone, green slate, and felsic metavolcanic rocks. The main body of greenstone in the Frontenac is fault-bounded by the Deadwater Ridge fault to the west and the Connary Brook fault to the east. Felsic and minor mafic metavolcanic rocks of the Perry Formation and chlorite schist, amphibolite, and minor felsic metavolcanic rocks and sulfidic phyllites of the Rangeley Formation lie to the east of the Connary Brook fault. These rocks are bounded to the east by the Deer Pond fault and the Devonian Littleton Formation. The Thrasher Peaks fault bounds the northeastern edge of the Littleton and separates it from the Dead River Formation to the east. Part of the southern portion of the belt of Littleton Formation is bounded on the east by the Ordovician, rusty-weathering sulfidic to graphitic schist and quartzite of the Dixville Formation. The Cambrian-early Ordovician Dead River Formation consists of thinly laminated metapelite and quartzite described as "pin-striped." The belts of rock just described extend southward to just below the Mohawk River in the southern portion of the terrane. South of the main body of Dead River Formation is an area underlain by the Ammonoosuc Volcanics. The Dead River, Rangely, Gile Mountain, Dixville, and Waits River Formations also underlie small areas in the central and southern portions of this terrane. The southwestern extension of the terrane in northern Grafton County is underlain by the Rangely and Littleton Formations, the Ammonoosuc Volcanics, the Clough Quartzite, and the Fitch Formation. Devonian two-mica granite, Jurassic alkalic and calc-alkalic granites, and Ordovician gabbro to diorite intrude the metasedimentary and metavolcanic rocks in the southern and eastern portions of the terrane.

GLACIAL GEOLOGY

Stratigraphic evidence from New England and the Gulf of Maine indicates that there were at least four, and as many as six, glacial advances in this region during the Pleistocene epoch. Two Wisconsinan (Late Pleistocene) till units have been identified in New Hampshire from surface and subsurface data (Stone and Borns, 1986). The "lower till" is probably early Wisconsinan in age, it is typically relatively fine grained (silt loam to silty clay loam) and compact, and it has a weathered zone or paleosol at the top (Stone and Borns, 1986). In some areas, the "lower till" may consist of more than one till unit, representing deposits of more than one glacial advance. In Northern New Hampshire, the Nash Stream Till (Koteff and Pessl, 1985) correlates with the "lower till" in most of New England (Stone and Borns, 1986). The "upper till" is late middle Wisconsinan to late Wisconsinan and it is a single surface till with a dominantly silty to sandy matrix. Variations in dominant grain size, color, and stoniness of the tills are closely related to bedrock lithology (Stone and Borns, 1986). Glaciers moved in a generally north-south or northwest-southeast direction across New Hampshire, terminating on Long Island, New York; Martha's Vineyard, Massachusetts; and George's Bank, off Cape Cod, at their maximum extent (Stone and Borns, 1986). Glacial lakes occupied several valleys during the interstades and following the final retreat of glaciers from New Hampshire, which occurred about 12,500 years ago (Stone and Borns, 1986). Glacial Lake Hitchcock occupied the Connecticut Valley from about 16,000 to 13,500 years ago, and marine sand, silt, and clay was deposited in the coastal zone of southeastern New Hampshire when sea level rose due to melting of glacial ice. The sea occupied the area from about 13,800 years BP to about 11,500 years BP, when post-glacial rebound caused the land surface to re-emerge above sea level (Stone and Borns, 1986).

Till is the most common and widespread type of glacial deposit in New Hampshire (fig. 6). It is an unsorted deposit of gravel, sand, silt, and clay, with some cobbles and boulders.

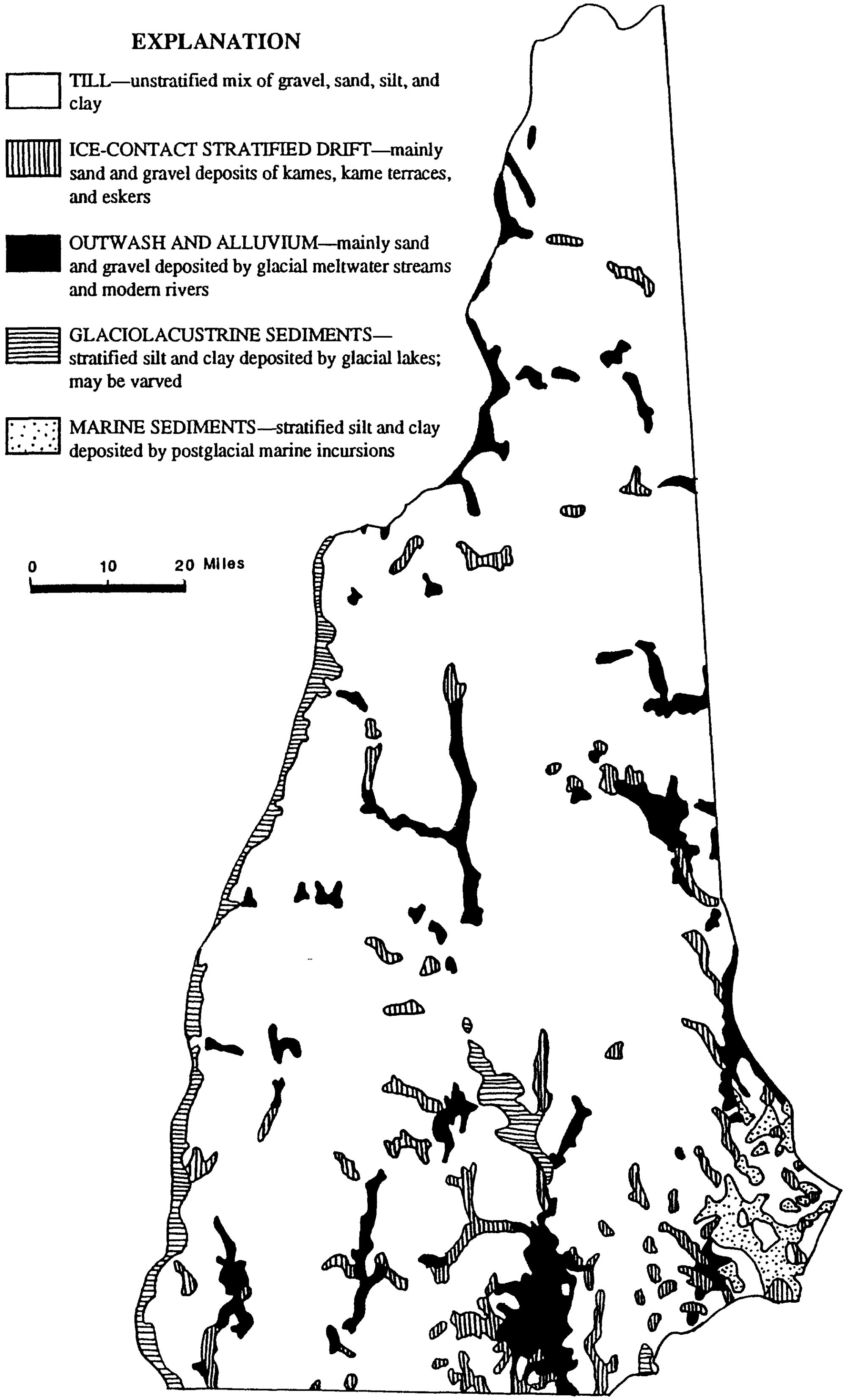

Figure 6. Generalized glacial map of New Hampshire (modified from Flint and others, 1959).

Thickness of the till ranges from a thin, discontinuous veneer of less than one meter to locally more than 100 m, but it is generally in the range of 4-6 m thick (Goldthwait and others, 1951). There are two distinctly different types of till in New Hampshire. One is a dense, compact till containing rounded, striated boulders and a relatively high amount of erratics (cobbles and boulders from distant bedrock sources), called basal till. Although its compactness suggests a relatively high clay content, the clay content of basal till is generally less than 30 percent; however, basal till contains more clay than ablation till and it usually contains a significant amount of silt, which together with the clay is responsible for the compactness of the basal till. The other type of till is a loosely packed, very sandy till containing angular boulders of local bedrock and little or no clay. This type of till is called ablation till. Ablation till overlies either basal till or bedrock. These two types of till are found throughout most of New England and are more commonly referred to simply as the "upper till" and "lower till" (Goldthwait and others, 1951; Stone and Borns, 1986; Richmond and Fullerton, 1987, 1991, 1992). The two types of till are not differentiated on the surficial geologic map of New Hampshire (Goldthwait and others, 1950), of which figure 6 is a generalized version. Glacial landforms typically associated with till include drumlins, kettles, and moraines. Moraines, accumulations of till deposited at the margins of retreating ice, are not common features in New Hampshire, due in large part to the State's rugged topography. Drumlins, however, are very common in the southern part of the State (Goldthwait and others, 1951).

Glaciofluvial deposits are stratified sediments deposited by glacial meltwater adjacent to or in front of the ice margin. These ice-marginal or ice-contact deposits include kames, kame terraces, kame moraines, eskers, and outwash deposits. Except for outwash, all of these features exhibit sedimentary structures indicative of slumping that occurred when the ice against which they were deposited melted away. Characteristic of all types of glaciofluvial deposits is their coarse texture, being composed primarily of sand and gravel. Kame terraces formed between the edge of a glacier and a valley wall. Kame moraines are deposits of gravel that formed in front of the glacier and they have topography similar to that of a till moraine. Like moraines composed of finer-grained till, kame moraines mark the position of a former glacial border. Eskers are sinuous ridges composed of outwash sand and gravel deposited by rivers that flowed in tunnels underneath an ice sheet or valley glacier. Eskers in New Hampshire range from highly discontinuous to long, sinuous ridges that can be traced for many kilometers, such as the esker chain that stretches 23 km from Lyme to West Lebanon (Goldthwait and others, 1951). Kames, terraces, and eskers constitute a significant source of sand and gravel. Outwash sand and gravel was deposited in some valleys by rivers that drained the melting glaciers. In New Hampshire the outwash commonly covers the floors of valleys in a broad, flat sheet called an outwash plain. One such outwash plain north of Dover measures 14 km long by 3 km wide. Outwash deposits east of Concord are more than 20 m thick (Goldthwait and others, 1951). Sand plains are most common in southeastern New Hampshire, where they occur with kames and kame terraces in parallel, northwest-trending belts several km apart (Goldthwait and others, 1951).

Lacustrine (lake) and marine sediments are layered silts and clays deposited by large postglacial lakes and in marine (ocean) environments, respectively. Because the valleys and lowlands were the sites of final melting of stagnant ice masses, drainage was blocked and many small lakes developed. Glacial lakes occupied the Connecticut, Merrimack, and Ashuelot valleys (Goldthwait and others, 1951). Lake bottom sediments are composed of silt and clay; shallow-water sediments are composed primarily of sand, and beach and delta deposits contain primarily sand and gravel. Marine sediments have characteristics similar to lacustrine sediments, in that they also are classified into fine-grained bottom deposits, sandy shallow-water deposits, and sand and gravel beach and deltaic deposits. Marine sediments were deposited in the coastal lowland of southeastern New Hampshire when sea level rose due to glacial melting. Marine sediments are distinguished from lake deposits by the presence of fossil shells and by the absence of varves (alternating layers of finer and coarser sediment or lighter and darker-colored sediment related to storms or seasonal deposition in lakes).

SOILS

Soils in New Hampshire include Inceptisols, mineral soils with weakly expressed horizons of alteration or accumulation of metal oxides such as iron, aluminum, or manganese; Spodosols, mineral soils with subsurface accumulations of organic matter and compounds of aluminum and iron that have been leached from the surface and transported downward through the soil; Entisols, mineral soils with no discernible horizons because their parent material is inert (such as quartz sand) or because the soils are very young; and Histosols, wet, organic-rich soils (peat and muck) in swamp and marsh environments (U.S. Soil Conservation Service, 1987). Figure 7 is a generalized soil map of New Hampshire. The following discussion is condensed from Pilgrim and Peterson (1979). This report and other State- and county-scale soil survey reports should be consulted for more detailed descriptions and information.

Soils in Valleys and Lowlands

Soils of the valleys (fig. 7) are characterized by nearly level floodplains of river valleys in New Hampshire. The soils are deep, well drained to excessively drained, silty, sandy, and gravelly soils formed on floodplains and alluvial terraces. These soils are moderately to highly permeable and the water table is more than three feet, and usually more than five feet, below the ground surface. Soils on coastal lowlands are restricted to the southeastern part of the State (fig. 7). The soils are deep, poorly drained to excessively drained, clays and clayey and silty loams. About 10 percent of this map unit is formed on sand and gravel. The soils have low to moderate permeability except where they are formed on gravelly terraces or delta deposits, which have high permeability. Many of the soils in this map unit are wet for extended periods. Areas underlain by tidal marsh soils include Seabrook, Hampton, North Hampton, and part of Rye (Pilgrim and Peterson, 1979), along the coastline in southeastern New Hampshire (fig. 7). The map area also includes some beaches and sand dunes. Tidal marsh soils are mostly deep and very poorly drained. They are subject to inundation by tidal waters twice daily. The surface two or three feet of these soils is organic matter (peat and muck), typically underlain by sand, silt, or clay. In some areas, the organic materials overlie bedrock. These soils have moderate to high permeability to water but their gas permeability is low due to constant wet conditions.

Soils on Hills and Uplands

Soils on hills and low mountains in southeastern and south-central New Hampshire are deep, moderately well drained to excessively drained, clayey, silty, and sandy loams with compact substrata. Gas and water movement through the soil is restricted by the hardpan layer, giving these soils generally low to locally moderate permeability. Soils on hills and low mountains in central and southwestern New Hampshire are deep, moderately well to well drained, loams, sandy loams, and gravelly loams with a distinct hardpan layer about two feet below the ground surface. Air and water movement through the soil is restricted by the hardpan layer, giving these soils low

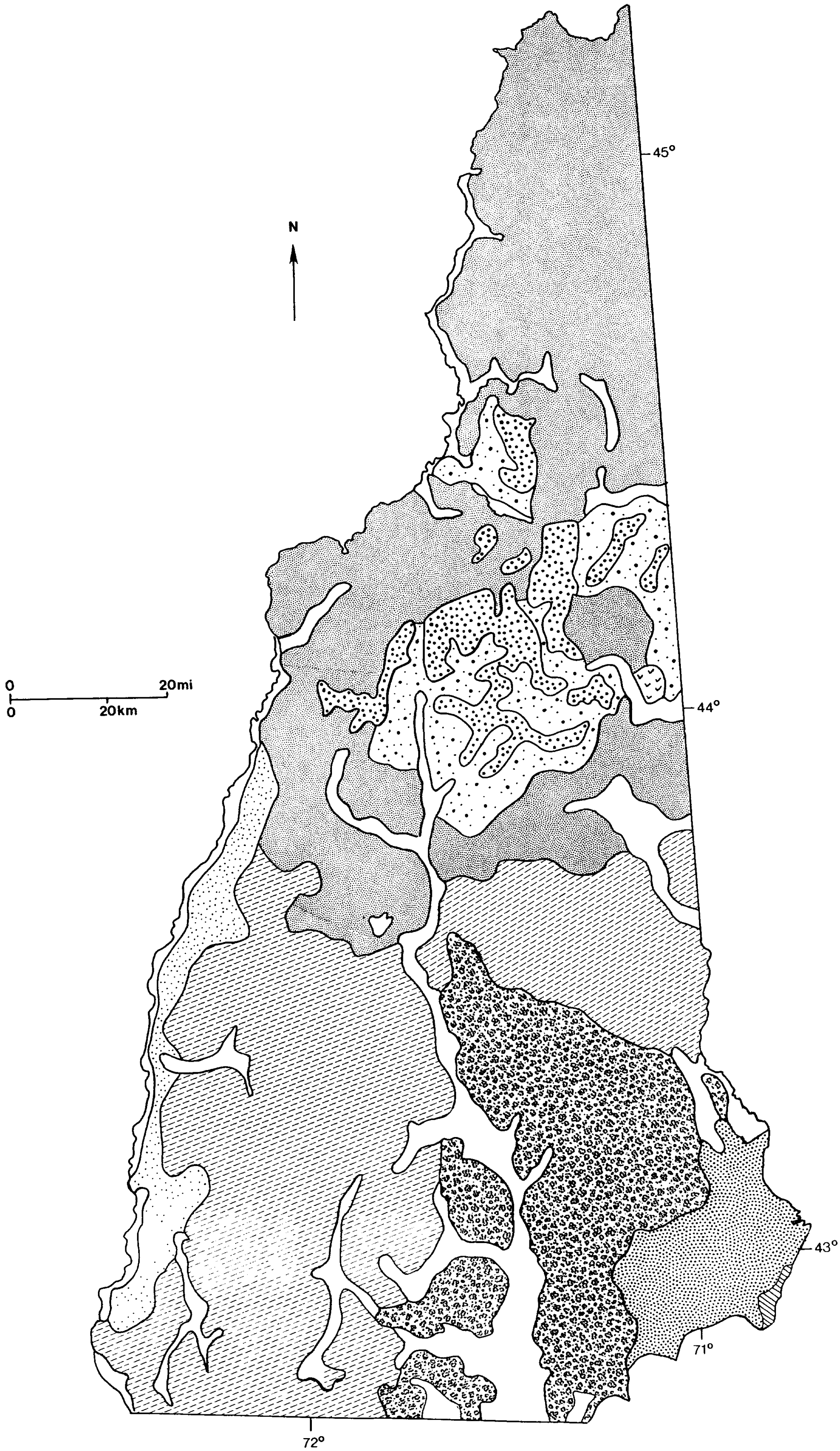

Figure 7. Generalized soil map of New Hampshire (after Pilgrim and Peterson, 1979).

GENERALIZED SOIL MAP OF NEW HAMPSHIRE
LEGEND

SOILS OF VALLEYS (Spodosols, Entisols, and Inceptisols)— deep, well and excessively drained, silty, sandy, and gravelly soils; *moderate to high permeability*

SOILS ON COASTAL LOWLANDS (Inceptisols)— deep, poorly to excessively drained, clays, clay loams, and silty loams; *low to moderate permeability*; about 10% of map unit is gravelly soils of terraces with high permeability

SOILS ON HILLS AND LOW MOUNTAINS IN SOUTHEASTERN AND SOUTH-CENTRAL NEW HAMPSHIRE (Inceptisols)— deep, moderately to excessively drained, clayey, silty, and sandy loams with compact substrata; *low permeability*

SOILS ON HILLS AND LOW MOUNTAINS IN CENTRAL AND SOUTHWESTERN NEW HAMPSHIRE (Spodosols)— deep, moderately well to well drained, loams, sandy loams, and gravelly loams with a subsurface hardpan layer; *low to locally moderate permeability*

SOILS ON HILLY UPLANDS BORDERING THE CONNECTICUT RIVER VALLEY (Inceptisols)— shallow to deep, well drained, loams, silt loams, and silts formed on tills; *low to moderate permeability*

SOILS ON HILLS AND LOW MOUNTAINS IN NORTHERN NEW HAMPSHIRE (Spodosols)— shallow to deep, moderately well to well drained, silty and sandy loams with a hardpan substrata; *low permeability, locally moderate to high permeability where soils are sandy*

SOILS OF THE WHITE MOUNTAINS AND ASSOCIATED FOOTHILLS (Spodosols)— shallow to deep, well drained, loams; *mostly moderate permeability, soils with compact substrata have low permeability*

SOILS DEVELOPED ON CONWAY GRANITE (Spodosols)— shallow to deep, well drained, sandy and gravelly loams; *high permeability*

SOILS ON ALPINE AND SUBALPINE AREAS OF THE WHITE MOUNTAINS (Spodosols)— moderately deep to deep, silty and sandy soils; *moderate to locally high permeability*

SOILS OF TIDAL MARSHES (Histosols)— deep, poorly drained, organic soils; *moderate to high permeability*, typically wet to locally moderate permeability. Some soils of this map unit have perched water tables of short duration during the wet season. Soils on hilly uplands bordering the Connecticut River Valley occur from Chesterfield in Cheshire County north to Piermont in Grafton County (fig. 7). These soils are shallow to deep, well drained, loams, silt loams, and silts formed on compact till and silty till. Soils formed on compact till have low permeability and those formed on silty till have moderate permeability. Soils on hills and low mountains in northern New Hampshire are shallow to deep, moderately well drained to somewhat excessively drained, silty and sandy loams. Soils of this map unit formed on compact tills have low permeability due to the hardpan layer about two feet below the ground surface. The fabric of the hardpan typically consists of alternating layers of compact sand and loam. Soils with hardpans commonly have perched water tables for short duration during the wet season. Soils of this map unit formed on sandy tills have moderate to high permeability.

Soils of the White Mountains and associated foothills are shallow to deep, well drained, loamy soils. About 20 percent of the soils in this map unit have a compact substratum and, consequently, low permeability. The remainder of the soils in this map unit have moderate permeability. Soils formed on the Conway Granite in and around the town of Conway are shallow to deep, well drained, sandy and gravelly loams with high permeability. Soils on alpine and subalpine areas of the White Mountains occupy areas with elevations greater than 2500 feet. These soils are moderately deep to deep, silty and sandy soils formed in bedrock and glacial till. They have well-developed organic surface horizons and subsurface accumulations of aluminum, iron, and organic matter. Although not discussed by Pilgrim and Peterson (1979), these soils probably have moderate to locally high permeability.

RADIOACTIVITY

An aeroradiometric map of New Hampshire (fig. 8) compiled from the National Uranium Resource Evaluation (NURE) flightline data (Duval and others, 1989) shows several areas of high equivalent uranium (eU) in the State, most of which are associated with uranium-bearing igneous plutons. Low eU (<1.5 ppm) is associated with the clastic metasedimentary, mafic metavolcanic, and mafic plutonic rocks. Moderate eU (1.5-2.5 ppm) is associated with the Precambrian stratified metamorphic rocks in the Avalonian Composite Terrane and the high grade metamorphic rocks in the central and eastern Gander Terrane. Most of the high radioactivity in New Hampshire is related to Jurassic-Cretaceous biotite granites of the White Mountain plutonic series, Devonian-Carboniferous two-mica granites of the New Hampshire plutonic series, some of the Olivarian domes in eastern New Hampshire, and the Massabesic Gneiss.

Radioactivity and uranium in New Hampshire has been actively studied since the early 1950s. One of the earliest reports containing uranium analyses on the uranium-bearing igneous rocks of the State was by Lyons (1964). Other uranium literature for New Hampshire which concentrates on the uranium content of the igneous rocks includes Butler (1975), Boudette (1977), and Hoisington (1977). Lyons (1964) reported uranium concentrations of 2.6-5.0 ppm for the calc-alkaline Highlandcroft rocks, 0.6-15.9 ppm for the Oliverian Plutonic Series, and 1.5-39 ppm for the New Hampshire Plutonic Series. In the Oliverian Plutonic Series, Lyons (1964) notes an increase in uranium abundance with felsic content. He also notes that pegmatites of the different plutonic series often had the highest uranium contents. This may account for the apparent lower radioactivity of the large body of Oliverian granite and syenite in the northern Gander Terrane. Lyons reports an average of 3.3 ppm of uranium for the Kinsman Quartz monazite and an average

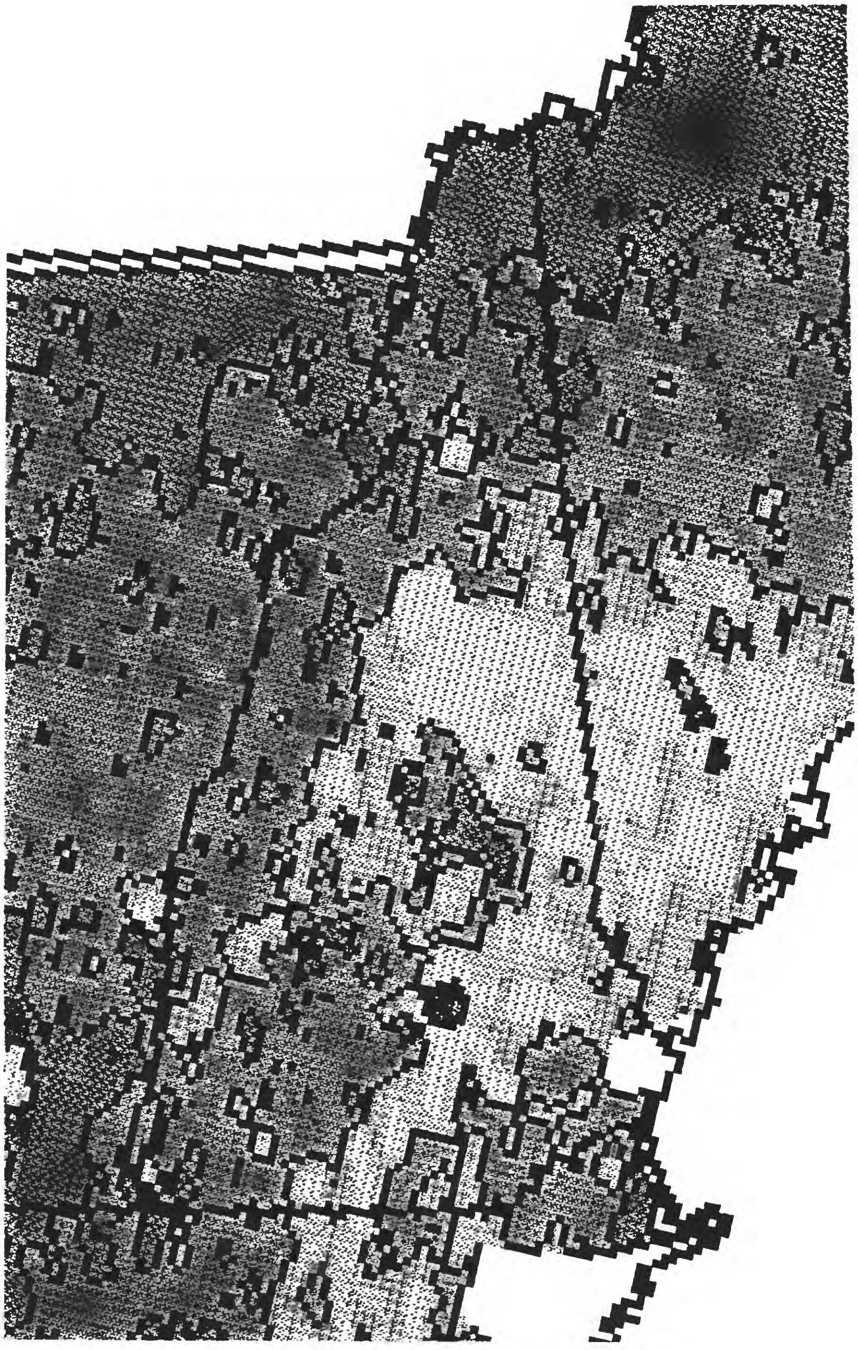

Figure 8. Aerial radiometric map of New Hampshire (after Duval and others, 1989). Contour lines at 1.5 and 2.5 ppm equivalent uranium (eU). Pixels shaded at 0.5 ppm eU increments; darker pixels have lower eU values; white indicates no data.

of 3.4 ppm for the Bethlehem Gneiss. He also noted that much of the uranium in these rocks was concentrated on grain boundaries and in interstitial spaces, not necessarily within accessory minerals. Wathen (1987) also found that uranium in two-mica granite was found as grain coatings.

As part of the NURE program, Chiasma Consultants, Inc. (1982) analyzed a number of rock types in New Hampshire. The alkalic, biotite-rich Conway Granite had the highest concentrations of uranium, with typical concentrations of 4-31 ppm U_3O_8. They also indicated that concentrations average between 20-40 ppm U_3O_8 in red granite and aplitic dikes. Jaupart and others (1982) report average uranium concentrations of 12.6-15.9 ppm in the White Mountain granites, based upon more than 1000 gamma-ray spectrometer measurements in New Hampshire. The more amphibole-rich Mount Osceola Granite of this series has consistently lower values of U_3O_8 (less than 19 ppm U_3O_8 reported by Chiasma Consultants, Inc, 1982) and Bothner (1978) reports lower surface radiation values (1.6 times background versus 2-5 times background for the Conway Granite). The two-mica granites of the New Hampshire series have eU of 2.5 to greater than 5.5 ppm on the aeroradiometric map (fig. 8). These also have elevated uranium concentrations—for example, Chiasma Consultants, Inc. (1982) reported a range of 10-800 ppm U_3O_8, Bothner (1978) reported an average of 15 ppm U, and Jaupart and others (1982) reported an average of 7.6 ppm, based on 145 gamma-ray spectrometer measurements. Two-mica granites that have exceptionally high uranium concentrations occur northeast of Lake Winnipesaukee, on the eastern margin of the White Mountains, and north of Sunapee Lake. Additional occurrences of high uranium concentrations in two-mica granites include the areas around Concord and Rochester, north of Newfound Lake, north of the White Mountains, southeastern Cheshire County, and central Coos County. The Bethlehem Gneiss Intrusive Suite (granitic gneiss) in western New Hampshire defines a northeast-trending radiometric high with eU of 2.5 to less than 4.5 ppm (fig. 8). Lyons (1964) indicates an average uranium concentration of 3.4 ppm based on 28 measurements. The Kinsman tonalite and quartz monzonite, which forms a parallel belt east of the Bethlehem gneiss, defines an area of moderate eU values (2-2.5 ppm) on the aeroradiometric map, except where it is adjacent to White Mountain series intrusives which have values of 3.0-4.5 ppm. The Winnipesaukee quartz diorite in the vicinity of Lake Winnipesaukee and in southeastern Cheshire County has distinctly low radioactivity on the aeroradiometric map (1.0-2.5 ppm), and Jaupart and others (1982) report U concentrations of 0.5-1.9 ppm. Diorite and granodiorite of the Exeter pluton west of Portsmouth have moderate to high radioactivity on the aeroradiometric map (2.0 to greater than 3.5 ppm) and have an average uranium concentration of 2.8 ppm (Roy and others, 1968).

The Precambrian Massabesic gneiss is a migmatitic biotite gneiss or quartz monzonite that forms a northeast-trending belt in southeastern New Hampshire with eU values of 2.5 to 4.5 ppm on the aeroradiometric map. Jaupart and others (1982) reported uranium concentrations in the Massabesic of 0.7-6.7 ppm. Ordovician granite and quartz monzonite of the Oliverian plutonic series produce moderate to high aeroradiometric patterns (less than 2.5 to greater than 3 ppm eU) along the western border of New Hampshire and in a northeast-trending belt, mostly in southern Coos County. Bendix Field Engineering (1982) reports U_3O_8 values of 5-10 ppm and Jaupart and others (1982) provide one analysis of 1.9 ppm U.

Most of the metasedimentary and metavolcanic rocks exhibit low to moderate eU (0-2.5 ppm) on the aeroradiometric map and some units have moderate to high eU where they are in contact with the Conway granite or New Hampshire Series two-mica granites. The higher concentrations are in part due to pegmatite dikes of granite incorporated into the surrounding rocks and in part due to higher metamorphic grades of the surrounding rocks. The Ordovician-Devonian stratified metamorphic rocks have eU values greater than 2 ppm adjacent to the White Mountain batholith. Other areas of the metamorphic rocks are mostly between 1 and 2 ppm eU. The highest values are associated with the sillimanite-grade metamorphism. A similar relationship is indicated by Jaupart and others (1982), who reported uranium concentrations in the range of 0.8 to 16.9 ppm, with the highest values associated with rocks in proximity to uranium-rich granites. Jaupart and others (1982) indicate U concentrations of 1.0-3.1 ppm for schist in the Bronson Hill Anticlinorium, 1.8-3.6 ppm for the Berwick, and a single measurement of 2.6 ppm for the Rye. The Ordovician Ammonoosuc Volcanics also have consistently moderate to high eU on the aeroradioactivity map (less than 2 to less than 3). Jaupart and others (1982) report a single measurement of 4.4 ppm U in a sample adjacent to an Oliverian granite.

It is difficult to associate specific geologic units with uniformly low eU values (0-1.5 ppm). In the Merrimack Group, the amphibolite-rich metavolcanics of the Rye Formation and the Kittery Quartzite both appear to have low eU. Along the western edge of the State, Ordovician chloritic schistose quartzite is associated with low equivalent uranium. Jaupart and others (1982) report a single measurement of 0.4 ppm U from Ordovician schistose quartzite. The Ordovician Gile Mountain and Waits River Formations in the northern part of the State have low eU, although Jaupert and others (1982) report a single uranium measurement of 1.9 ppm in the Gile Mountain from that area. Cambro-Ordovician gabbros and serpentinites with low radioactivity underlie small areas around White Mountain intrusives in the central part of the State.

INDOOR RADON

The New Hampshire Division of Public Health Services initiated a survey of randomly-selected homes throughout the State to assess the extent of the indoor radon problem in New Hampshire. Testing began in February 1988 and continued through 1990. The majority of townships with high indoor radon are underlain by uranium-bearing granites, particularly in the northern and western portions of the State.

Indoor radon data from 1810 homes sampled in the Department of Public Health Services/Governor's Energy Office survey conducted in New Hampshire during the winter heating seasons from 1988-1990 are shown by township in figure 9 and in Table 1. A map of counties is included for reference (fig. 10). The data represent short-term (2-7 day) charcoal canister tests. The maximum value recorded in the survey was 478.9 pCi/L. Townships with indoor radon averages exceeding 4 pCi/L are clustered in central and eastern Hillsborough County; most of Rockingham and Strafford Counties, particularly in the upland parts of these counties, and in the southern Coastal Lowland; eastern Carroll County; southern Coos County; western and central Grafton County; and locally in other areas of the State.

Radon contributed from domestic well water may also constitute a significant indoor air radon problem in New Hampshire. Several studies indicate that degassing of radon from water can cause spikes in indoor air concentrations, especially during peak water-use periods (Hess and others, 1986; Nazaroff and Nero, 1988). Several studies of radon in ground water and geology for New Hampshire were compiled by Paulsen (1991) and are shown in Table 2. These studies found that the distribution of radon in ground water is primarily controlled by bedrock geology. The distribution of uranium within the rock is also an important control (Wathen, 1987). On the average, the felsic igneous plutonic rocks are sources of the highest radon in ground waters. Two-mica granites are especially good radon sources because the uranium in them is in relatively high

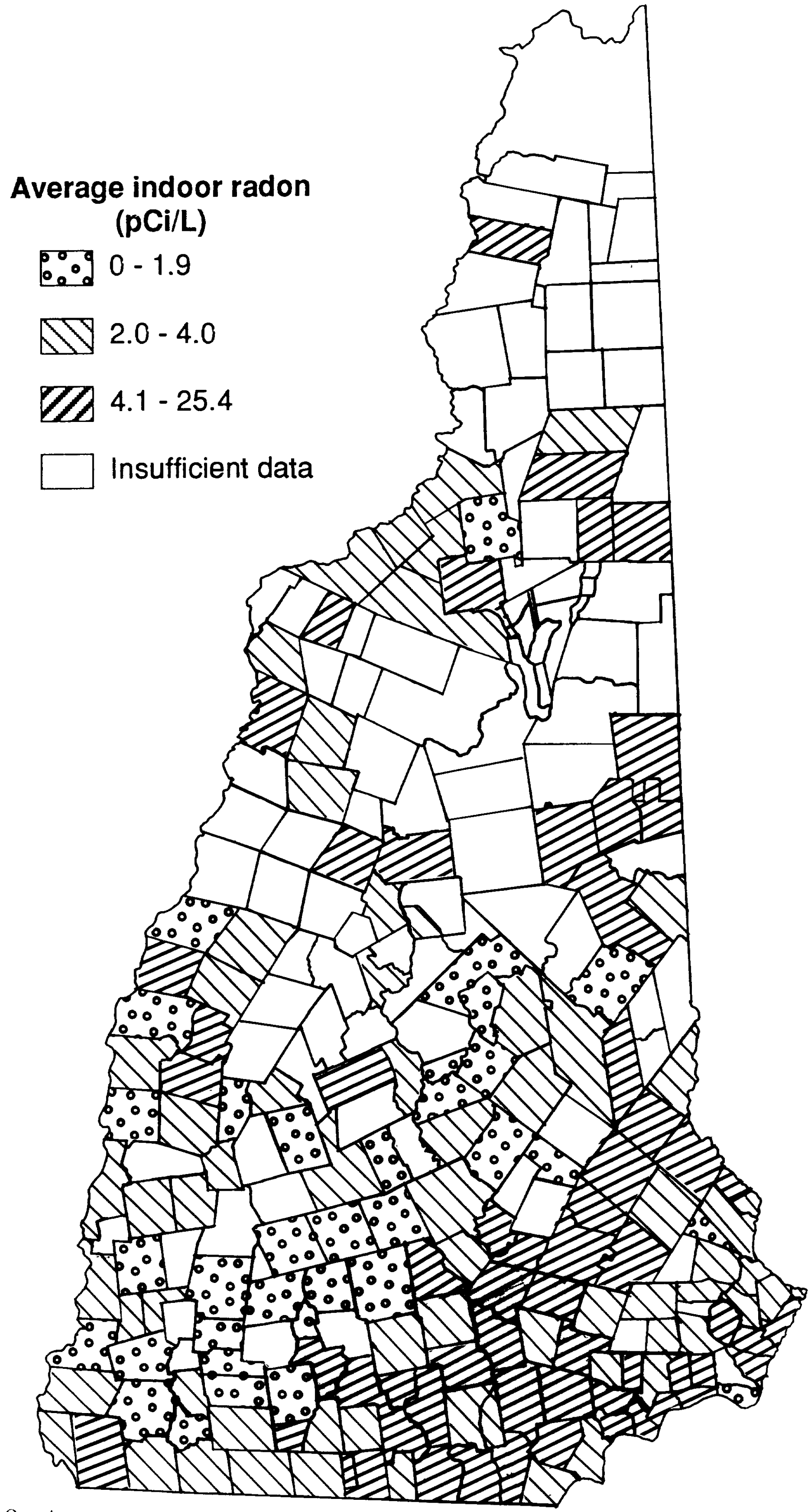

Figure 9. Average indoor radon concentrations, by town, from the New Hampshire Radon Survey (data from Pirie and Hannington, 1989, and 1990 addendum).

Table 1. New Hampshire 1987-1990 Winter Indoor Radon Survey data by Town. Data are from short-term charcoal canister measurements.

Town	No. of Meas.	Mean	Town	No. of Meas.	Mean
Acworth	6	2.2	Conway	8	9.6
Albany	2	7.7	Cornish	6	2.0
Alexandria	4	1.6	Croydon	5	5.2
Allenstown	8	6.7	Dalton	5	3.1
Alstead	5	1.8	Danbury	2	6.8
Alton	5	2.2	Danville	5	11.4
Amherst	16	8.6	Deerfield	16	4.4
Andover	7	4.5	Deering	7	1.2
Antrim	7	0.7	Derry	21	4.9
Ashland	7	3.4	Dixville	2	1.8
Atkinson	15	8.6	Dorchester	4	2.0
Auburn	14	3.9	Dover	10	3.0
Barnstead	3	4.7	Dublin	5	1.2
Barrington	11	3.1	Dummer	3	3.5
Bartlett	3	7.7	Dunbarton	8	9.7
Bath	7	2.5	Durham	11	2.8
Bedford	19	7.6	East Kingston	6	5.4
Bennington	6	0.8	Easton	4	2.4
Benton	5	3.0	Eaton	5	25.4
Berlin	26	5.4	Effingham	5	3.8
Bethlehem	6	3.8	Ellsworth	1	1.8
Boscawen	2	0.8	Enfield	5	2.6
Bow	17	3.6	Epping	11	3.6
Bradford	2	7.7	Epsom	4	3.0
Brentwood	6	3.1	Errol	3	4.5
Bridgewater	4	2.8	Exeter	8	2.4
Bristol	6	2.4	Farmington	6	4.4
Brookfield	4	3.2	Fitzwilliam	6	2.3
Brookline	6	3.5	Francestown	3	1.3
Campton	5	5.9	Franconia	3	3.0
Canaan	8	2.1	Franklin	14	2.6
Candia	13	4.9	Freedom	3	33.4
Canterbury	6	2.4	Fremont	4	11.1
Carroll	5	7.4	Gilford	10	3.7
Center Harbor	2	0.9	Gilmanton	7	2.1
Charlestown	7	2.2	Gilsum	6	3.0
Chatham	2	6.8	Goffstown	14	3.2
Chester	10	4.5	Gorham	15	14.7
Chesterfield	6	3.3	Goshen	6	2.0
Chichester	2	3.0	Grantham	5	4.5
Claremont	8	1.7	Greenfield	6	7.4
Clarksville	2	35.5	Greenland	7	3.0
Colebrook	8	5.6	Greenville	6	4.1
Columbia	4	19.9	Groton	3	1.1
Concord	21	2.5	Hampstead	17	5.0

Table 1 (continued).

Town	No. of Meas.	Mean	Town	No. of Meas.	Mean
Hampton	7	8.9	Merrimack	28	3.1
Hampton Falls	4	4.8	Middleton	4	4.3
Hancock	4	0.8	Milan	5	3.7
Hanover	13	1.4	Milford	10	4.9
Harrisville	5	1.3	Milton	6	3.0
Hart's Location	2	266.6	Monroe	4	1.3
Haverhill	17	4.3	Mont Vernon	6	3.9
Hebron	4	2.0	Moultonboro	3	0.8
Henniker	9	1.6	Nashua	37	7.0
Hill	4	2.1	Nelson	6	1.1
Hillsboro	13	0.8	New Boston	6	3.8
Hinsdale	11	2.0	New Castle	6	3.7
Holderness	4	2.2	New Durham	7	13.3
Hollis	21	7.3	New Hampton	2	3.4
Hooksett	14	6.9	New Ipswich	9	3.0
Hopkinton	5	0.9	New London	7	2.8
Hudson	18	5.5	Newbury	4	5.6
Jackson	3	11.8	Newington	5	2.6
Jaffrey	14	2.6	Newmarket	5	4.0
Jefferson	5	1.8	Newport	5	3.0
Keene	23	1.7	Newton	10	7.0
Kensington	5	5.8	North Hampton	13	6.4
Kingston	12	3.9	Northfield	8	1.1
Laconia	12	1.8	Northumberland	3	14.1
Lancaster	13	2.9	Northwood	10	4.4
Landaff	2	1.0	Nottingham	8	4.1
Lebanon	27	4.5	Orange	4	2.6
Lee	3	7.5	Orford	1	1.3
Lempster	5	2.7	Ossipee	7	7.5
Lincoln	1	1.3	Pelham	15	3.9
Lisbon	5	5.3	Pembroke	9	4.1
Litchfield	18	2.6	Peterborough	12	1.2
Littleton	13	2.2	Piermont	3	1.3
Londonderry	15	7.8	Pittsburg	3	2.0
Loudon	5	1.4	Pittsfield	5	0.8
Lyman	4	5.8	Plainsfield	7	0.9
Lyme	3	2.5	Plaistow	10	4.1
Lyndeborough	8	4.8	Plymouth	15	3.9
Madbury	5	1.9	Portsmouth	36	3.5
Madison	5	17.3	Randolph	4	7.1
Manchester	38	5.1	Raymond	8	3.4
Marlborough	7	2.7	Richmond	6	2.4
Marlow	2	2.5	Rindge	7	2.8
Mason	6	4.5	Rochester	42	4.9
Meredith	12	1.7	Rollinsford	8	2.8

Table 1 (continued).

Town	No. of Meas.	Mean	Town	No. of Meas.	Mean
Roxbury	2	1.6	Winchester	5	19.2
Rumney	7	6.8	Windham	16	4.2
Rye	13	7.0	Windsor	1	0.4
Salem	19	2.6	Wolfeboro	9	1.2
Salisbury	4	1.0	Woodstock	4	15.2
Sanbornton	4	0.8			
Sandown	7	2.5			
Sandwich	2	3.8			
Seabrook	7	1.9			
Sharon	7	6.3			
Shelburne	7	17.6			
Somersworth	8	4.5			
South Hampton	5	6.1			
Springfield	4	1.5			
Stark	4	17.1			
Stewartstown	3	2.9			
Stoddard	5	0.7			
Strafford	7	20.3			
Stratford	4	54.2			
Stratham	10	6.2			
Sugar Hill	4	1.3			
Sullivan	3	1.4			
Sunapee	5	1.5			
Surry	7	2.8			
Sutton	5	1.0			
Swanzey	11	0.9			
Tamworth	10	9.9			
Temple	7	2.9			
Thornton	3	4.0			
Tilton	10	1.5			
Troy	6	1.6			
Tuftonboro	3	2.2			
Unity	4	1.0			
Wakefield	3	4.8			
Walpole	8	2.4			
Warner	6	2.0			
Warren	5	2.2			
Washington	2	1.1			
Weare	7	1.9			
Webster	7	1.0			
Wentworth	4	2.6			
Westmoreland	6	1.6			
Whitefield	7	2.3			
Wilmot	4	2.5			
Wilton	5	3.2			

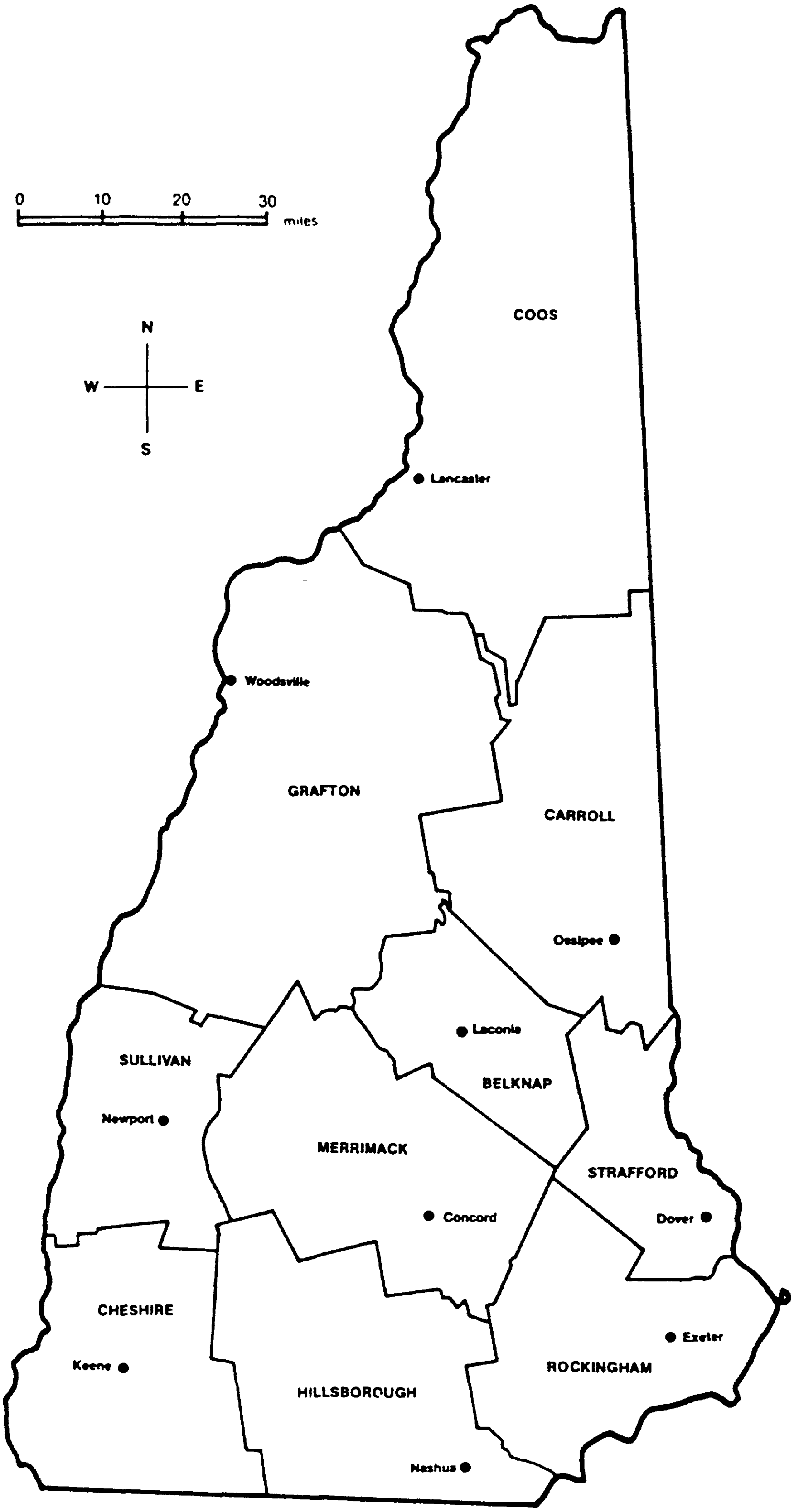

Figure 10. New Hampshire Counties (from Facts on File, 1984).

concentrations and is labile (Boudette, 1977). A sampling of 5,457 public and private water supplies by the New Hampshire Department of Environmental Services indicate that 20 percent of the water supplies tested had radon concentrations of 10,000 pCi/L or more (E. Boudette, pers. comm., 1990). The amount of radon that is contributed to indoor air from water varies substantially and is related to the volume of air in the house and the volume of water used over a given period of time.

TABLE 2. Radon-222 concentrations in ground water, by geologic formation (from Paulsen, 1991, who derived the data from Hall and others, 1985; Hess and others, 1980; and Smith and others, 1961).

FORMATION	# OF SAMPLES	AVERAGE (pCi/L)
Kittery	10	1,900
Eliot	12	2,250
Berwick	20	11,900
Littleton	11	10,600
Exeter Diorite	10	1,800
Quartz diorite	3	3,570
Quartz monzonite	14	34,000
two-mica granite	11	45,1000
Conway granite	15	22,370
Fitchburg Granite	2	284,000

GEOLOGIC RADON POTENTIAL

The following discussion examines the above data in terms of geologic radon potential for the land in New Hampshire. A numeric ranking is given in Table 3 and illustrated in figure 11. Olszewski and Boudette (1986) have compiled a generalized geologic map of New England with emphasis on uranium endowment and radon production. Our analysis here corresponds very well with their uranium endowment map. We have adopted Olszewski and Boudette's (1986) geologic/geochemical divisions for figure 11.

Avalonian Terrane

The Avalonian Composite Terrane has been ranked moderate to high in geologic radon potential. The Avalonian Composite Terrane is underlain by the Merrimack Group, Massabesic Gneiss, the Rye Formation and several bodies of two-mica granites, alkalic plutonic rocks, and mafic plutonic rocks. Soils in this area have generally low permeability that is locally moderate to high. The Merrimack Group has low to moderate equivalent uranium, whereas other rocks have generally moderate to high equivalent uranium, particularly the Massabesic Gneiss and associated faults. Abundant faults and small granitic intrusions contribute to the overall high radon potential of the Massabesic Gneiss and granitic rocks. Faults and fractures are often mineralized with uranium in crystalline terranes and may cause locally anomalously high indoor radon (Gundersen, 1991) The Merrimack Group and Rye Formation have overall moderate radon potential, with locally low radon potential. Average indoor radon for the townships underlain by Avalonian rocks is predominantly moderate (2-4 pCi/L) to high (> 4 pCi/L). Olszewski and Boudette (1986)

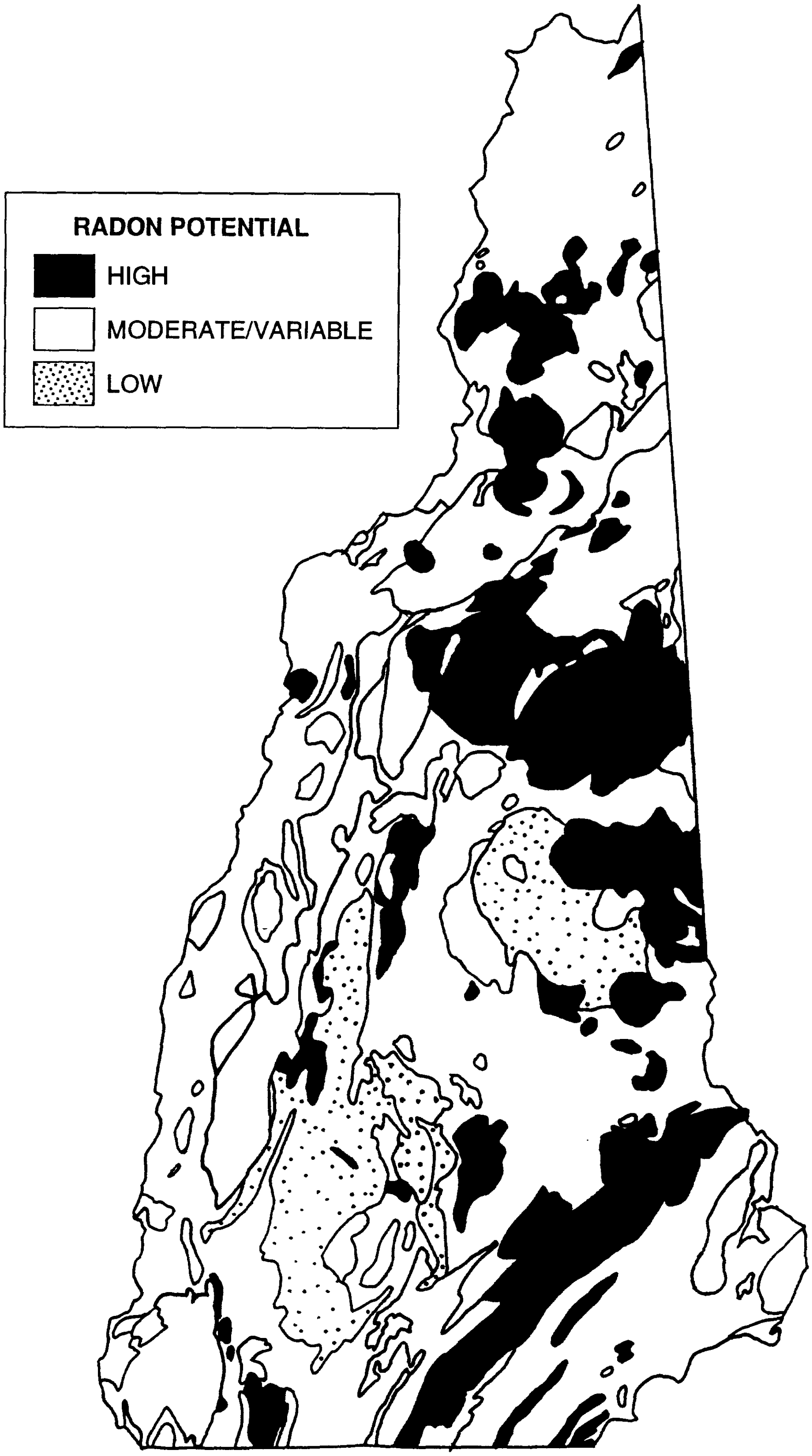

Figure 11. Geologic radon potential areas of New Hampshire.

classified the Precambrian metasedimentary and metavolcanic rocks of the Merrimack group and the granitic gneiss of the Massabesic as having variable (low to high) uranium endowment. They classified the two-mica granites as having high uranium endowment.

The Gander and Boundary Mountains Terranes

About half of New Hampshire is underlain by Cambrian-Devonian stratified metamorphic rocks of igneous or sedimentary origin that have been ranked moderate in radon potential. Olszewski and Boudette (1986) classified these Paleozoic metasedimentary and metavolcanic rocks as having variable uranium endowment, with increasing uranium as metamorphic grade increases, and with local uranium concentrations in fractures and faults. Uranium analyses for the metasedimentary and metavolcanic rocks (previously cited in the radioactivity section of this report) indicate uranium concentrations of less than 3 ppm in general. Graphitic slates, phyllites, and schists are known to be uranium sources in several areas of the Appalachians (Ratté and Vanacek, 1980; Gundersen and others, 1988) and this may be the case in New Hampshire. Where indoor radon data are available, the stratified metamorphic rocks appear to be associated with low to moderate indoor radon in the western portion of the State and with higher indoor radon in the eastern portion of the State and in the vicinity of plutonic rocks. Soils developed on these rocks in low mountains and lowlands have generally low to moderate permeability. Intermediate to mafic plutonic rocks generally have low or variable radon potential. The Lake Winnipesaukee Quartz Diorite and the Kinsman Quartz Monzonite appear to have low equivalent uranium and low indoor radon associated with them. The Spaulding Quartz Diorite, from geologic arguments, might be considered low to moderate in radon potential, although the township indoor radon data appears moderate to high. Several of the Oliverian domes have distinct radiometric highs associated with them (fig. 8) except for the northernmost and largest of the Oliverian rocks in the northern Gander Terrane, which have low radioactivity. Indoor radon in the townships underlying this area is variable from low to high.

Two mica granites, calc-alkaline granites, and alkalic plutonic rocks in New Hampshire have been ranked high in radon potential. Olszewski and Boudette (1986) classified these rocks as moderate to high in uranium endowment. Uranium in these granites is commonly more than 3 ppm and up to several hundred ppm. Uranium occurs as primary uranium oxides such as uraninite or in abundant accessory minerals. Two-mica granites occur throughout the central and eastern portions of New Hampshire. Calc-alkaline granites occur from east-central to northwestern New Hampshire. The largest body of calc-alkaline granite underlies the White Mountains and has very high radioactivity associated with it (fig. 8). Indoor radon in several townships in this area is high (fig. 9) and the soils usually have moderate permeability.

SUMMARY

For the purpose of this assessment, New Hampshire has been divided into 6 geologic radon potential areas and each area assigned a Radon Index (RI) and a Confidence Index (CI) score (Table 3). The RI is a semi-quantitative measure of radon potential based on geology, soils, radioactivity, architecture, and indoor radon. The CI is a measure of the relative confidence of the RI assessment based on the quality and quantity of the data used to assess geologic radon potential (see the Introduction chapter to this regional book for more information). The geologic radon potential areas are shown on a map of New Hampshire in figure 11.

This is a generalized assessment of the State's geologic radon potential and there is no substitute for having a home tested. The conclusions about radon potential presented in this report cannot be applied to individual homes or building sites. Indoor radon levels, both high and low, can be quite localized, and within any radon potential area there will likely be areas with higher or lower radon potential 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 State radon program or EPA regional office. More detailed information on state or local geology may be obtained from the state geological survey. Addresses and phone numbers for these agencies are listed in chapter 1 of this booklet.

TABLE 3. RI and CI scores for geologic radon potential areas of New Hampshire.

FACTOR	Massabesic Gneiss RI	Massabesic Gneiss CI	Two Mica, calc-alkaline and alkalic granites RI	Two Mica, calc-alkaline and alkalic granites CI	Oliverian and intermediate composition plutonic RI	Oliverian and intermediate composition plutonic CI
INDOOR RADON	3	3	2	3	2	2
RADIOACTIVITY	3	2	3	2	1	2
GEOLOGY	2	3	3	3	2	3
SOIL PERM.	2	3	2	3	2	3
ARCHITECTURE	3	-	3	-	3	-
GFE POINTS	0	-	0	-	0	-
TOTAL	13	11	13	11	10	10
	High	High	High	High	Mod	High

FACTOR	Lake Winnepesaukee, Kinsman, and other intermediate to mafic plutons RI	Lake Winnepesaukee, Kinsman, and other intermediate to mafic plutons CI	Stratified metamorphic rocks, Gander and Boundary Mts. RI	Stratified metamorphic rocks, Gander and Boundary Mts. CI	Merrimack Group Rye Formation RI	Merrimack Group Rye Formation CI
INDOOR RADON	2	2	2	2	2	3
RADIOACTIVITY	1	2	2	2	2	2
GEOLOGY	1	3	2	3	2	3
SOIL PERM.	1	3	1	3	2	3
ARCHITECTURE	3	-	3	-	3	-
GFE POINTS	0	-	0	-	0	-
TOTAL	8	10	10	10	11	11
	Low	High	Mod	High	Mod	High

RADON INDEX SCORING:

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

Possible range of points = 3 to 17

CONFIDENCE INDEX SCORING:

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

Possible range of points = 4 to 12

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PRELIMINARY GEOLOGIC RADON POTENTIAL ASSESSMENT OF RHODE ISLAND

by
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INTRODUCTION

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

PHYSIOGRAPHIC AND GEOGRAPHIC SETTING

The physiography of Rhode Island (fig. 1) is in part a reflection of the underlying bedrock (fig. 2) and surficial geology. All regions of Rhode Island were greatly altered by glaciation. The western portion of the State has rolling hills with an elevation as high as 800 feet above sea level. The remainder of the State is gently hilly to level. Rhode Island has four major physiographic regions: the East Bay Coastal Area; the Narragansett Lowlands; the West Bay Coastal Area; and the Western Rocky Upland. The Western Rocky Upland is underlain by igneous and metamorphic rocks forming hills with elevations from 300 to 800 feet above sea level and local relief of several hundred feet. Many of the hills are capped by glacial till. The West Bay Coastal Area includes areas with elevations up to 200 feet above sea level, but is generally undulating to flat terrain underlain by alluvial valley fill, stratified glacial deposits, and till. The Narragansett Lowlands includes the till-covered islands of Narragansett Bay, with elevations up to 200 feet above sea level. The East Bay Coastal Area is flat lying, with till cover and significant marshland.

In 1990, Rhode Island's population was 1,003,464, with 87 percent of the population living in urban areas (fig. 3). The population density is approximately 819 per square mile. The climate of Rhode Island is moderate, with an annual average temperature of 50° F and annual precipitation of about 37 inches (fig. 4).

GEOLOGIC SETTING

Rhode Island is underlain by Proterozoic through Paleozoic igneous plutonic, metasedimentary, and metavolcanic rocks (fig. 2). Geologic descriptions presented in the following section are derived from Quinn (1971) and Hermes and others (in press) who have recently remapped the bedrock geology of the State. The terminology used is from Hermes and others (in press), however, much of the previous literature concerning radioactivity and uranium

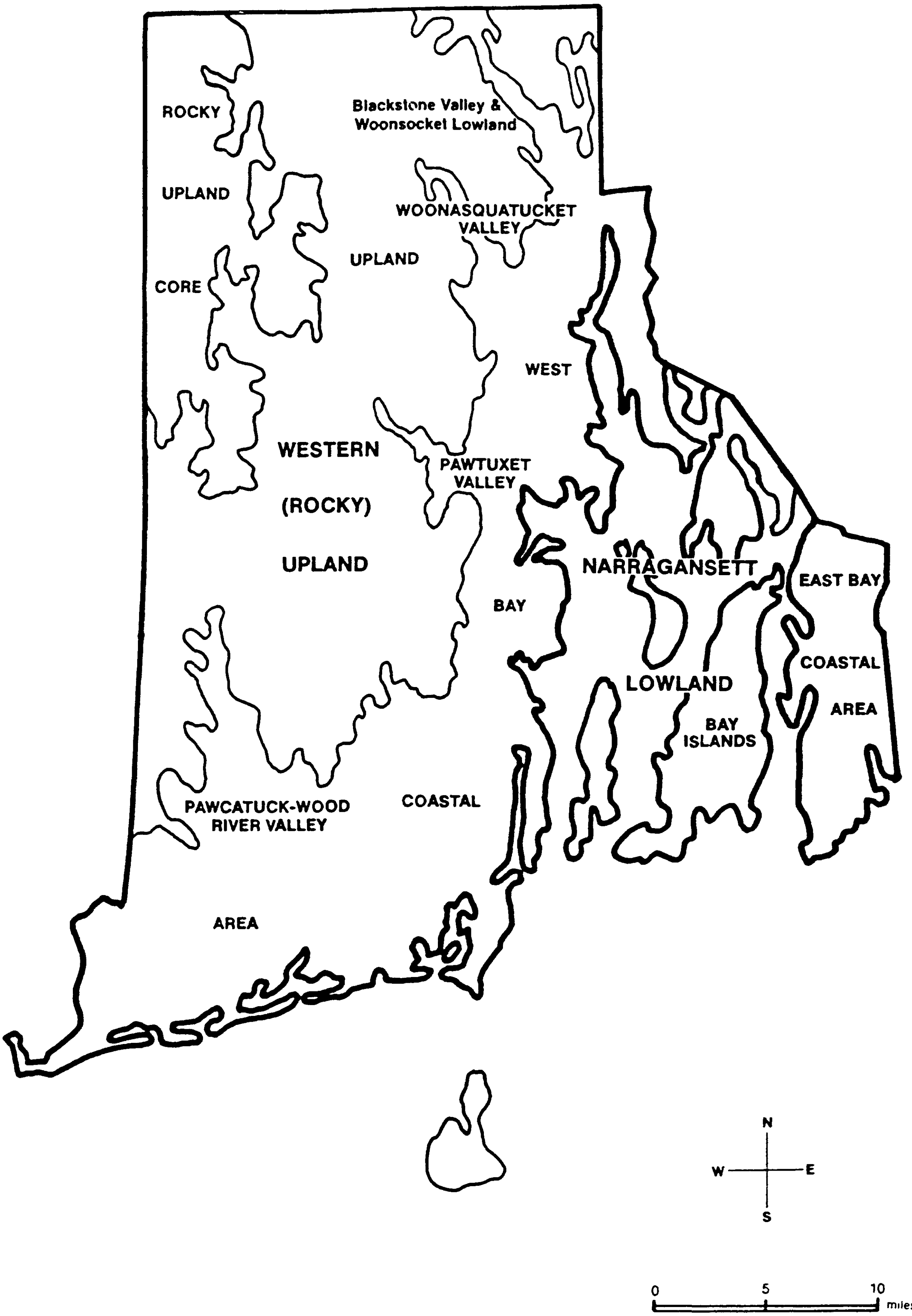


Figure 1. Physiographic regions of Rhode Island (from Facts on File, 1984).

Figure 2. Generalized bedrock geologic map of Rhode Island (from Hermes and others, in press).

GENERALIZED GEOLOGIC MAP OF RHODE ISLAND
EXPLANATION

AVALON TERRANE

CRETACEOUS

Kr Raritan Formation

JURASSIC

monchiquite dike

TRIASSIC

diabase dike

vein quartz

PERMIAN

Narragansett Pier Plutonic Suite—fine grained to porhyritic granite, granite, leucogranite

PENNSYLVANIAN

NARRAGANSETT BAY GROUP (Narragansett Bay Region)

Dighton Conglomerate

Purgatory Conglomerate

1 Rhode Isalnd Formation

Wamsutta Formation

Sachuest Arkose

Pondville Conglomerate

metaclastic rocks undifferentiated

MISSISSIPPIAN-DEVONIAN

Alkali-feldspar granite of Cumberland

DEVONIAN

SCITUATE IGNEOUS SUITE (West-Central Rhode Island)

volcaniclastic rock

rhyolite

Scituate and associated granites

fine grained granite, alkali-feldspar granite, and granite

granodiorite

monzonite/monzodiorite

diorite/gabbro

ORDOVICIAN-CAMBRIAN

CONANICUT GROUP (Southern Narragansett Bay Region)

Dutch Island Harbor Formation

2 Fort Burnside and Jamestown Formations (includes small outcrop of Cambrian Pirate Cove Formation in East Bay Area)

undifferentiated rock

minette dike

LATE PROTEROZOIC

HOPE VALLEY SUBTERRANE (Southwestern and northwestern Rhode Island)

Waterford Group

- 3 Ropes Ferry Gneiss
- Mamacoke Formation
- Plainfield Formation

Sterling Plutonic Series

- granite gneiss and alaskite gneiss
- mafic/intermediate gneiss

ESMOND-DEDHAM SUBTERRANE-WEST BAY AREA

- Cumberlandite
- gabbro-diorite

ESMOND IGNEOUS SUITE

- felsic volcaniclastic rocks
- Esmond Granite, including fine-grained granite, granite, granodiorite, augen granite gneiss, and granite gneiss
- mafic/intermediate rock

Harmony Group (North-Central Rhode Island)

- Woonasquatucket Fm.
- Absalona Fm.
- Nipsachuck Fm.

Blackstone Group

- quartzite
- epidote and biotite schist
- 4 greenstone, amphibolite, and serpentenite
- undifferentiated rock

ESMOND-DEDHAM SUBTERRANE-EAST BAY AREA

Newport Group

- Fort Adams Fromation
- Newport Neck Formation (includes small outcrop of Cambro-Ordovician East Passage Formation in East Bay Area)
- Price Neck Formation
- mica schist

Granites of Southeastern Rhode Island

- granite
- porphyritic granite

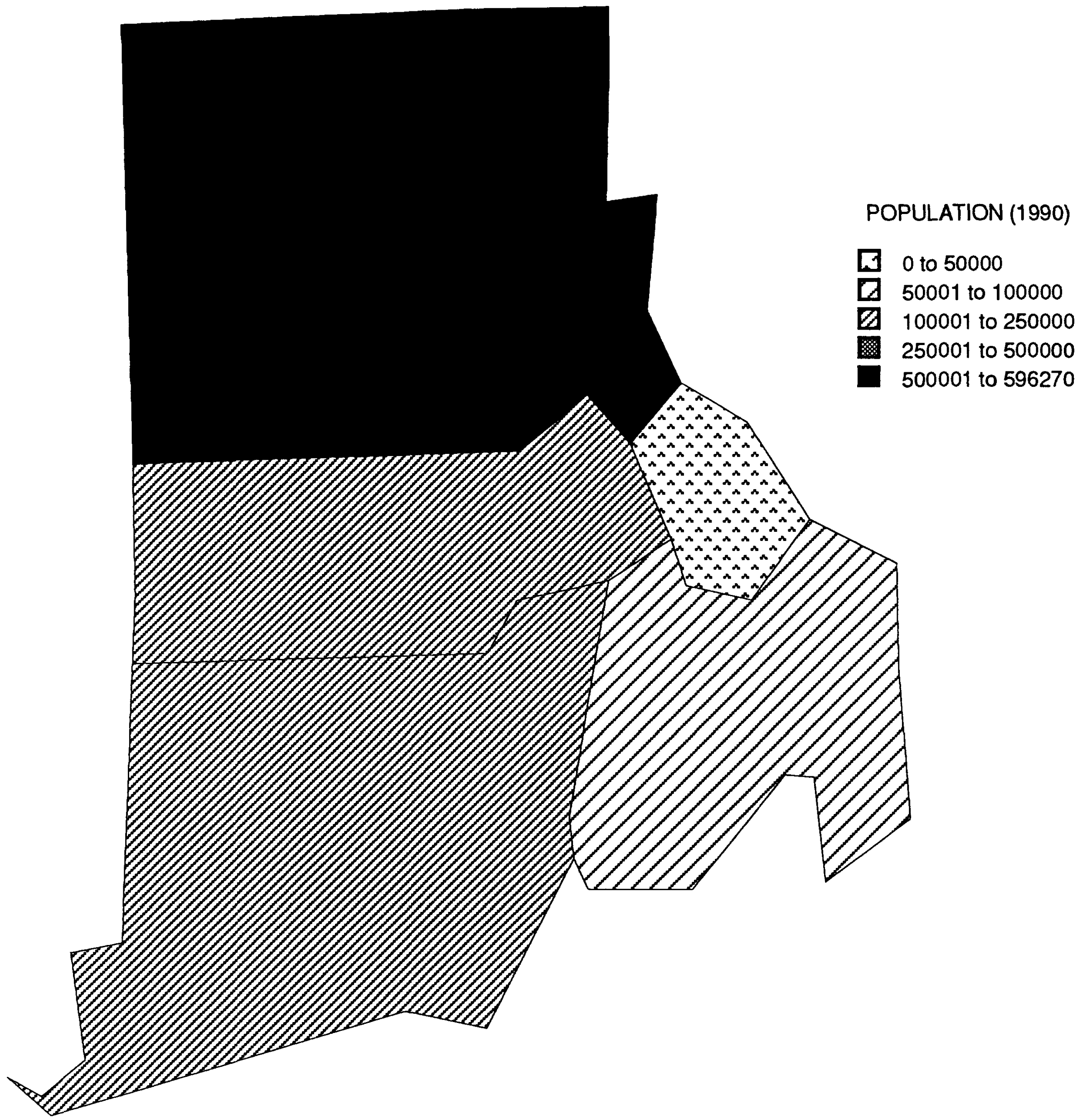


Figure 3. Population of counties in Rhode Island (1990 U.S. Census data).

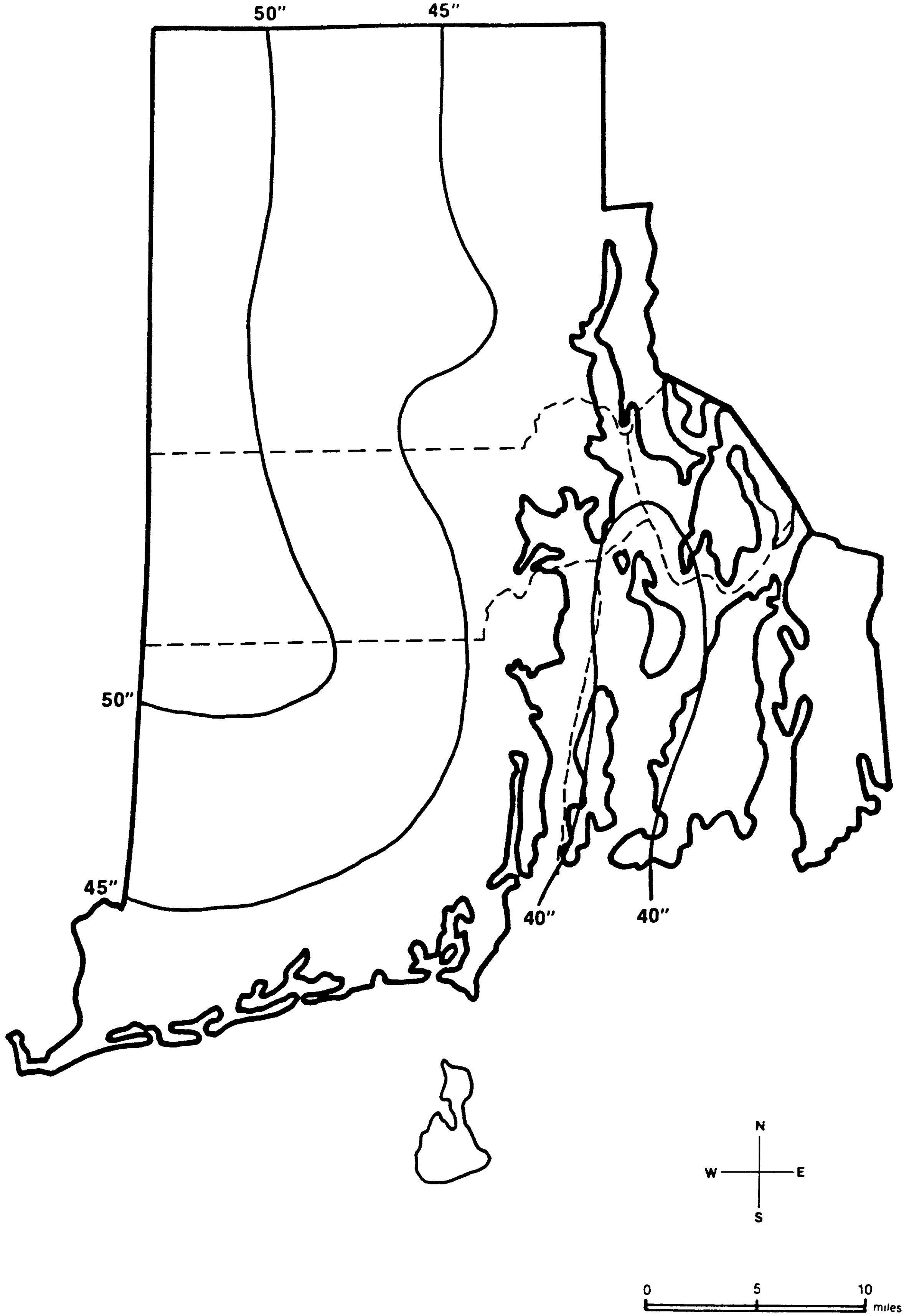


Figure 4. Average annual precipitation in Rhode Island (from Facts on File, 1984).

occurrences in the State uses the terminology of Quinn (1971). An effort has been made to make reference to the older terminology where appropriate.

The complicated igneous and metamorphic geology of Rhode Island falls within the Avalon Terrane and is divided into the Hope Valley Subterrane and the Esmond-Dedham Subterrane. These terrane designations will be referred to throughout the text.

The Hope Valley Subterrane

The Hope Valley Subterrane includes the southwestern and northwestern corners of the State. It is separated from the Esmond-Dedham Subterrane by the Hope Valley Shear Zone. Rocks of the Hope Valley Subterrane include deformed and recrystallized rocks of the Late Proterozoic-age Sterling Plutonic Group and stratified metamorphic rocks of Late Proterozoic or older age. The Sterling Plutonic Group [formerly the Hope Valley Alaskite Gneiss of Quinn (1971)] consists of light colored, quartz-feldspar alaskite gneiss with a strong lineation produced by the alignment of minerals. Pink microcline-quartz gneiss crops out southwest of the main body of alaskite and forms small bodies in northern parts of the alaskite outcrop area. Intermediate to mafic layered gneiss occurs in the central part of the alaskite outcrop area. The stratified rocks to the southwest of the main body of alaskite belong to the Waterford Group and consist of the Rope Ferry Gneiss, a layered felsic gneiss; the Mamacoke Formation, a layered and foliated hornblende amphibolite; and the Plainfield Formation, comprised of feldspar-quartz-biotite gneiss, schistose gneiss, quartzite, mica schist, and calc-silicate rock. The Westerly Granite of Quinn (1971) and Narragansett Pier Granite intrude the above units and occur as small intrusive dikes and irregular bodies.

Esmond-Dedham Subterrane-West Bay Area

This terrane comprises a Late Proterozoic-age suite of granitic rocks that intrude older metasedimentary and mafic metavolcanic rocks. Younger metasedimentary rocks overlie the entire sequence.

Stratified metamorphic rocks of the Blackstone Group crop out in several parts of northern Rhode Island. They are characterized by interlayered quartzite, epidote and biotite schist, greenstone, amphibolite, and serpentinite. The Harmony Group crops out in north-central Rhode Island and comprises the Absalona, the Woonasquatucket, and the Nipsachuck Formations. The Absalona is a schistose, dark-colored, biotite gneiss and is the most extensive formation of the Harmony Group. It is composed of several kinds of feldspar, quartz, biotite, and minor amounts of muscovite, epidote, and hornblende. The Woonasquatucket Formation is chiefly light-colored schist and gneiss with feldspar, quartz, muscovite, and biotite. It is not well foliated or layered. The Nipsachuck Formation consists of light-colored, medium-grained gneiss with prominent biotite streaks and foliation. It is made up of feldspar, quartz, biotite, and muscovite.

The Esmond Igneous Suite lies to the east of the Hope Valley Shear Zone and to the north and south of the Scituate Igneous Suite. It is characterized by various calc-alkaline granites and granitic gneiss, predominantly augen granite gneiss with lesser amounts of granodiorite, granite gneiss, fine grained granite, and intermediate to mafic rocks. Felsic volcaniclastic rocks also occur. The Esmond Igneous Suite includes the Esmond and Dedham Granite, and the formerly named Ponaganset Gneiss, the Grant Mills Granodiorite, the Tenrod Granite (Quinn, 1971) and unnamed diorite, felsic gneiss, and gabbro.

The Scituate Igneous Suite underlies much of west-central Rhode Island. It comprises several granites and alkaline granites of Devonian age that intrude the above-mentioned rock units.

The Scituate Igneous Suite is predominantly a light-colored, medium- to coarse-grained granite gneiss composed of feldspar, quartz, biotite, and minor hornblende and magnetite. Biotite occurs in splotches with sphene, magnetite, zircon, allanite, epidote, and apatite, which define a lineation common to the granite. The formerly named Cowesett Granite (Quinn, 1971) crops out on the eastern flank of the main body of Scituate and consists of pink, medium to coarse-grained granite. A small body of felsic volcanic rocks, formerly named the Spencer Hill Volcanics (Quinn, 1971) also crops out in this area. Mississippian alkali granite of the Cumberland, also known in part as the Rhode Island Quincy Plutonic Suite of Quinn (1971) occurs as a small body of granite in the northeastern corner of the State.

The Narragansett Bay Group underlies most of the Narragansett Lowlands and extends north into Massachusetts. It is a complex, deformed sequence of Pennsylvanian sedimentary rocks that form a series of basins known as the Narragansett (which underlies most of the Narragansett Lowlands), the Woonsocket (in north-central Rhode Island near Woonsocket), and the North Scituate basins. Rock units include the Dighton Conglomerate, Purgatory Conglomerate, Rhode Island Formation, Wamsutta Formation, Sachuest Arkose, and the Pondville Conglomerate. The Rhode Island Formation is the most extensive of these rock units and comprises fine- to coarse-grained sandstone and lithic graywacke, black shale, conglomerate, minor meta-anthracite in the Narragansett basin, and is metamorphosed and characterized by aluminosilicate schists and conglomeratic schists in the other two basins. The Wamsutta Formation occurs in limited exposure in the northeastern part of Rhode Island and it is characterized by red sandstone, lithic graywacke, conglomerate, and shale. The Purgatory and Dighton Conglomerates have a scattered outcrop pattern, occurring principally in the East Bay area. The Pondville Conglomerate crops out along the western margin of the basin and to the north in Massachusetts.

The Narragansett Pier Granite is Permian in age and intrudes Pennsylvanian and older rocks, including both principal subterranes of the Avalon Terrane. It crops out along the length of the southwestern coast of Rhode Island. It is a light colored, medium grained, locally porphyritic, massive to weakly foliated quartz monzonite to granodiorite. It is composed of feldspar, quartz, biotite, and minor muscovite with accessory apatite, monazite, zircon, allanite, garnet, and rutile.

The East Bay Area

The East Bay area includes some of the sedimentary rocks of the Narragansett Group but also includes a variety of stratified metasedimentary and metavolcanic rocks of the Newport Group. These include the slate, quartzite, volcanic tuff, and mica schists of the Fort Adams Formation, Newport Neck Formation, and Price Neck Formation.

Several areas of the East Bay, including Conanicut Island, Newport Neck, Bristol Neck, and the East Bay Coastal Area, are also underlain by various granites and granite gneiss called the Granites of Southeastern Rhode Island.

Minor metasedimentary rocks (sandstones, phyllites, and quartzites) that are thought to be Cambrian through Ordovician in age underlie the Islands of the East Bay area. These include the Cambrian Pirate Cove Formation and the Cambrian through Ordovician metasedimentary rocks of the Conanicut Group, comnsisting of the Dutch Island Harbor Formation, Fort Burnside Formation, Jamestown Formation, and East Passage Formation.

GLACIAL GEOLOGY

Deposits of five or possibly six Pleistocene glacial advances in New England have been recognized or inferred from surface or subsurface data (Stone and Borns, 1986); however, two main till units are mapped throughout much of southern New England (Richmond and Fullerton, 1991). Glacial deposits exposed at the surface in Rhode Island are of Late Wisconsin age. Glaciers moved in a dominantly N-S or NW-SE direction across the State, terminating on Long Island and Martha's Vineyard at their maximum extent. In Late Wisconsin time, parts of three glacial lobes advanced across Rhode Island. The Connecticut Valley Lobe covered the western part of the State and the Narragansett Bay-Buzzard's Bay Lobe covered most of the eastern half. The Charles-Merrimack Lobe entered the northern part of Rhode Island (fig. 5). The final retreat of Wisconsinan glaciers from the State occurred about 12,000 years ago (Stone and Borns, 1986).

Glacial deposits in Rhode Island range from a few meters to about 40 meters in thickness. Figure 6 is a generalized map of glacial deposits in Rhode Island. The glacial deposits are divided into two main categories, till and stratified glacial deposits. Till, sometimes referred to as glacial drift or ground moraine, is the most widespread glacial deposit (fig. 6). Till was deposited directly by glacier ice and it is composed of a poorly sorted matrix of sand, silt, and clay containing variable amounts of rounded cobbles and boulders. Till composition generally reflects the local bedrock. The "upper till", which covers most of the surface mapped as till on figure 6, is sandy to gravelly and locally calcareous. It typically overlies a "lower till" which is more clayey, more compact, and less bouldery than the upper till (Richmond and Fullerton, 1991). Till thickness is generally 1.5-4 m, and is rarely more than 10 m (Richmond and Fullerton, 1991). Areas largely underlain by till include the Upland Till Plains and the Narragansett Till Plains. The Upland Till Plains covers most of the western half of Rhode Island. In this area the till is derived primarily from gneiss, schist, and granite. Stones and boulders are scattered across the surface of the till, and bedrock outcrops occur locally (Rector, 1981). The Narragansett Till Plains occupy the Narragansett Lowlands. This area is covered by till derived primarily from sandstone, shale, conglomerate, and locally, coal. Bedrock is generally poorly exposed in this area. Glacial landforms associated with till include drumlins, kettles, and moraines.

Several glacial end moraines are found in Rhode Island; the largest and most important of these are the Charlestown and Block Island moraines. The Charlestown Moraine, which roughly follows the coastline from Wakefield to Watch Hill in southwestern Rhode Island (fig. 6), is dated at approximately 18,000 years B.P. (Stone and Borns, 1986). The Charlestown moraine blocks normally southward-flowing drainages, diverting them to the east and west. The Block Island Moraine, which covers all of Block Island, is part of a larger end moraine complex that stretches from Long Island to Martha's Vineyard. The Block Island Moraine was deposited approximately 21,000 years ago (Stone and Borns, 1986).

Stratified glacial deposits were laid down by glacial meltwater in streams and lakes in front of the retreating ice margin. They are characterized by layers of poorly-sorted to well-sorted gravel and sand with minor beds of silt and clay. Stratified glacial deposits are further subdivided into two categories on figure 6. Outwash consists of layers of sand and gravel deposited by glacial meltwater streams. Outwash is generally the coarsest-grained class of glacial deposits because most of the silt and clay was removed by the rapidly-moving water. Ice-contact stratified drift includes deposits of kames, eskers, kame terraces, and collapsed stratified drift. These coarse-grained deposits range from poorly sorted to well sorted and consist of sand, gravel, cobbles, and

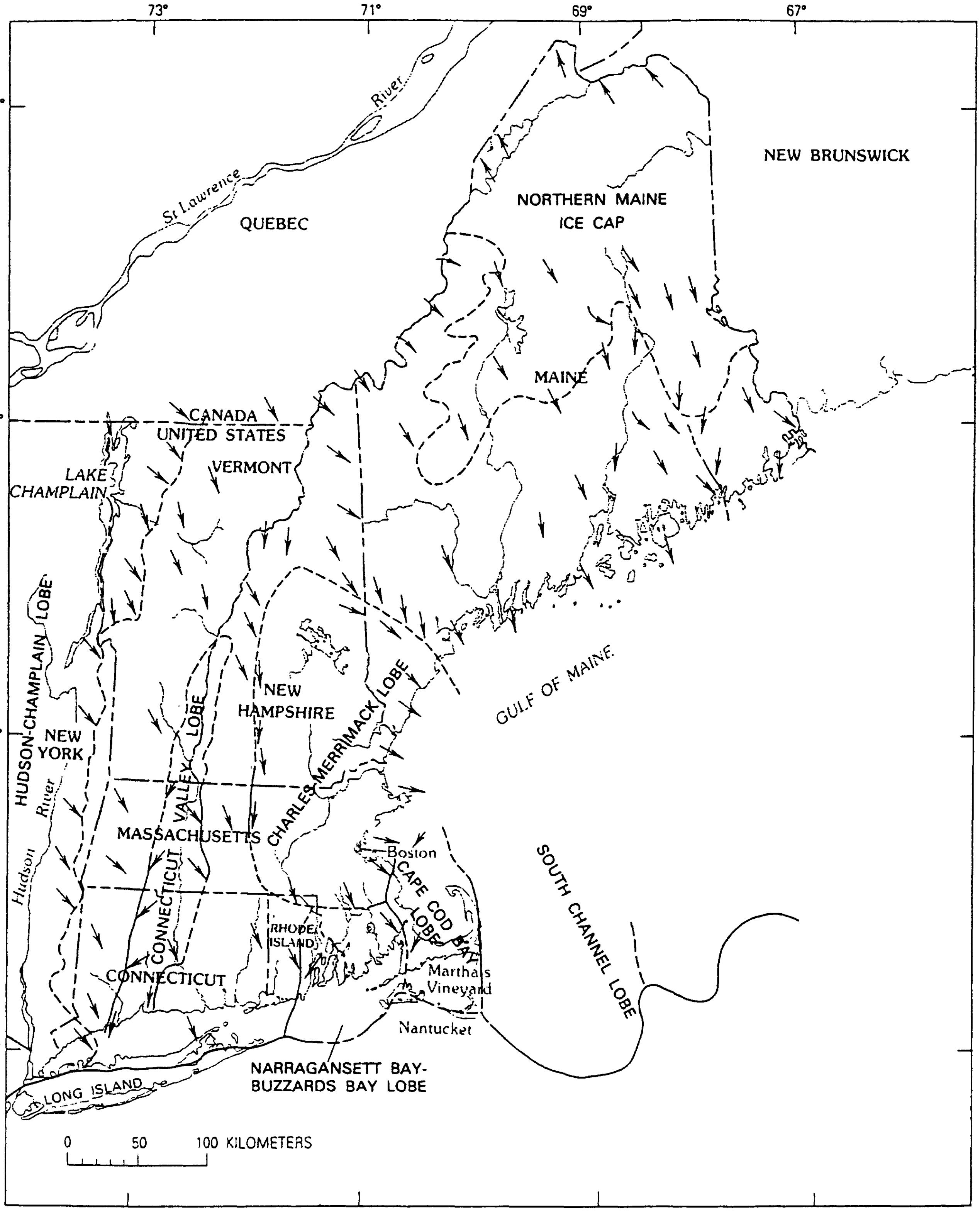


Figure 5. Major late Wisconsin glacial lobes of New England. Arrows indicate general directions of glacial advances (from Stone and Borns, 1986).

Figure 6. Generalized glacial geologic map of Rhode Island (modified from Richmond and Fullerton, 1991).

GENERALIZED GLACIAL GEOLOGIC MAP OF RHODE ISLAND
EXPLANATION

HOLOCENE

BEACH AND DUNE SAND--Beach sand is well sorted, medium to coarse; commonly contains scattered shell fragments, seaweed, and, locally, organic and inorganic debris. Associated dune sand is commonly present as narrow strips adjacent to and immediately inland from beach sand. Thickness of beach sand 1-3 m, dune sand 1-5 m

HOLOCENE AND LATE WISCONSIN

SWAMP DEPOSIT--Muck, mucky peat, peat, and organic residues mixed with fine-grained mineral sediment. Occurs in ice-block depressions, abandoned glacial meltwater channels, and in basins dammed by glacial deposits. Thickness generally 1-3 m, rarely more than 5 m

LATE WISCONSIN

LAKE SILT AND CLAY--Stratified silt and clay. Local thin beds of fine sand. Predominantly thinly laminated; locally varved. Most deposits underlie flat, low areas or valley floors formerly occupied by glacial lakes. Thickness generally 1-10 m; rarely more than 25 m

OUTWASH SAND AND GRAVEL--Fine to coarse sand or pebbly sand alternating with layers of granule- to cobble-gravel and minor beds of silt; locally bouldery. Underlies terraces, outwash plains, valley trains, fans, and meltwater-channel fills. Thickness generally 1-10 m; rarely as much as 60 m

OUTWASH SAND AND UNDERLYING LAKE DEPOSITS--Medium to coarse sand with sparse scattered pebbles and local lenses of gravel. Underlying lake deposits chiefly flat bedded, lenticularly crossbedded, or ripple-bedded medium to fine sand and laminated or varved silt and clay. Thickness of outwash sand 5-10 m; underlying lake deposits 5-30 m

ICE-CONTACT SAND AND GRAVEL--Fine to coarse sand and gravel containing minor beds of silt and clay and local lenses or masses of till or flowtill. Underlies kame terraces and forms complexes of crevasse fillings, eskers, mounds, and hummocks in valleys. Inferred to have been deposited against irregular remnants of stagnant ice. Surface locally pitted with ice-block depressions, and in places strewn with boulders. Thickness 5-20 m

ICE-CONTACT DELTA SAND AND GRAVEL--Sand and pebble- or cobble-gravel. Most ice-contact deposits are in valleys, but some are perched on terrain above the valley floor. They are inferred to have been deposited at successive ice marginal positions by streams flowing from stagnant ice into ice-marginal lakes or ponds. Thickness 5-15 m; locally as much as 40 m

SANDY TILL--Texture highly variable, stony sand to stony sandy loam; locally dense, fissile silty clay with boulders. Commonly gravelly, cobbly, bouldery, or rubbly. Locally weakly calcareous to noncalcareous, reflecting composition of source materials. Generally friable; loose to moderately compact. Rock types reflect local bedrock, which changes markedly over relatively short distances. The sandy till at the surface, or "upper till," locally overlies a "lower till," not separately mapped, which is dark gray brown or dark gray and more clayey, more compact, and less bouldery than the "upper till". The "upper till" forms ground moraine, which varies greatly in thickness but is rarely very thick, and attenuated drift, which is very thin and discontinuous with intervening areas of glaciated bedrock. Thickness generally 1.5-4 m; rarely more than 10 m

KAME MORAINE--Loose sandy till several meters thick underlain by sand and gravel that locally includes masses of lake silt and clay or sandy loamy till. Forms end moraine ridge as long as 20 km and as high as 10-20 m in southern Rhode Island. Thickness 5-80 m

LATE WISCONSIN AND EARLY WISCONSIN

SANDY TO CLAYEY TILL--Complex deposit of late Wisconsin sandy to clayey till and early Wisconsin clayey till (Montauk Till) on Block Island. Early Wisconsin till exposed only in coastal bluffs. Both tills discontinuous. Thickness 3-5 m; locally more than 10 m

PLIOCENE AND OLDER CENOZOIC

GLACIATED GRANITIC GRUS--Coarse granitic grus; overlain locally by patches of thin sandy till, sand, and widely scattered glacial pebbles, cobbles, and boulders from local and distant sources. Grus is developed in coarse mafic rocks as well as in granite in Rhode Island. Remnant thickness 0.5-3 m boulders, with varying amounts of silt and clay, though they generally contain considerably less fine-grained material than till.

SOILS

Most of the soils in Rhode Island are classified as Inceptisols, soils with weakly developed horizons in which materials have been altered or removed but in which little accumulation has occurred. These soils are typically developed on glacial till or bedrock. Inceptisols cover about 85 percent of Rhode Island's land surface. Some of the soils developed on outwash and alluvium are classified as Entisols, relatively young soils with no pedogenic horizons. Entisols occupy about 10 percent of the State's land surface area. Soils in low-lying inland areas that contain an abundance of organic matter (peat and muck) are classified as Histosols. Histosols occupy about 5 percent of the State's land surface area (Rector, 1981).

Figure 7 is a generalized soil map of Rhode Island. Soils of the glaciated uplands having a friable (loosely packed, easily separated, and permeable) substratum occur primarily in the western part of the State. These soils are deep, moderately well to excessively drained, and have a loamy, silty, or sandy texture. The soils are formed on glacial till derived from schist, gneiss, granite, and phyllite, and locally on bedrock. These soils have moderate permeability except for one unit, shown separately on figure 7, which is formed on till, moraines, and outwash, and has high permeability. This unit is the dominant soil type on the Charlestown Moraine (fig. 6, 7).

Soils of the glaciated uplands having a firm (clayey) substratum occur across the State (fig. 7). They are described as deep, poorly drained to well drained, coarse-loamy soils with a clayey subsurface horizon. The soils are developed on till derived from dark-colored sandstone and phyllite, argillite, conglomerate, shale, slate, schist, gneiss, and granite. They are commonly found on till-covered slopes and uplands, and on the slopes and tops of drumlins. These soils have moderate permeability in the surface horizons and low permeability below 0.5-0.75 m depth (Rector, 1981).

Soils developed on outwash plains and terraces, kames, eskers, and recent alluvium are scattered across the State and are described as deep, poorly to excessively drained, coarse-loamy and sandy soils with sandy and gravelly substrata (Soil Conservation Service, 1978). The soils are formed on outwash, glaciofluvial deposits, and alluvium derived from schist, gneiss, phyllite, and granite. Soils on outwash plains and terraces are generally well- to excessively drained, whereas those in depressions and on floodplains are poorly drained. These soils have moderate permeability in the surface horizons and high permeability at depth (Rector, 1981).

Organic soils form in swamps and marshes in depressions and small drainages of upland tills, outwash plains, and moraines (fig. 7). These soils have a thin to thick surface layer of peat or organic muck overlying a sandy substratum (Rector, 1981). Although these soils have moderate to high permeability, they are poorly drained and tend to be wet.

Soils of beaches and coastal lowlands are sandy and have high permeability. Soils of coastal marshes have a surface layer of organic material and are poorly drained, whereas beach soils are sandy throughout the profile and are excessively drained (Rector, 1981).

RADIOACTIVITY

An aeroradiometric map of Rhode Island (fig. 8) was compiled from spectral gamma-ray data acquired during the U.S. Department of Energy's National Uranium Resource Evaluation (NURE) program (Duval and others, 1989). For the purposes of this report, low equivalent

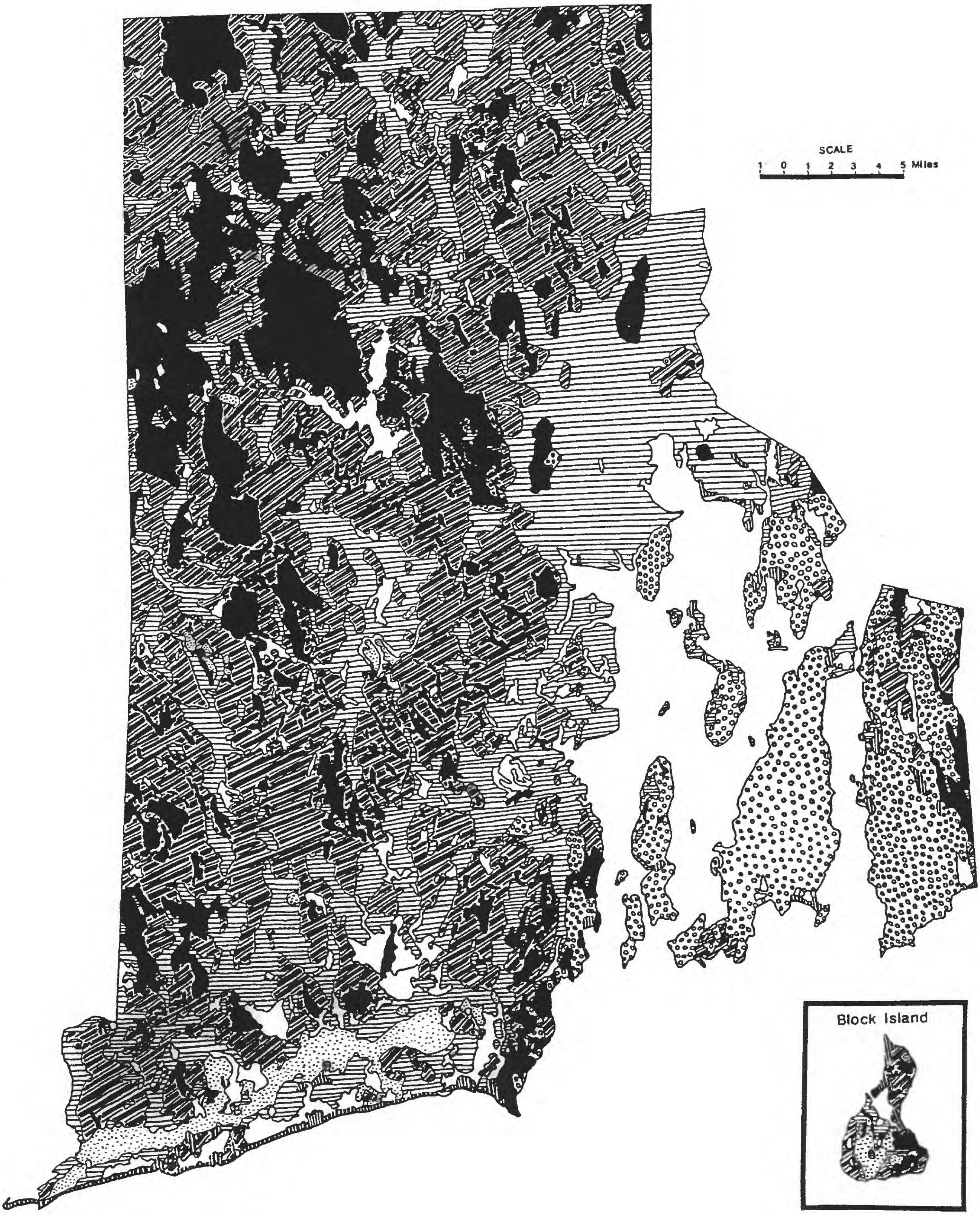


Figure 7. Generalized soil map of Rhode Island (modified from Rector, 1981).

GENERALIZED SOIL MAP OF RHODE ISLAND
EXPLANATION

AREAS OF GLACIATED UPLANDS DOMINATED BY DEEP SOILS WITH A FRIABLE SUBSTRATUM (INCEPTISOLS)—moderately well and well drained, silty and loamy soils developed on till derived from schist, gneiss, phyllite, and granite; moderate to locally high permeability

AREAS OF GLACIATED UPLANDS DOMINATED BY DEEP, SANDY SOILS (INCEPTISOLS AND ENTISOLS)—somewhat excessively drained and excessively drained soils formed in mixed sandy till and stratified glacial deposits derived from schist, gneiss, and granite; high permeability

AREAS OF GLACIATED UPLANDS DOMINATED BY DEEP SOILS WITH A FIRM SUBSTRATUM DERIVED FROM MAFIC ROCKS (INCEPTISOLS)—very poorly drained to well drained, silty and loamy soils developed on till derived from phyllite, argillite, slate, schist, shale, and sandstone; low permeability

AREAS OF GLACIATED UPLANDS DOMINATED BY DEEP SOILS WITH A FIRM SUBSTRATUM DERIVED FROM CRYSTALLINE ROCKS (INCEPTISOLS)—poorly drained to well drained loamy soils developed on till derived from schist, gneiss, and granite; low permeability

AREAS OF OUTWASH PLAINS, TERRACES, KAMES, AND ESKERS DOMINATED BY DEEP SOILS (INCEPTISOLS AND SOME ENTISOLS) —poorly to excessively drained, silty and sandy soils with high permeability; derived mostly from schist, gneiss, and phyllite

AREAS OF INLAND DEPRESSIONS AND LOW-LYING POSITIONS DOMINATED BY ORGANIC SOILS (HISTOSOLS)—very poorly drained soils formed in organic deposits derived from plant materials; moderate to high permeability, commonly wet

AREAS OF COASTAL LOWLANDS AFFECTED BY TIDAL WATER AND DOMINATED BY SOILS FORMED IN SANDY SEDIMENTS (ENTISOLS)—very poorly drained and excessively drained sandy soils of tidal marshes, dune areas, and beaches; high permeability

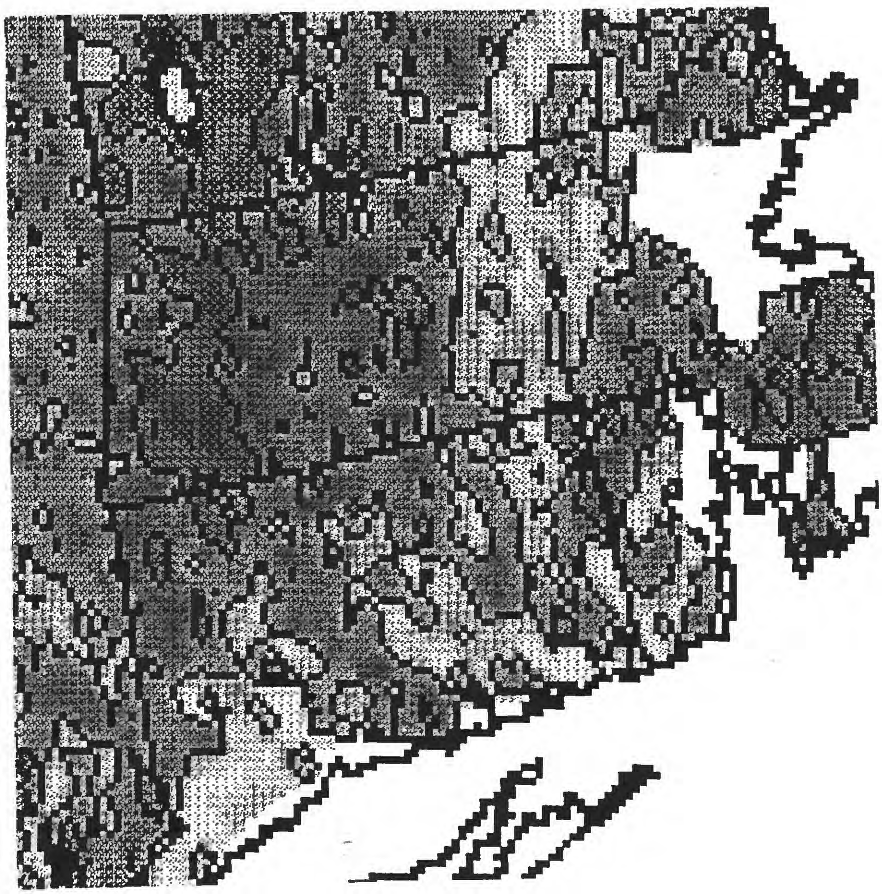


Figure 8. Aerial radiometric map of Rhode Island and surrounding areas (after Duval and others, 1989). Contour lines at 1.5 and 2.5 ppm equivalent uranium (eU). Pixels shaded from 0 to 6.0 ppm eU at 0.5 ppm eU increments; darker pixels have lower eU values; white indicates no data.

TABLE 1. Uranium concentrations in major rock types of Rhode Island (from Nevins, 1991).

Rock types	no. of samples	U (ppm) range	U (ppm) mean
Hope Valley Group			
Alaskite gneiss	7	1.7-5.8	3.3
Other Precambrian Igneous Rocks			
Felsite	2	2.0-2.1	2.1
Blackstone Series			
Greenstone	3	0.1-0.7	0.4
Esmond Plutonic Suite			
Tonalite	2	1.5-1.7	1.6
Granodiorite	2	1.5-2.5	2.0
Fine-gr. granite	1		4.0
Granite	4	0.9-2.8	1.9
Augen gneiss	5	1.5-2.3	1.9
Granite gneiss	1		2.8
Scituate Igneous Suite			
Felsite	4	2.2-9.8	7.3
Granite	16	2.2-13.2	4.1
Alkali-feld. gr.	9	2.2-22.1	7.9
RI Quincy Plutonic Suite			
Alkali-feld. gr.	2	11.4-16.5	14.0
Narragansett Pier-Westerly Plutonic Suite			
Fine-gr. granite	3	2.1-3.4	3
Granite	6	2.7-13.8	5.9
Leucocratic gr.	3	5.0-13.1	9.7
Narragansett Bay Group			
Sandstone	2	3.2-3.9	3.6
Carb. shale	2	1.8-3.3	2.6
Carb. slate	2	4.9-5.1	5.0
Siltstone	1		7.0

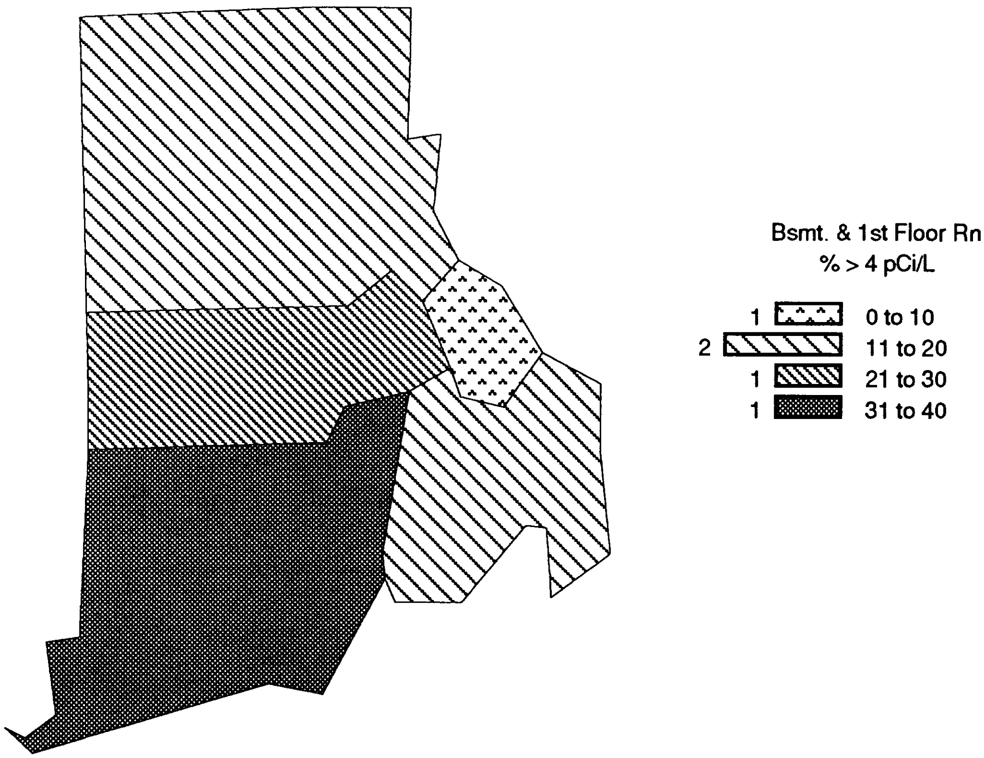
alkali-feld. gr. = alkali-feldspar granite, fine-gr.granite = fine-grained granite, carb. shale = carbonaceous shale uranium (eU) on the map is defined as less than 1.5 parts per million (ppm), moderate eU is defined as 1.5-2.5 ppm, and high eU is defined as greater than 2.5 ppm. In figure 8, the three highest areas of eU appear to be associated with the Scituate Igneous Suite, its intrusive contact with the Blackstone Series, and the alkalic granite of the Cumberland. Low eU is found in the northwest and central parts of the State and appears to be associated with the Woonsocket Basin, the Harmony Group, and the northwestern outcrops of the Esmond Igneous Suite and Blackstone Group. Moderate eU covers much of the rest of the State. The total gamma radioactivity map of Popenoe (1966) covers the entire State and shows similar patterns of radioactivity. Anomalously high areas of radioactivity include a small outcrop of alkalic granite near Cumberland; most of the area underlain by the Scituate Igneous Suite (including a particularly high area where the granite intrudes the Blackstone Group); the Narragansett Pier Plutonic Suite, parts of the Sterling Plutonic Group in both the southwest and northwest corners of the State; and the granites of southeastern Rhode Island in the East Bay Area. The NURE report for the Providence Quadrangle (Zollinger and others, 1982) gives a maximum of 33 ppm uranium for alkalic granite of Cumberland; 24 ppm uranium for Scituate granite where it intrudes the Blackstone Group; and 7 ppm uranium in the Narragansett Pier Plutonic Suite. Uranium chemistry of the major rock units in Rhode Island was also investigated by Nevins (1991) and her data are presented in Table 1. Rock units with uranium concentrations greater than 2 ppm include alaskite gneiss of the Sterling Plutonic Group (Hope Valley Group), Precambrian-age felsite, granitic rocks of the Esmond Plutonic Suite, alkali granitic rocks of the Scituate Igneous Suite, the Rhode Island Quincy Plutonic Suite, the Narragansett Pier and Westerly Granites, and carbonaceous sediments of the Narragansett Bay Group. The data in Table 1 suggests that many of the principal rock units in Rhode Island, especially the igneous suites, are uraniferous and may provide an significant source of radon to homes.

INDOOR RADON DATA

Indoor radon data from 376 homes sampled in the State/EPA Residential Radon Survey conducted in Rhode Island during the winter of 1987 are shown in figure 9 and listed in Table 2. A map of counties is included for reference (fig. 10). Indoor radon was measured by charcoal canister. The maximum value recorded in the survey was 64.1 pCi/L in Kent County. The average for the State was 3.3 pCi/L and 20.7 percent of the homes tested had indoor radon levels exceeding 4 pCi/L. Kent and Washington Counties have indoor radon averages greater than 4 pCi/L. Bristol County has the lowest average indoor radon and Newport and Providence Counties have indoor radon averages between 2-3 pCi/L.

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

COUNTY	NO. OF MEAS.	AVERAGE	GEOM. MEAN	MEDIAN	STD. DEV.	MAXIMUM	%>4 pCi/L	%>20 pCi/L
BRISTOL	22	1.8	1.4	1.6	1.5	7.7	5	0
KENT	80	4.7	2.2	2.0	9.0	64.1	25	4
NEWPORT	37	2.9	1.5	1.3	5.3	29.5	16	3
PROVIDENCE	185	2.6	1.8	1.7	2.9	27.8	17	1
WASHINGTON	52	4.1	2.7	2.3	4.4	23.5	37	4



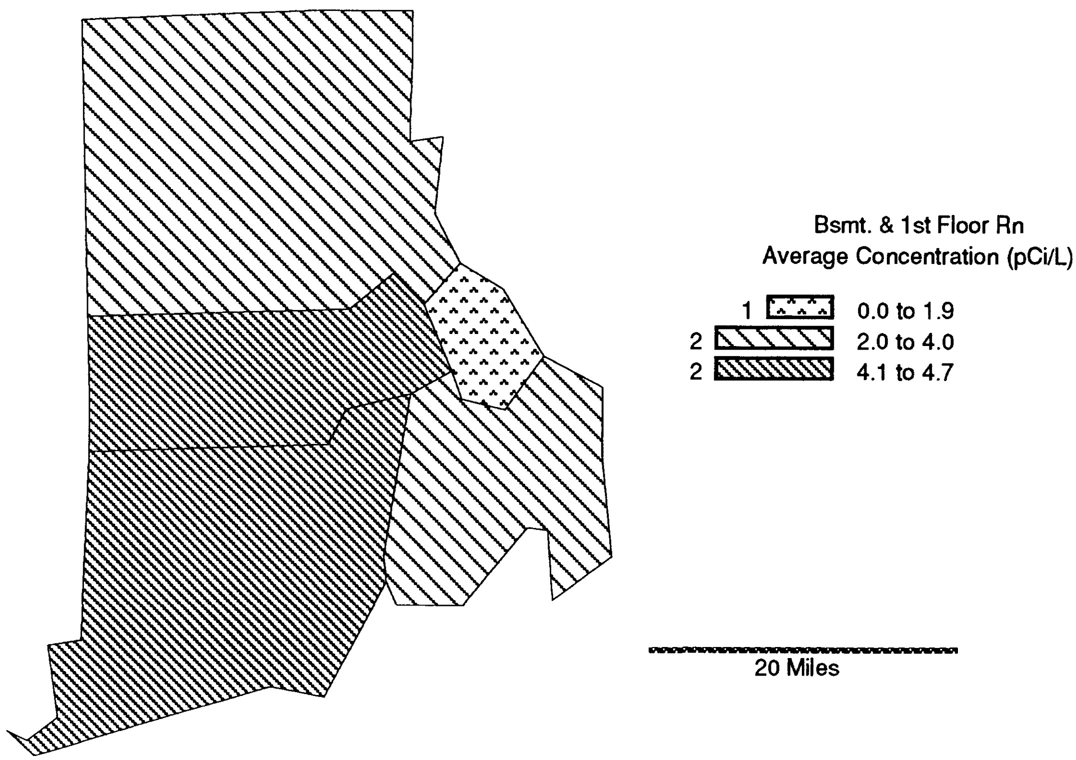


Figure 9. Screening indoor radon data from the EPA/State Residential Radon Survey of Rhode Island, 1986-87. Data are from 2-7 day charcoal canister tests. Histograms in map legends show the number of counties in each category. The number of samples in each county (See Table 2) may not be sufficient to statistically characterize the radon levels of the counties, but they do suggest general trends. Unequal category intervals were chosen to provide reference to decision and action levels.

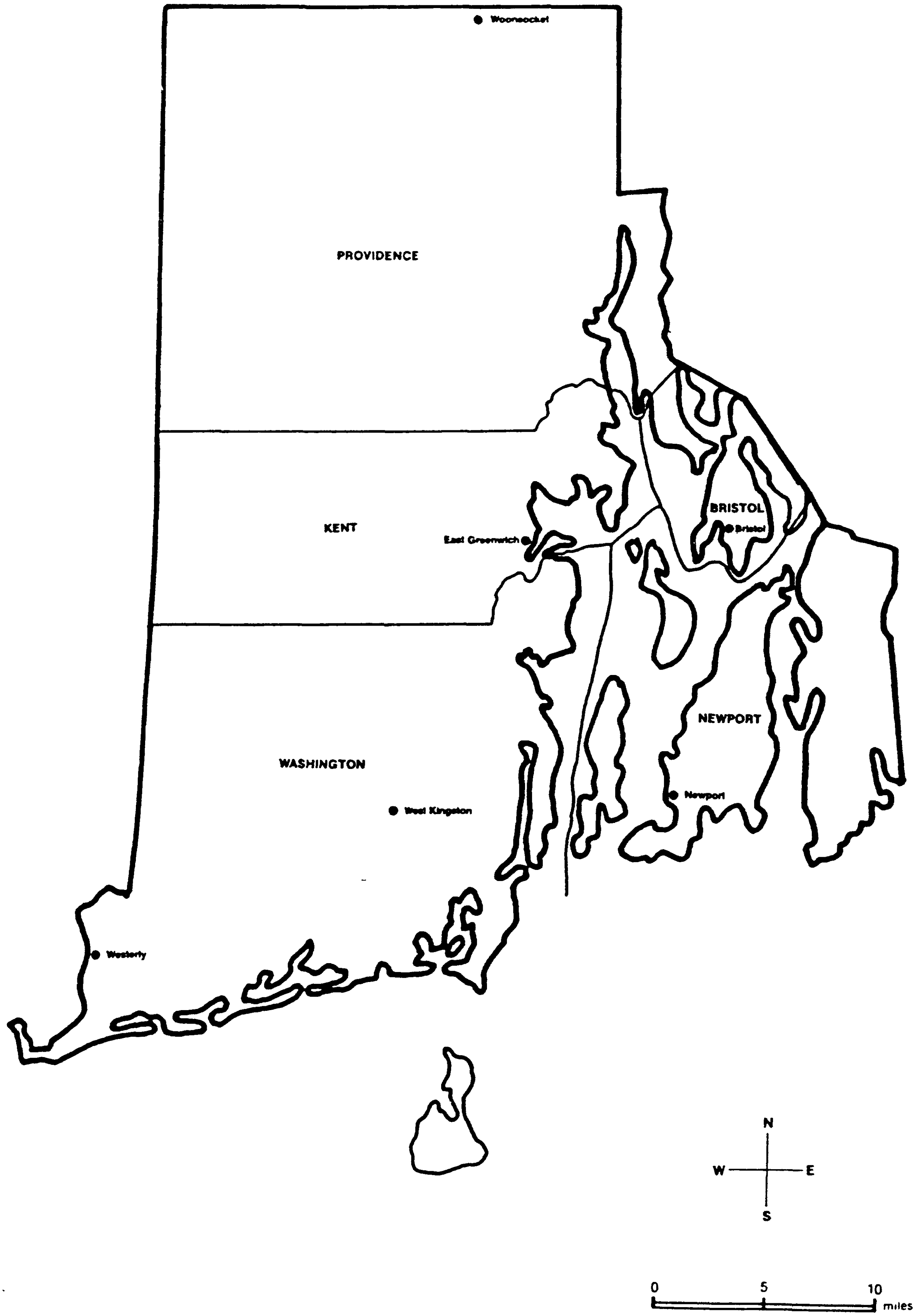


Figure 10. Rhode Island counties (from Facts on File, 1984).

GEOLOGIC RADON POTENTIAL

The geologic radon potential of Rhode Island has been investigated by Nevins (1991). Her analysis includes data on uranium concentrations in all the major rock types (Table 1), radon in water, and correlations with non-random indoor radon data collected through the Rhode Islanders Saving Energy (RISE) Program. Data from RISE (fig. 11) show that the greatest percentage of homes with 4 pCi/L or more of radon are concentrated in the southern part of the State over the Scituate, Narragansett Pier, and parts of the Esmond Igneous Suite, as well as with two areas also noted for high uranium: the northwestern corner of the State, which has anomalously high radioactivity on Popenoe's (1966) map and is underlain by the Sterling Plutonic Group, and in the East Bay Area over the granites of Southeastern Rhode Island. Frohlich and Pearson (1988) also suggested, from examining Popenoe's (1966) map, that the Scituate Granite and the Rhode Island Quincy Granite constitute significant geologic radon potential. The northern half of the Narragansett basin (where the Pennsylvanian-age sediments are less metamorphosed and thick glacial outwash is present) and the northernmost township of Woonsocket (corresponding to the Woonsocket Basin) have the lowest percentage of indoor radon readings exceeding 4 pCi/L.

Non-random data are expected to have higher readings than random data overall (White and others, 1989); however, the State/EPA data set and the RISE data do appear to agree in that both show that the southwestern half of the State has the greatest number of readings over 4 pCi/L. Nevins (1991) concluded that the lowest indoor radon is geographically associated with the Narragansett Bay Group whereas the higher percentages of indoor radon over 4 pCi/L are associated with the Scituate Igneous Suite, the alaskite gneiss in the Hope Valley Subterrane, and the Narragansett Pier granite.

The effect of glacial deposits is difficult to assess in Rhode Island since most of the materials making up the glacial deposits are locally derived and primarily reflect a collection of the surrounding bedrock. The majority of soils and glacial deposits are moderate to high in permeability and most probably enhance the geologic radon potential. Popenoe's (1966) map may reveal a secondary influence of the glacial deposits on surface radioactivity. In the southern half of the State, stratified glacial deposits appear to have lower radioactivity than areas of till over the same bedrock. Stratified glacial deposits are most common along valley floors and in the Narragansett Basin, and are thicker and generally coarser grained than the till. The thickness of the stratified deposits may damp the radioactivity of the bedrock or indicate an overall lower radioactivity for the glacial deposit. Although the coarser stratified glacial sediments have higher permeability than some of the tills, their radon emanation coefficient tends not to be as high as for some tills. Tills commonly have higher radon emanating power because of the higher proportion of finer-grained sediments. This is also true of some glacial lake deposits. Radon emanation is enhanced by the higher specific surface area of the fine-grained fraction (Schumann and others, 1991). Thick deposits of outwash sand and gravel blanket much of the northern Narragansett Lowlands and appear to have both low radioactivity and low indoor radon associated with them. The southern part of the Narragansett Lowlands and East Bay Area, however, have a significantly higher percentage of indoor radon readings greater than 4 pCi/L. This may be due to the fact that the southern part of the Narragansett Lowlands and East Bay Area are dominated by thin glacial till with components of uraniferous granite and phyllite. Another example of glacial deposit influence may be seen in the area of the Narragansett Pier Granite, where high percentages of homes with indoor radon over 4 pCi/L exist. The types of glacial deposits there include kames, glacial lake deposits, and till, which are known to have enhanced radon emanation coefficients. These glacial

Town	No. of Homes Tested
Barrington	122
Bristol	42
Burrillville	26
Central Falls	9
Charlestown	64
Coventry	120
Cranston	300
Cumberland	68
East Greenwich	200
East Providence	135
Exeter	36
Forster	24
Glocester	35
Hopkinton	17
Jamestown	28
Johnston	75
Lincoln	59
Little Compton	13
Middletown	0
Narragansett	66
Newport	106
North Kingstown	176
North Providence	42
North Smithfield	5
Pawtucket	126
Providence	433
Portsmouth	47
Richmond	24
Scituate	60
South Kingstown	102
Smithfield	94
Tiverton	92
Warren	25
Warwick	325
West Greenwich	1
West Warwick	92
Westerly	48
Woonsocket	62

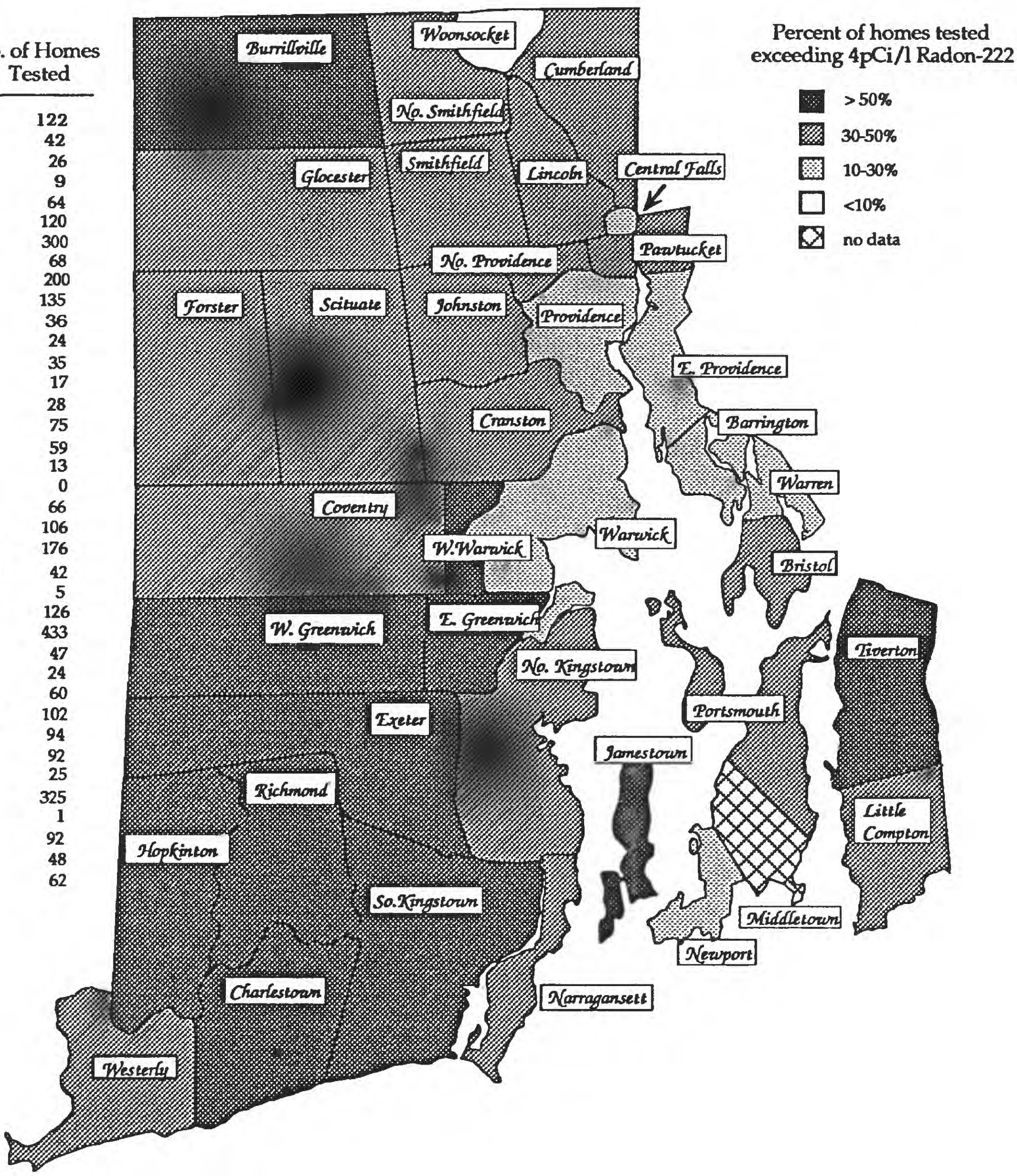


Figure 11. Screening indoor radon data by township from the RISE survey (from Nevins, 1991).

deposits may also have significant source components in the adjacent Scituate Igneous Suite and Sterling Plutonic Group as well as the Narragansett Pier granite, which all have some high uranium concentrations (fig. 5).

Although there are no obvious radioactivity anomalies associated with the major shear zones in Rhode Island, evidence from many other shear zones (Gundersen, 1991) suggests that shear zones can create isolated incidences of severe indoor radon, especially when they deform uraniferous rocks. The Hope Valley Shear zone that separates the two subterranes does have anomalous radioactivity associated with it in parts of Connecticut and may be a source of high radon in Rhode Island.

SUMMARY

For the purpose of this assessment, Rhode Island has been divided into six geologic radon potential areas and each area assigned a Radon Index (RI) and a Confidence Index (CI) score (Table 3). These areas are shown in figure 12. The RI is a semi-quantitative measure of radon potential based on geology, soils, radioactivity, architecture, and indoor radon. The CI is a measure of the relative confidence of the RI assessment based on the quality and quantity of the data used to assess geologic radon potential (see the Introduction chapter to this regional booklet for more information).

The radon potential of Rhode Island appears to be influenced most by the composition of the underlying bedrock and secondarily affected by glacial deposits. Igneous intrusive rocks of the Scituate Igneous Suite, rocks of the Hope Valley Group, granites of southeastern Rhode Island, the Narragansett Pier Granite, and alkalic granites of the Cumberland area have significant uranium concentrations and surface radioactivity and the greatest potential for creating indoor radon problems. Many of the areas underlain by these rocks also have locally derived tills, kames, and glacial lake deposits that may contribute significantly to the overall high radon potential. The lowest radon potential appears to be associated with the less metamorphosed sediments of the Rhode Island Formation that are overlain by glacial outwash deposits in the northern portion of the Narragansett Lowlands. Low to moderate radon potential appears to be associated with stratified metamorphic rocks of the Blackstone Group, the Harmony Group, the Plainfield Formation, parts of the Esmond Igneous Suite, and scattered stratified metamorphic rocks in the Narragansett Lowlands.

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

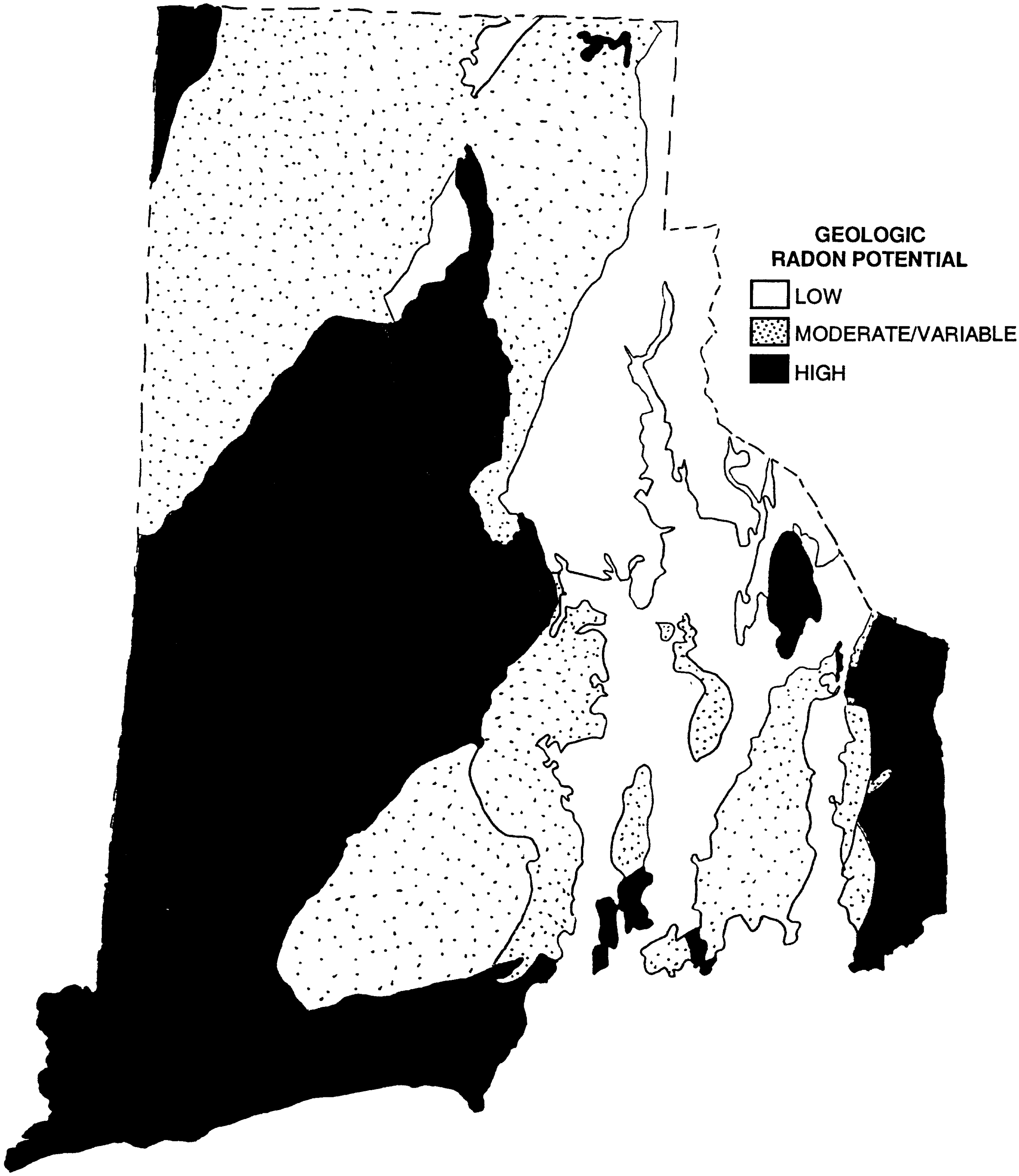


Figure 12. Geologic radon potential map of Rhode Island.

TABLE 3. RI and CI scores for geologic radon potential areas of Rhode Island.

FACTOR	Hope Valley Igneous Suite RI	Hope Valley Igneous Suite CI	Scituate Igneous Suite Eastern RI granites and Narragansett Pier RI	Scituate Igneous Suite Eastern RI granites and Narragansett Pier CI	Esmond Igneous Suite RI	Esmond Igneous Suite CI
INDOOR RADON	3	3	3	3	2	2
RADIOACTIVITY	3	2	3	2	2	2
GEOLOGY	3	3	3	3	2	2
SOIL PERM.	3	3	3	3	2	3
ARCHITECTURE	3	-	3	-	3	-
GFE POINTS	0	-	0	-	0	-
TOTAL	15	11	15	11	11	9
	High	High	High	High	Mod	Mod

FACTOR	Stratified Metamorphic Rock RI	Stratified Metamorphic Rock CI	S. Narragansett Lowlands RI	S. Narragansett Lowlands CI	N. Narragansett Lowlands/Woonsocket Basin RI	N. Narragansett Lowlands/Woonsocket Basin CI
INDOOR RADON	2	2	2	2	1	2
RADIOACTIVITY	2	2	2	2	1	2
GEOLOGY	2	2	2	2	1	2
SOIL PERM.	2	3	2	3	2	3
ARCHITECTURE	3	-	3	-	3	-
GFE POINTS	0	-	0	-	0	-
TOTAL	11	9	11	9	8	9
	Mod	Mod	Mod	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

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 VERMONT

by
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U.S. Geological Survey

INTRODUCTION

The radon potential of Vermont is generally moderate but can be variable across the State. Indoor radon data from 710 homes sampled in the State/EPA Residential Radon Survey conducted in Vermont during the winter of 1988-89 have an average of 2.6 pCi/L. Sixteen percent of the measurements exceeded 4 pCi/L. Several types of rocks in Vermont have the potential to produce high radon levels. These include granitic and micaceous metamorphic rocks in parts of the Green Mountains, Vermont Piedmont, and Northeastern Highlands, granite plutons in the Northeastern Highlands and Vermont Piedmont, graphitic and carbonaceous phyllites, slates, and schists in parts of the Taconic Mountains, Green Mountains, and Vermont Piedmont, and some clastic and carbonate sedimentary rocks in the Green Mountains, Vermont Valley, and Champlain Lowlands, including the Cheshire quartzite, breccias in the Clarendon Springs and Dunham Dolomite, and related black shales. Low radon potential is associated with mafic igneous and metamorphic rocks, including amphibolite, hornblende gneiss, gabbro, and serpentinite found throughout the State, especially in the Green Mountains, Vermont Piedmont, and Northeastern Highlands.

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

PHYSIOGRAPHIC SETTING

The physiography of Vermont (fig. 1) is in part a reflection of the underlying bedrock geology (fig. 2) and the effects of glaciation in the State. Vermont has six major physiographic regions: the Champlain Lowlands, the Taconic Mountains, the Vermont Valley, the Green Mountains, the Vermont Piedmont, and the Northeastern Highlands. Vermont's elevation ranges from 95 to 4,393 feet, with the highest elevations in the Green Mountains and the lowest elevations in the Champlain Lowlands. The Champlain Lowland is a structural trough between the Adirondacks in New York and the Green Mountains. The Lowlands have elevations generally less than 500 feet and are underlain by Cambrian-Ordovician sedimentary rocks with little or low-grade metamorphism. The Taconic Mountains lie in the southwestern part of the State and are as rugged and steep as the Green Mountains, but average elevations range from 1000-2000 feet above sea level. Cambrian through Ordovician metamorphosed sedimentary rocks form the steep to hilly topography. The Vermont Valley separates the Taconic and Green Mountains and is a long,

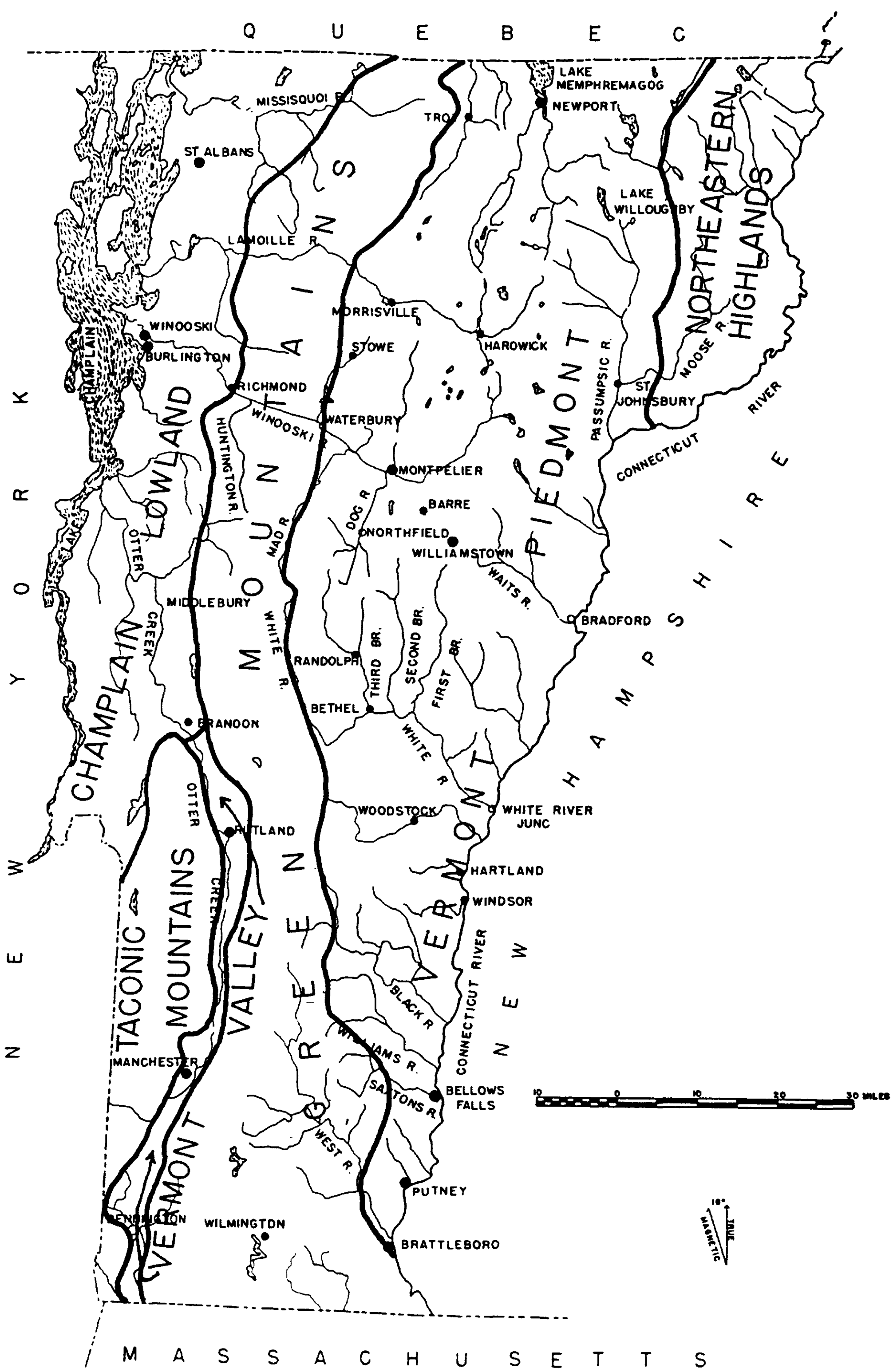


Figure 1. Physiographic areas of Vermont (modified from Stewart and MacClintock, 1969).

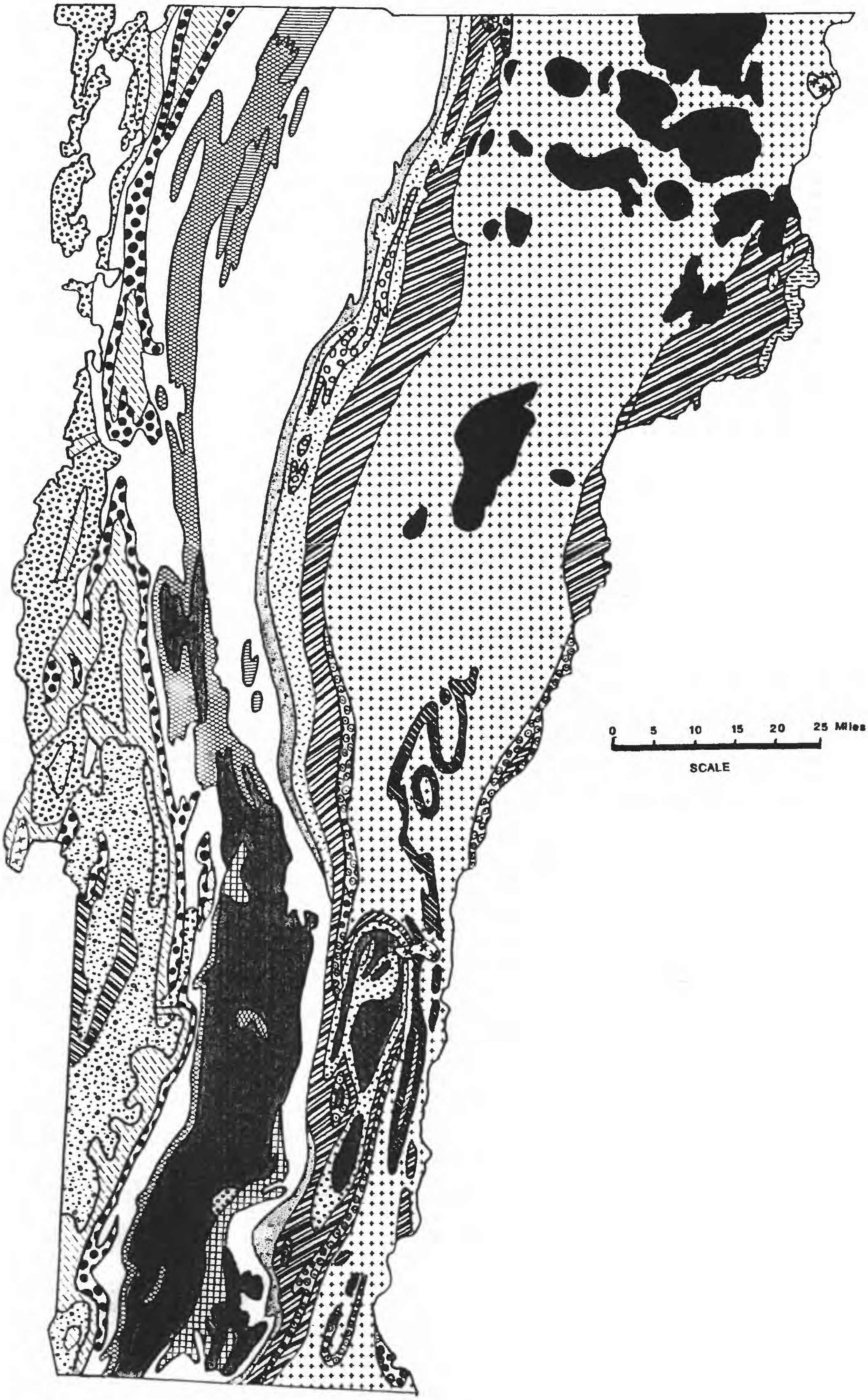


Figure 2. Generalized bedrock geologic map of Vermont (modified from Bennison, 1976).

Explanation for the Geologic Map of Vermont

Precambrian
Predominately biotite gneiss, chloritic in western areas, and amphibolite-hornblende gneiss, with minor mica schist, quartzite, calc-silicate granulite,and pegmatitic and gneissic granite of the Mount Holly Complex. Massive quartzite and micaceous quartzite associated with marble is important in western Windham and Windsor Counties and eastern Rutland County. Granitic gneiss of the Stamford gneiss in southernmost Bennington County.

Gneiss, quartzite, and calc-silicate granulite.

Gneissic biotite granite, quartz monzonite, and granodiorite.

Quartz-muscovite schist with minor marble of the Cavendish Formation. Mostly quartz-plagioclase gneiss in west-central Windham County.

Cambrian
Green, and variegated slate and phyllite of the St. Catherine Formation, black phyllite with marble interbeds of the Brezee Formation, and carbonaceous black slate of the West Castleton Formation. Graywacke sandstone of the St. Catherine and calcareous quartzite of the Hatch Hill Formation comprise about one-third the unit in northwestern Rutland County.

Schistose graywacke of the Pinnacle Formation with common quartz-cobble and boulder conglomerate near base comprises most of the rocks north of the Windsor-Rutland County line. Felspathic quartz schist, that is locally carbonaceous, and schistose quartzite of the Tyson, Dalton and Hoosac Formations dominate to the south

Albitic greenstone, locally pillowed and vesicular, of the Tibbit HIll volcanic member of the Pinnacle Formation.

Gray-green, quartz-albite schist , in places carbonaceous, of the Underhills, Hazens Notch and Hoosac Formations, carbonaceous phyllites of the Pine Hollow Formation and the Plymouth Member of the Hoosac, and quartzites, carbonates, and black phyllites and slates of the Cheshire and Monkton Quartzites, Dunham Dolomite, Forestdale Marble, Moosalamoo Phyllite, Hatch Hill and West Castleton Formations, and Parker Slate.

Quartz-plagioclase gneiss (Bull Hill Gneiss) of the Cavendish Formation overlain by locally carbonaceous, quartz-albite schist of the Hoosac Formation.

predominately dolomites and quartzites of the Winooski, Saxe Brook, Clarendon Springs, Ticonderoga, and Rock River Dolomites and the Rugg Brook, Danby, and Potsdam Formations. Upper part includes black slates, carbonates, and conglomerates of the Sweetsburg and Gorge Formations.

Black, carbonaceous phyllite and schist with quartzite interbeds of the Ottauquechee Formation.

Ordovician

Quartz-sericite phyllite and schist of the Stowe Formation. Phyllitic graywacke is an important component north of the Lamoille-Orleans county line.

Greenstone and amphibolite of the Stowe Formation.

Predominately limestone, dolomite, and marble with minor sandstone and quartzite of the Highgate, Shelbourne, Whitehall, and Strites Formations, Cutting Dolomite, Orwell, Isle La Motte, and Lowville Limestones, and Hortonville, Cumberland Head, Glens Falls,Bascom, Chipman, and Morses Line Formations.

Predominately quartzite, quartz-plagioclase granulite, and feldspathic quartzite interbedded with gray green phyllite, slate, and schist of the Missisquoi and Albee Formations. Black carbonaceous slate and phyllite increase upsection and westward in the Crum Hill Member of the Missisiquoi, and in the Ordville, Partridge, Mount Hamilton, and Pawlet Formations.

Biotite and hornblende gneiss and amphibolite of the Barnard Volcanic Member of the Missisiquoi Formation and the Partridge Formation and biotite gneiss and greenstone of the Ammonoosuc Volcanics, Ordville Formation ,and the Coburn Hill Volcanic Member of the Missisiquoi. The Ammonoosuc is composed of rhyolitic tuff, breccia, and flows in the northeast part of the state. Also includes amphibolite mapped as the Standing Pond Member of the Waits River Formation and Ordovician diorite gneiss in Windham County.

Black shale, calcareous shale, and carbonaceous slate and phyllite of the Cumberland, Hortonville, Stony Point, Iberville, and Hathaway Formations.

Granitic rocks of the Highlandcroft plutonic series.

The Pawlet Formation is gray to black, carbonaceous and pyritiferous silty slate interbedded with rusty weathering thin beds of graywacke.

Silurian-Devonian

Predominately quartzose micaceous limestone interbedded with gray phyllite and schist of the Waits River Formation, and gray phyllite and schist with micaceous quartzite interbeds of the Gile Mountain Formation and their metamorphic equivalents. Basal quartzose limestone and conglomerate of the Shaw Mountain and Clough Formations are overlain by slate and phyllite of the Northfield, Fitch, and Littletone Formations, followed by the Waits River and Gile Mountain Formations. Also includes granitic gneiss of the Bethlehem Gneiss in Windom County.

Amphibolite, garnet amphibolite and schist, hornblende maculite, and greenstone of the Standing Pond Volcanic Member of the Waits River Formation.

Granite and granitic gneiss of the New Hampshire plutonic series.

Permian/Jurassic?

Hornblende and biotite granite, diorite gneiss, augite syenites of the White Mountain plutonic series.

narrow lowland underlain by Cambrian-age metamorphosed sedimentary rocks. Elevations are generally 500 to 1000 feet. The Green Mountains are rugged, steeply sloping mountains underlain by Proterozoic to Paleozoic igneous, metamorphic, and sedimentary rocks. Elevation averages 2000 feet and the mountains form a central topographic high trending north to south across the State. To the east of the Green Mountains lies the Vermont Piedmont, which is part of the New England Upland. It is underlain by Paleozoic metavolcanic and metasedimentary rocks that are intruded by igneous plutonic rocks. This part of the New England Upland is a dissected plateau with numerous steep-sided valleys and undulating to hilly topography averaging 1000-2000 feet above sea level. The Northeastern Highlands, in the northeastern corner of the State, are the western margin of the White Mountains of New Hampshire. The mountains comprise late Paleozoic to Mesozoic-age igneous rocks intruded into Silurian-Devonian metasedimentary and metavolcanic rocks. Elevations are generally 1000-2000 feet with several mountains reaching 3000 feet or more.

In 1990, the population of Vermont was 562,758, including 34 percent urban population (fig. 3). The average population density is approximately 58 persons per square mile. The climate of Vermont is temperate, with considerable temperature extremes and heavy snowfall in the mountains. Winter temperatures can drop to -30° F, and summer temperatures are generally less than 90° F. Average precipitation ranges from 34 to 40 inches per year (fig. 4) and is highest in the Green Mountains.

GEOLOGIC SETTING

The metamorphic and sedimentary rocks of Vermont form folded and faulted, north-south trending belts that are intruded by a series of granitic plutons in the eastern part of the State. Cambrian and Ordovician rocks are bounded by large north-south trending thrust belts in the western part of the State, most notably in the Taconic Mountains of the southwest. Proterozoic igneous and metamorphic rocks form the core of a large anticlinorium in the southern Green Mountains and Devonian metasedimentary and metavolcanic rocks form the core of a large synclinorium in the northern Vermont Piedmont. A detailed lithologic description of the important rock units is provided below. The geologic descriptions that follow are derived from Doll and others (1961) and a general geologic map is given for reference in figure 2. It is suggested, however, that the reader refer to the published Geologic Map of Vermont (Doll and others, 1961) and other publications available from the State Geological Survey of Vermont.

The Green Mountains

The Green Mountains contain the oldest rocks in the State and are underlain predominantly by biotite gneiss, amphibolite, and hornblende gneiss of the Mount Holly Complex, thought to be Proterozoic-Y age. Quartzite that is locally micaceous, graphitic schist, and marble comprise fold belts within the Mount Holly Complex, particularly in western Windham and Windsor Counties and eastern Rutland County. The Stamford Gneiss, a granitic gneiss, underlies a small area in southernmost Bennington County and a small body of gneissic granite and quartz monzonite is located in western Windham County. Proterozoic-Z rocks are predominantly quartz-muscovite schist with minor marble of the Cavendish Formation, which grade northward into quartz-plagioclase gneiss in west-central Windham County. Slate and phyllite in southwestern Bennington County is also thought to be Proterozoic-Z age.

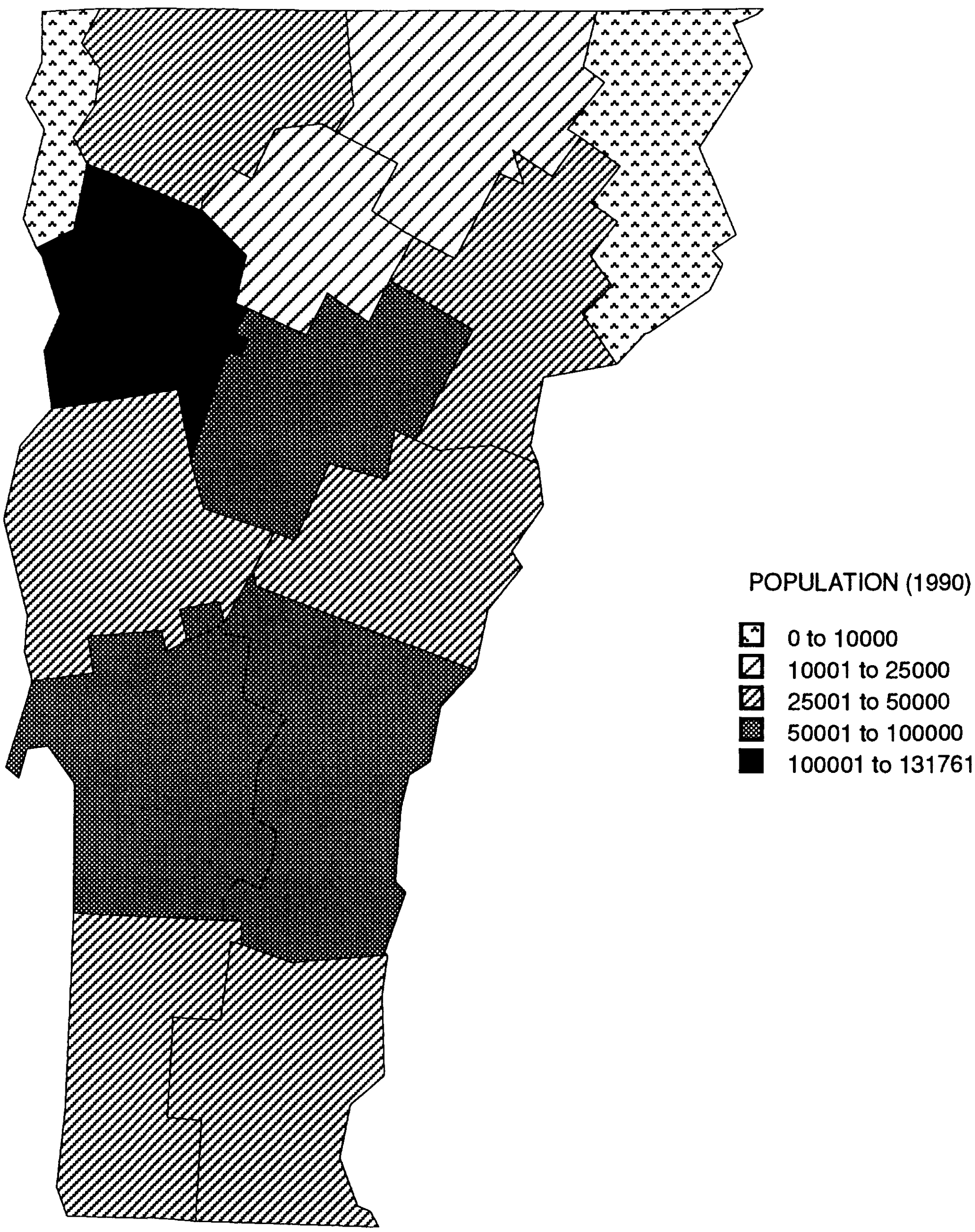


Figure 3. Population of counties in Vermont (1990 U.S. Census data).

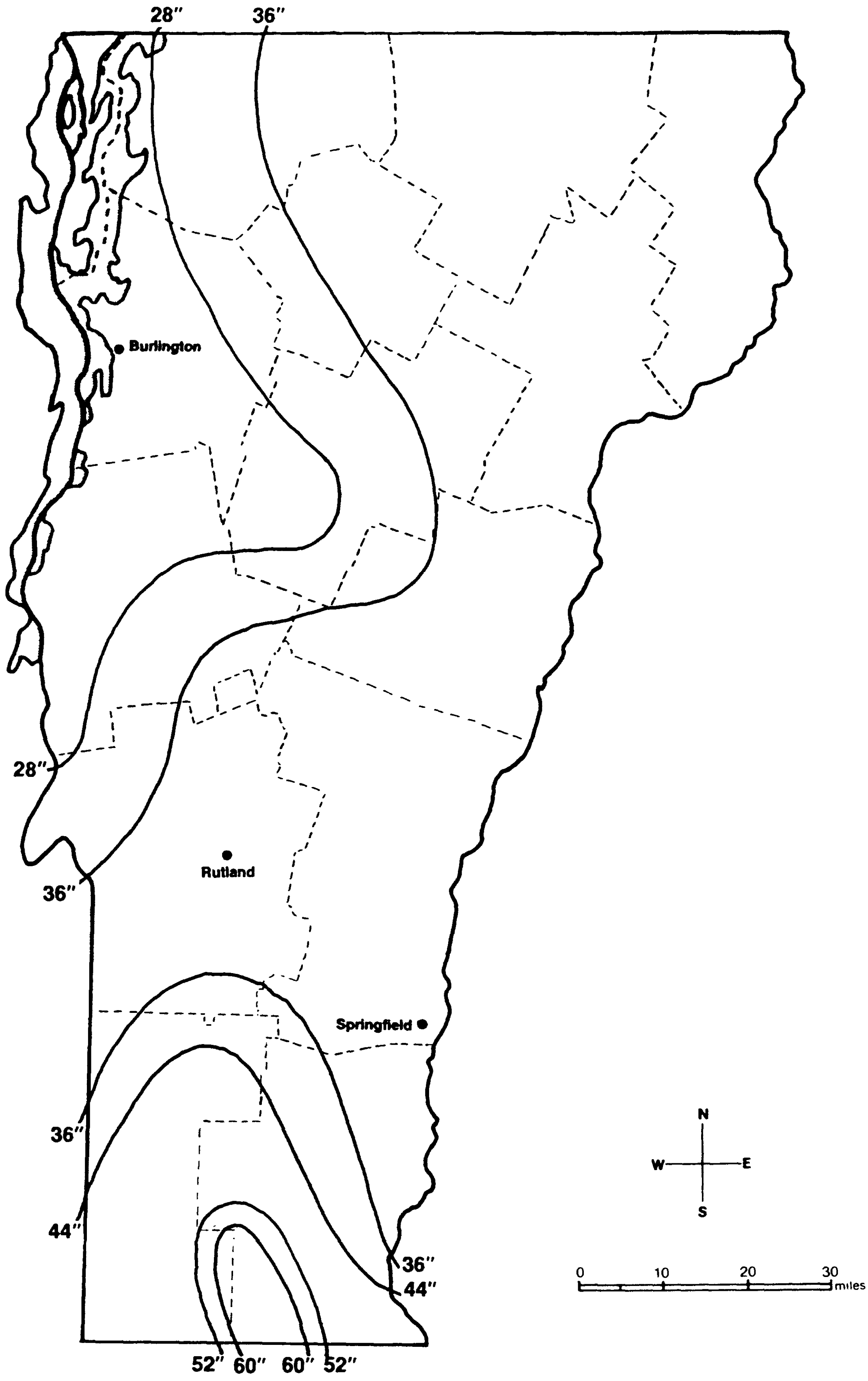


Figure 4. Average annual precipitation in Vermont (from Facts on File, 1984).

Cambrian rocks dominate the northern half of the Green Mountains. The belt of late Proterozoic-early Cambrian rocks that forms the western margin of the Green Mountains is characterized by schistose graywacke of the Pinnacle Formation, north of the Windsor-Rutland county line The Pinnacle graywackes intertongue northward with albitic greenstone of the Tibbet Hill Member in Lamoille County. Locally carbonaceous, gray-green feldspathic quartz schist and schistose quartzite of the Tyson, Dalton, and Hoosac Formations comprise equivalent age rocks to the south and dominate the broad belt of Lower Cambrian rocks in the eastern Green Mountains. This belt also includes the Underhill and Hazens Notch Formations to the north and the Hoosac Formation to the south. These rocks become more micaceous and phyllitic upsection to the west and south and include the Pinney Hollow Formation and the dolomitic, carbonaceous Plymouth Member of the Hoosac Formation. The easternmost edge of the Green Mountains consists of a narrow band of black, carbonaceous phyllite and schist with quartzite interbeds of the Ottauquechee Formation. The westernmost portion of the southern Green Mountains is underlain by the Cheshire and Monkton Quartzites, Dunham Dolomite, Forestdale Marble, and the black, carbonaceous Moosalamoo Phyllite and Parker Slate. In eastern Windsor and Windham Counties, a narrow belt of Bull Hill Gneiss, a quartz-plagioclase gneiss, overlies the Mount Holly Complex and is overlain by narrow belts of the Hoosac and Underhill Formations.

Champlain Lowlands and Vermont Valley

In the Champlain Lowlands, the easternmost bedrock is a belt of Pinnacle Formation graywackes and albitic greenstones, overlain by Cheshire Quartzite, and bounded on the west by the Hinesburg thrust fault. West of this fault and south into the Vermont Valley, the Cambrian rocks consist predominantly of dolomites and quartzites, including the Winooski, Saxe Brook, Clarendon Springs, Ticonderoga, and Rock River Dolomites, as well as the Cheshire, Monkton, Rugg Brook, Danby, and Potsdam Formations. The Dunham Dolomite comprises the most extensive outcrop belt within these units. The upper part of the Cambrian sequence in the Champlain Lowlands includes black slates, carbonate rocks, and conglomerates of the Sweetsburg and Gorge Formations. The Sweetsburg forms a prominent unit extending across the Franklin-Chittenden county line. The Champlain thrust belt is the western boundary of most of the Cambrian rocks in the Champlain Lowlands.

The lower Ordovician rocks in the Champlain Lowlands and Vermont Valley consist predominantly of limestone, dolomite, and marble with minor calcareous sandstone and quartzite of the Highgate, Shelburne, Whitehall, and Strites Formations; Cutting Dolomite; Orwell, Isle La Motte, and Lowville Limestones; and Hortonville, Cumberland Head, Glens Falls, Bascom, Chipman, and Morses Line Formations. These units form narrow outcrop belts, except the Bascom Formation, which forms a broader belt of limestone, marble, quartzite, and conglomerate in the Vermont Valley. This sequence is overlain to the west, in the Champlain Lowlands, by a belt of black shale, calcareous shale, and carbonaceous slate and phyllite of the Cumberland, Hortonville, Stony Point, Iberville, and Hathaway Formations.

The Taconic Mountains

Cambrian-age rocks in the Taconic Mountains are dominated by green and variegated slate and phyllite of the St. Catherine Formation, black phyllite with marble interbeds of the Brezee Formation, and carbonaceous black slate of the West Castleton Formation. Graywacke sandstone of the St. Catherine Formation and calcareous quartzite of the Hatch Hill Formation make up about one-third of the Cambrian rocks underlying northwestern Rutland County. A narrow, U-shaped belt of Ordovician rocks, consisting of black to variegated shales interbedded with quartzites and limestones of the Mount Hamilton Formation, overlain by black carbonaceous shale of the Pawlet Formation, lies along the State's western border.

Vermont Piedmont and Northeastern Highlands

The western Vermont Piedmont is underlain by a belt of quartz-sericite phyllite and schist of the Stowe Formation that intertongues with phyllitic graywacke and volcanic greenstone and amphibolite north of the Lamoille-Orleans county line. These rocks are overlain to the east by a belt of predominantly quartzite, quartz-plagioclase granulite, and feldspathic quartzite interbedded with gray-green phyllite, slate, and schist of the Missisquoi Formation. Black carbonaceous slate and phyllite become more abundant upsection to the east in the Crum Hill and Whetstone Members of the Missisquoi. South of the Orange-Windham county line, biotite and hornblende gneiss and amphibolite of the Barnard Volcanic Member of the Missisquoi Formation forms an eastern belt. In northernmost Orleans County, the Coburn Hill Volcanic Member of the Missisquoi, consisting of greenstone and hornblende amphibolite, comprises half the width of the outcrop belt. The sedimentary and volcanic rocks of the Missisquoi extend south along the eastern margin of the Green Mountains in Windham County.

Along the eastern margin of the Vermont Piedmont and the southern end of the Northeastern Highlands, quartzites and feldspathic quartzite, interbedded with gray-green slate and phyllite of the Albee Formation, dominate the Ordovician sedimentary rocks. South of the Caledonia-Orange county line, black carbonaceous slate and phyllite of the Partridge and Orfordville Formations comprise most of the narrow belts. Greenstone, chloritic schist, and amphibolite of the Post Pond Volcanics in the Orfordville Formation comprise a prominent belt across the Orange-Windsor county line. The Ammonusac Volcanics, consisting of biotite gneiss and greenstone in the southern part of the State and rhyolitic tuff, breccia, and flows in the northeastern part of the State, form small, isolated patches along the belt. Other Ordovician rocks include granitic rocks of the Highlandcroft Plutonic series in eastern Essex County and isolated patches of biotite-quartz diorite gneiss of the Oliverian Plutonic series.

Most of the Vermont Piedmont and Northeastern Highlands are underlain by the Devonian Waits River and Gile Mountain Formations. The Waits River forms two broad outcrop belts in the central and western portions of the Vermont Piedmont that join to the south. It consists of quartzose micaceous limestone interbedded with gray quartz phyllite and schist. The western belt is less quartzose and more phyllitic than the central belt. In the southern part of the Vermont Piedmont, amphibolite, garnet amphibolite, schist, and greenstone of the Standing Pond Volcanic Member of the Waits River Formation forms several narrow belts. The Gile Mountain also forms two broad belts that join to the south and to the north underlying most of the northern part of the Highlands. The Gile Mountain Formation consists of gray phyllite and schist with micaceous quartzite interbeds. A narrow belt of gray slate comprises the easternmost margin of the formation. Along the western margin of the Vermont Piedmont, a very narrow belt of Silurian quartzites, conglomerates and limestones of the Shaw Mountain Formation is overlain by a narrow belt of black slate or phyllite with thin limestone beds of the Northfield Formation. In the eastern portion of the Northeastern Highlands and the southeastern most part of the Green Mountains, the Silurian to Devonian transition comprises narrow belts of the Clough Formation conglomerate and quartzite, the Fitch Formation limestone and dolomite, and gray slate and phyllite of the Littleton Formation.

Several large granite and granitic gneiss bodies of the New Hampshire plutonic series intrude the sedimentary rocks of the northern Vermont Piedmont and Northeastern Highlands. Where these intrude the sedimentary rocks they are commonly altered to more metamorphic assemblages. Granite and granitic gneiss of the Bethlehem Gneiss also forms some small intrusive bodies. In northeastern Essex County, Monadnock Mountain is underlain by hornblende, biotite, quartz, and augite syenites of the White Mountain plutonic series.

GLACIAL GEOLOGY

Deposits of three Wisconsinan (Late Pleistocene) glacial advances in Vermont have been recognized or inferred from surface or subsurface data. The Bennington Glacial Stade is the first positively identified glacial advance that left datable deposits in Vermont. During this period, glaciers advanced across the State from the northwest and covered all of Vermont (Stewart and MacClintock, 1969). The Shelburne Stade followed the Bennington and was marked by a glacial advance from the northeast that covered all but the extreme southern part of Vermont. The Burlington Stade marked the final Pleistocene glacial advance, which progressed across Vermont from the north-northwest, covering the Champlain Lowland, all of the Green Mountains north of Brandon, and the Memphremagog Basin in northern Vermont (Stewart and MacClintock, 1969). Between each advance was a period of weathering and erosion called an interstade. Glacial lakes occupied several valleys during the interstades and following the final retreat of glaciers from Vermont, which occurred about 12,500 years ago (Stewart and MacClintock, 1969). Major glacial lakes include Lake Vermont, which occupied the Champlain Lowland; Lake Hitchcock in the Connecticut Valley; a lake in the Manchester-Bennington area of the southern Vermont Valley; and lakes that occupied the Memphremagog Basin and the Lamoille, Winooski, Huntington, and Mad Dog River valleys in north-central Vermont (Stewart and MacClintock, 1969). Glacial lake deposits in parts of the Champlain Lowland are overlain by marine deposits from a postglacial incursion of the sea into the lowland about 11,900 years ago (Stone and Borns, 1986) when sea level rose due to input of water from melting glacial ice. The sea subsequently retreated when the land surface rose due to postglacial rebound.

Figure 5 is a generalized map of glacial deposits in Vermont. Three main classes of glacial deposits are shown on the map—till, glaciofluvial deposits, and glacial lake and marine sediments. Each of these general units is further subdivided into units which reflect the origin of the deposits in more detail. Except where noted, the following discussion is condensed from Stewart and MacClintock (1969, 1970).

Till is the most common and widespread type of glacial deposit in Vermont. It is an unsorted deposit of gravel, sand, silt, and clay, with occasional cobbles and boulders, that was left by the glacier. Thickness of the till ranges from a thin, discontinuous veneer of less than one meter to more than 30 meters in some valleys, but it is generally less than 8 m thick. Till is typically thinner on uplands and thicker in valleys. The composition of the till typically reflects the underlying bedrock, and sandy till is much more common in Vermont than clayey till. There are two distinctly different types of till in Vermont. One is a dense, compact till containing rounded, striated boulders and a relatively high amount of erratics (cobbles and boulders from distant bedrock sources), called basal till. The clay content of basal till is generally less than 30 percent; however, basal till usually contains a significant amount of silt, which together with the clay is responsible for the compactness of the basal till. The other type of till is a loosely packed, very sandy till containing angular boulders of local bedrock and little or no clay. This type of till is

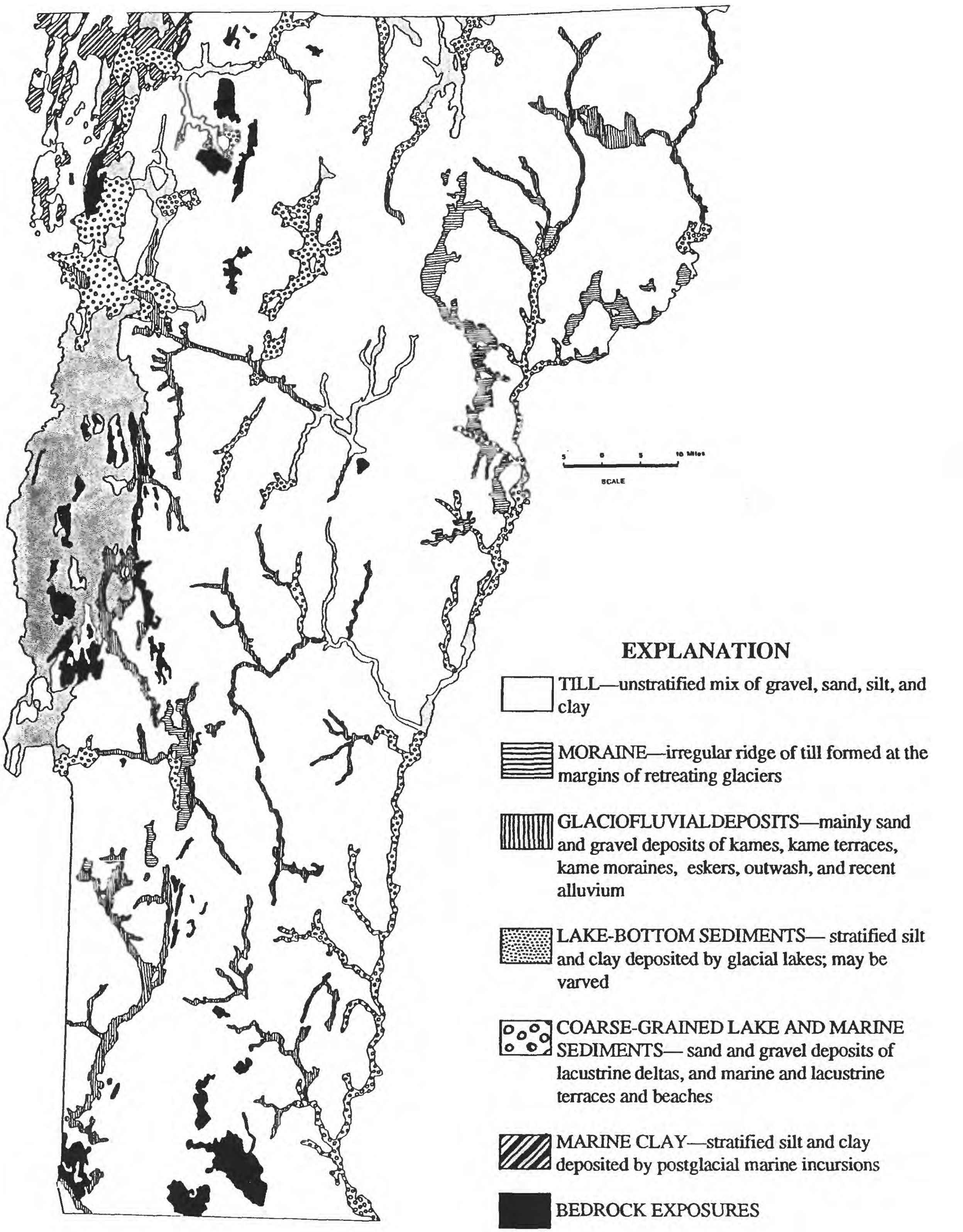


Figure 5. Generalized glacial geologic map of Vermont (after Stewart and MacClintock, 1969).

called ablation till. Ablation till is the upper till unit, always overlying either basal till or bedrock. Often the ablation till and underlying basal till have fabrics (orientations of elongated pebbles and glacial striations) oriented in different directions, indicating that the two till units were deposited during different glacial episodes. These two types of till are found throughout most of New England and are more commonly referred to simply as the "upper till" and "lower till" (Richmond and Fullerton, 1991, 1992). The two types of till are not differentiated on the surficial geologic map of Vermont (Stewart and MacClintock, 1970), of which figure 5 is a generalized version. Glacial landforms typically associated with till include drumlins, kettles, and moraines. Moraines are accumulations of till deposited at the margins of retreating ice and are not common features to Vermont. Only a few significant moraines occur in three regions in Vermont—the St. Johnsbury region in northeastern Vermont, the Rutland area in the west-central portion of the State, and the Manchester-Bennington area of southwestern Vermont (fig. 5).

Glaciofluvial deposits are stratified sediments deposited by glacial meltwater adjacent to, or in front of, the ice margin. These ice-marginal or ice-contact deposits include kames, kame terraces, kame moraines, eskers, and outwash deposits. Characteristic of all types of glaciofluvial deposits is their coarse texture, being composed primarily of sand and gravel. Kame terraces formed between the edge of a glacier and a valley wall. They are one of the most common glacial features in Vermont and constitute a significant source for sand and gravel in the State. Kame moraines are deposits of gravel that formed in front of the glacier and have topography similar to that of a till moraine. Eskers are sinuous ridges composed of outwash sand and gravel deposited by rivers that flowed in tunnels underneath an ice sheet or valley glacier. Eskers in Vermont range from highly discontinuous to long, sinuous ridges that can be traced for many kilometers; for example, an esker in the Passumpic Valley extends from West Burke southward beyond St. Johnsbury, a distance of almost 39 km (Stewart and MacClintock, 1969). Outwash gravel was deposited in some valleys by rivers that drained the melting glaciers; however, it is a relatively uncommon type of glacial deposit in Vermont.

Lacustrine (lake) and marine sediments are layered silts and clays deposited by large postglacial lakes and in marine (ocean) environments, respectively. Because the valleys and lowlands were the sites of final melting of stagnant ice masses, drainage was blocked and many small lakes developed. Larger lakes, including Lake Vermont, which occupied the Champlain Lowland, were dammed by glacial ice or by moraines. Lake-bottom sediments consist of silt and clay, shallow-water sediments are composed primarily of sand, and beach and delta deposits contain primarily sand and gravel. Marine sediments have characteristics similar to lacustrine sediments, in that they also are classified into fine-grained bottom deposits, sandy shallow-water deposits, and sand and gravel beach and deltaic deposits. Marine sediments were deposited in the Champlain Lowland when sea level rose and the ocean invaded the Champlain Lowland.

SOILS

Soils in Vermont include Inceptisols, mineral soils with horizons of alteration or accumulation of metal oxides such as iron, aluminum, or manganese; Spodosols, acid soils with subsurface accumulations of organic matter and compounds of aluminum and iron; Entisols, mineral soils with no discernible horizons because their parent material is inert (such as quartz sand) or because the soils are very young; and Alfisols, moist soils with subsurface horizons of clay accumulation (U.S. Soil Conservation Service, 1987). Figure 6 is a generalized soil map of Vermont. The following discussion is condensed from the general soils map of Vermont (U.S.

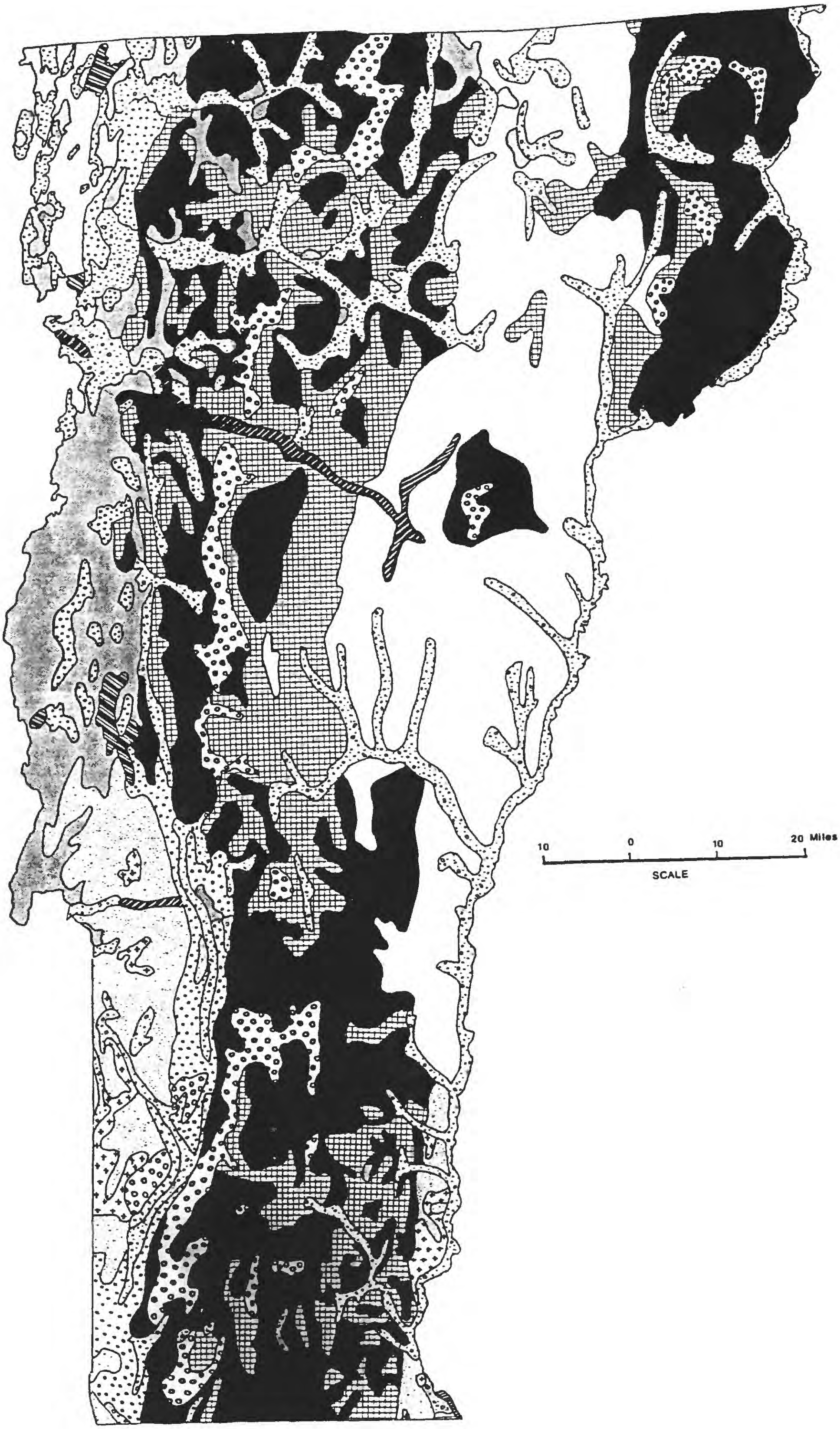


Figure 6. Generalized soils map of Vermont (after U.S. Department of Agriculture, 1982)

GENERALIZED SOIL MAP OF VERMONT
EXPLANATION

Soils on lake plains in the Champlain Valley—silty clays and clays with low permeability

Soils on glacial till uplands in the Champlain and Vermont Valleys—silty, sandy, and gravelly loams with low to moderate permeability

Soils within the Taconic Mountains and southeastern uplands adjacent to the Connecticut River

Areas dominated by deep, loamy soils—silty and sandy loams with low to moderate permeability

Areas dominated by shallow and moderately deep, loamy soils—silty loams with moderate permeability

Soils within the Green Mountains and associated foothills

Areas dominated by deep, loamy soils—silty loams, fine sandy loams, and gravelly loams with low to moderate permeability

Areas dominated by shallow and moderately deep, loamy soils—fine sandy loam and gravelly sandy loams with moderate permeability

Soils at high elevations with cryic soil temperature—silty and fine sandy loams with moderate permeability

Soils within eastern upland areas—loam, silty loam, and fine sandy loam with moderate permeability

Sandy and gravelly soils developed on stream terraces, outwash plains and terraces, kames, eskers, moraines, and deltas—sand, loamy sand, gravelly sand, and gravel with moderate to high permeability

Soils on bottomlands—silty and fine sandy loam with moderate permeability

Soils in swamps and marshes—Histosols (muck and peat)

Department of Agriculture, 1982) and from soil interpretation records ("Soils-5" forms) provided by the U.S. Soil Conservation Service for each of the soil series in the State (the information on the soil interpretation records can also be found in county soil surveys). State- and county-scale soil survey reports should be consulted for more detailed descriptions and information.

Soils developed on glacial lake deposits in the Champlain Lowland (fig. 6) are deep, poorly to moderately drained, silty loam, silty clay, and clay. This map unit also includes soils formed on deposits of small lake plains in northwestern Vermont. These soils have low permeability and are typically wet at least part of the year. Soils of marshes and swamps occupy some low-lying areas in the Champlain Lowland (fig. 6). These soils are organic-rich Histosols derived from muck and peat. These soils have low to high permeability but are commonly water-saturated.

Soils formed in glacial till on uplands within the Champlain and Vermont Valleys consist of shallow to deep, poorly to well drained, silty, sandy, and gravelly loams and loams. The till parent materials are derived primarily from limestone and metamorphic rocks. Soils of this group with clayey B horizons have low permeability; soils of this group with friable (loosely packed, easily separated, and permeable) substrata have moderate permeability.

Soils of the Taconic Mountains and soils of the uplands adjacent to the Connecticut River in southeastern Vermont are represented by two map units (fig. 6). Soils on lower slopes and valley floors are deep, moderately well to well drained, silty and sandy loams developed in till. Soils of this type, have firm substrata, low permeability, and are seasonally wet. Soils on steeper slopes in the Taconic Mountains and southeastern Vermont are shallow to moderately deep, excessively drained silt loams developed in glacial till with moderate permeability. Soils of both units are developed on glacial tills derived primarily from schist, phyllite, slate, and shale.

Soils of the Green Mountains and associated foothills cover about one-third of the State's land area (fig. 6). Moderately deep to very deep, poorly drained to moderately well drained, silty, sandy, and locally gravelly loams developed on compact, loamy till derived from schist and gneiss occur in the southern Green Mountains and in the foothills in the northern part of the State. Most of these soils have firm substrata and low permeability, and poorly drained soils of this unit may be wet at least part of the year. About one-third of the soils in this map area have moderate permeability. Soils in the northern Green Mountains are shallow to moderately deep, well drained, silty loams, fine sandy loams, and locally gravelly loams formed on loamy glacial till derived from schist and other metamorphic rocks. These soils have moderate permeability.

Soils at high elevations with cryic soil temperature (mean annual soil temperature is 0-8°C at 50 cm depth) are shallow to moderately deep, well drained silty and fine sandy loams developed on glacial till derived from mica schist. These soils have moderate permeability.

Soils within the eastern upland areas of Vermont are shallow to deep, well drained to excessively drained, fine sandy loams and silty loams developed in glacial till that is derived primarily from schist. These soils have moderate permeability and typically have friable substrata.

Soils developed on glacial outwash plains and outwash terraces, kames, eskers, moraines, lacustrine deltas, and stream terraces are deep, well drained to excessively drained (poorly drained on some floodplains), sands and loamy sands to gravelly sands and gravels. These soils occur adjacent to the Connecticut River and in the lower parts of many drainages in the upland areas of Vermont (fig. 6). These soils have moderately high to high permeability, but have low permeability to air if they are wet. Soils of bottomlands and floodplains are deep, poorly drained to moderately drained, silty loams and fine sandy loams. These soils have moderate permeability but they are commonly wet and subject to flooding.

RADIOACTIVITY

An aeroradiometric map of Vermont (fig. 7) compiled from the National Uranium Resource Evaluation (NURE) flightline data (Duval and others, 1989) shows several areas of high radioactivity (> 2.5 ppm) associated with rocks of the Mount Holly complex, phyllites and slates in the western Taconic Mountains (possibly the Pawlet Formation), granite exposed at Ascuteny Mountain, the Cheshire Quartzite in several parts of the Green Mountains, carbonaceous phyllite and schist in the Pinney Hollow Formation, graphitic schist and phyllite in several areas of the Green Mountains and Vermont Piedmont, and several of the granitic bodies in the Vermont Piedmont and Northeastern Highlands. Uranium deposits in hydrothermal veins account for a number of the anomalies in these rocks. Low radioactivity (<1.5 ppm eU) is found in northernmost Vermont, southern Vermont and parts of the Champlain Lowlands and Vermont Valley, associated most commonly with mafic metavolcanic and igneous rocks, diorite, and several of the Paleozoic carbonate and clastic rock units. Moderate radioactivity (1.5-2.5 ppm) covers most of central Vermont, especially in the Vermont Piedmont and Green Mountains.

There are several reports on radioactivity and uranium occurrences in Vermont. Popenoe's map (1964) of the aerial radioactivity of the southern half of Vermont includes geologic maps and descriptions describing the data and its association with geology. Several NURE reports present aerial radioactivity data (compiled in Duval and others, 1989) and stream sediment data for parts of Vermont (Cook and Koller, 1980; Cook, 1981a, b, c). Ratté and Vanacek (1980) have compiled a radioactivity map of Vermont derived from Popenoe (1964), NURE, and other available aerial and ground radioactivity surveys, as well as uranium occurrence data. Olszewski and Boudette (1986) have compiled a generalized geologic map of New England with emphasis on uranium endowment and radon production. Washington (1988) discusses some of the deposits containing the highest concentrations of uranium in southern Vermont.

In the Champlain Lowlands and Vermont Valley, Ratté and Vanacek (1980) have identified the Clarendon Springs and Dunham Dolomites as possible sources of uranium. Samples from Milton and Highgate have yielded high uranium concentrations in carbonate breccias of the Clarendon Springs. The radioactivity map of Duval and others (1989, fig. 7) shows some high to moderate radioactivity, particularly in Chittenden County associated with the Paleozoic clastic and carbonate rocks including the dolomites. Olszewski and Boudette (1986) classify these rocks as variable, with increasing uranium as metamorphic grade increases, and note local uranium concentrations in fractures and faults.

Ratté and Vanacek's (1980) uranium province map shows all the rocks of the Green Mountains as possible uranium resources. According to the authors, uranium is concentrated in veins within quartzite, in tourmaline-bearing pegmatites, in migmatite, in biotite-rich zones in mica schist, along fracture surfaces, and in shear zones. Uranium is also associated with graphite, pyrite, garnet, and blue quartz. High concentrations of accessory minerals such as uraniferous monazite, allanite, and zircon are local sources of high uranium concentrations. These minerals are common in the schists and gneisses of Vermont and may form placer-type deposits in Pleistocene to Recent gravels in river and stream sediments. Washington (1988) describes an unusually abundant occurrence of uraniferous allanite in a extensive hydrothermal deposit at Searsburg Ridge. Olszewski and Boudette (1986) classified the Green Mountains as variably low to high with a tendency for enrichment in the higher-grade metamorphic zones of quartzo-feldspathic (granitic) rocks, in veins, in accessory minerals and along grain boundaries.

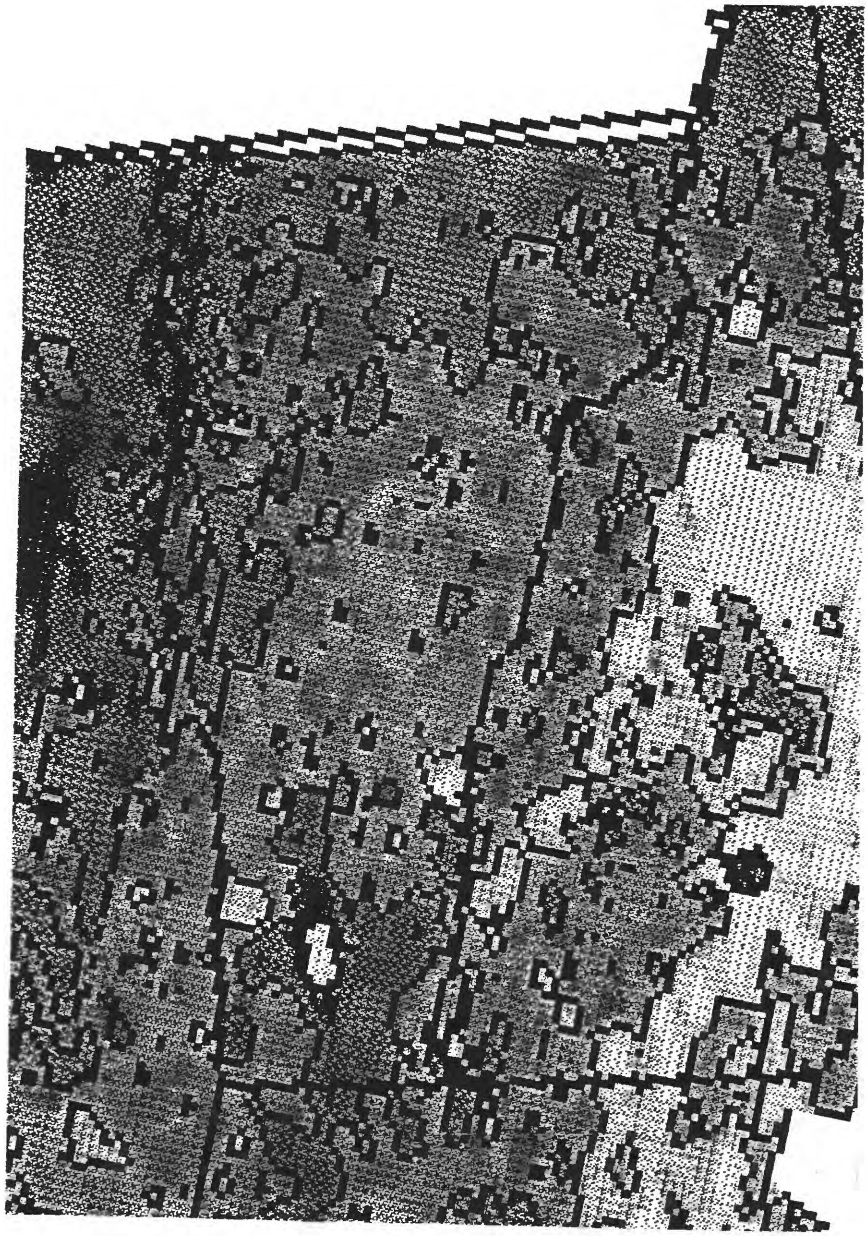


Figure 7. Aerial radiometric map of Vermont (after Duval and others, 1989). Contour lines at 1.5 and 2.5 ppm equivalent uranium (eU). Pixels shaded at 0.5 ppm eU increments; darker pixels have lower eU values; white indicates no data.

The Taconic Mountains have generally moderate to high radioactivity (fig. 7) but only a few uranium occurrences are reported from the northernmost part of the Taconic Mountains in the St. Catherine Formation (Ratté and Vanacek, 1980). The radioactivity (fig. 7) appears to be associated with carbonaceous and pyritic phyllites and slates of the Pawlet Formation. Similar kinds of black and carbonaceous slates also comprise the West Hill and West Castleton Formations.

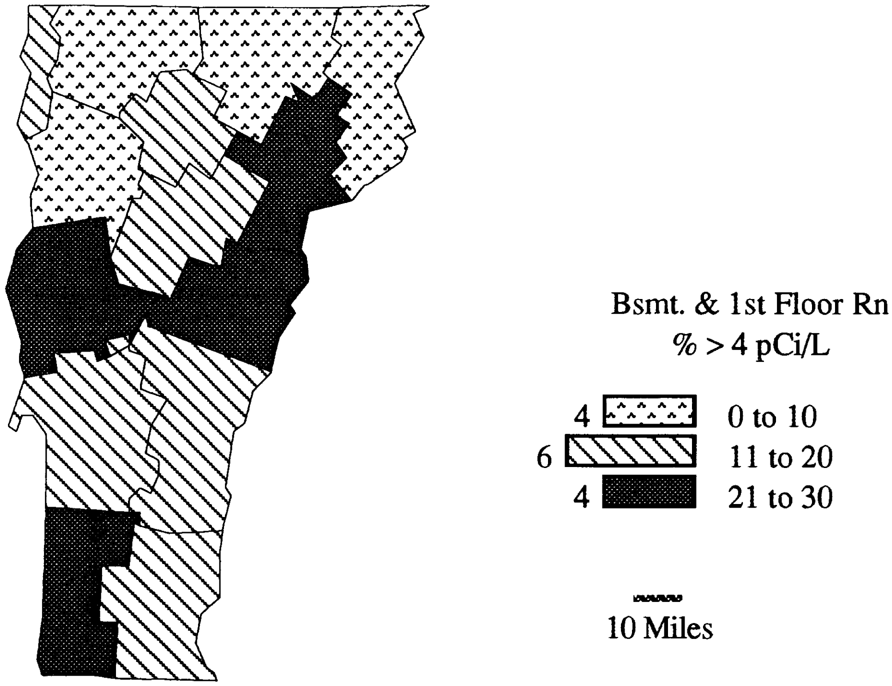
Olszewski and Boudette (1986) classified the igneous plutons of the Vermont Piedmont and Northeastern Highlands as two-mica granites with moderate to very high uranium enrichment. Uranium in these rocks occurs as primary uranium oxides such as uraninite or in abundant accessory minerals. They classify the Paleozoic metasedimentary and metavolcanic rocks of these areas as variable, with increasing uranium as metamorphic grade increases and local uranium concentrations in fractures and faults. Ratté and Vanacek (1980) designated the igneous plutons and granites of Ascuteny and Manadonock Mountains as uranium resources. These two mountains have distinct radiometric highs but the other plutons are variable in their radioactivity. The large pluton that underlies Knox, Spruce, and Hardwood Mountains along the Caledonia-Washington county line and the pluton in the vicinity of Lake Willoughby have distinct radiometric highs. The Giles Mountain and Waits River Formations underlie most of the Vermont Piedmont and several analyses cited in Ratté and Vanacek (1980) indicate an overall enrichment of uranium but at relatively lower concentrations, between 3 and 7 ppm of uranium.

INDOOR RADON

Indoor radon data from 710 homes sampled in the State/EPA Residential Radon Survey conducted in Vermont during the winter of 1989 are shown in figure 8 and listed in Table 1. A map of counties is included for reference (fig. 9). Indoor radon was measured by charcoal canister. The maximum value recorded in the survey was 47 pCi/L in Addison County. The average indoor radon for the State was 2.6 pCi/L and the 16.6 percent of the homes tested had indoor radon levels exceeding 4 pCi/L. Notable counties include Addison and Caledonia, with average indoor radon concentrations greater than 4 pCi/L, probably associated with the metamorphic and igneous rocks of the Green Mountains and Vermont Piedmont and with elevated uranium concentrations in some of the Paleozoic sedimentary rocks. Low (< 2 pCi/L) county indoor radon averages in Chittenden, Franklin, and Grand Isle Counties appear to be associated with the Champlain Lowlands. Generally moderate county indoor radon averages are found throughout the rest of Vermont.

GEOLOGIC RADON POTENTIAL

The geologic radon potential of the Champlain Lowlands is low, with areas of locally moderate to high radon potential possible. The Vermont Valley has generally moderate geologic radon potential. Clay-rich soils with low permeability dominate the lowlands and include glacial lake and marine clays which probably reduce the radon potential significantly. Radioactivity is generally low with a few scattered high and moderate areas that appear to be associated with the Clarendon Springs Formation and possibly with black shales and slates in surrounding rock units. Indoor radon levels in the counties underlain by the Champlain Lowlands are generally less than 4 pCi/L except in Addison County, where out of 26 readings, six were greater than 4 pCi/L and of these, two were greater than 20 pCi/L.



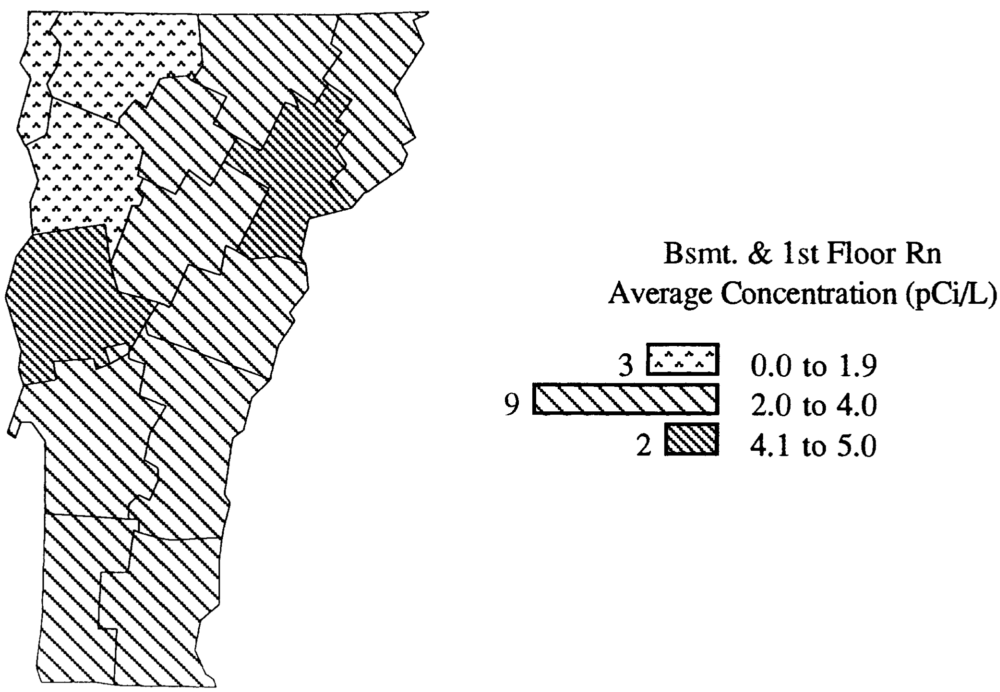


Figure 8. Screening indoor radon data from the EPA/State Residential Radon Survey of Vermont, 1988-89. Data are from 2-7 day charcoal canister tests. Histograms in map legends show the number of counties in each category. The number of samples in each county (See Table 1) may not be sufficient to statistically characterize the radon levels of the counties, but they do suggest general trends. Unequal category intervals were chosen to provide reference to decision and action levels.

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

COUNTY	NO. OF MEAS.	MEAN	GEOM. MEAN	MEDIAN	STD. DEV.	MAXIMUM	%>4 pCi/L	%>20 pCi/L
ADDISON	26	5.0	1.5	1.1	10.3	47.0	23	8
BENNINGTON	58	2.7	1.5	1.7	2.8	12.8	24	0
CALEDONIA	51	4.2	2.2	2.1	7.1	41.8	22	4
CHITTENDEN	102	1.4	0.8	0.8	1.8	10.6	8	0
ESSEX	14	2.3	1.3	1.1	3.6	14.5	7	0
FRANKLIN	24	1.7	0.8	0.7	3.4	15.6	8	0
GRAND ISLE	12	1.7	0.7	1.0	2.3	7.5	17	0
LAMOILLE	29	2.2	1.5	1.5	2.0	7.5	17	0
ORANGE	43	3.5	2.0	2.1	3.9	17.4	28	0
ORLEANS	50	2.2	1.3	1.3	2.7	15.1	8	0
RUTLAND	70	2.0	1.1	1.1	2.7	16.5	16	0
WASHINGTON	101	2.8	1.7	1.7	4.0	35.2	17	1
WINDHAM	51	3.0	1.8	1.8	3.3	17.9	18	0
WINDSOR	79	2.8	1.4	1.7	3.8	23.9	20	1

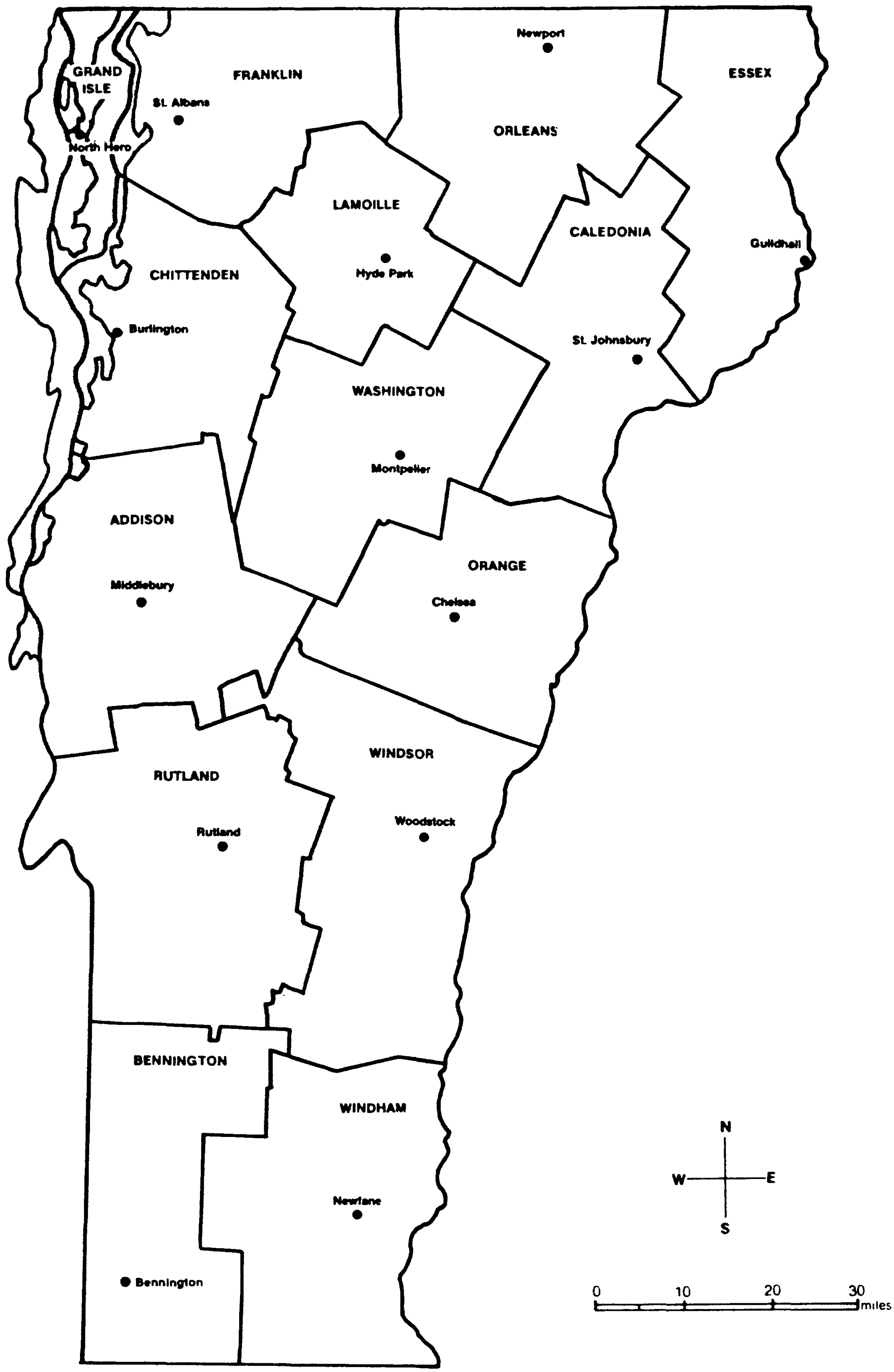


Figure 9. Vermont counties (from Facts on File, 1984).

Addison County is also underlain partly by the Green Mountains, which have been ranked moderate in radon potential; however, the radon potential is actually highly variable. Areas of the mountains with locally high radon potential are metamorphic rocks of Proterozoic age, including quartzite, graphite and pyrite-bearing schists and slates, migmatitic schist and gneiss, biotite-rich zones in mica schist, and schist and gneiss with high concentrations of the minerals monazite, allanite, and zircon, the Cheshire Quartzite, and local vein and fault deposits of uranium. Mafic metamorphic rocks such as amphibolite, hornblende gneiss, gabbro, and serpentinite are low in geologic radon potential. Permeability of the soils is generally moderate with some low permeability areas. The glacial deposits are mostly locally-derived tills. Radioactivity is variable–low in the southern portion with local high (>2.5 ppm eU) radioactivity anomalies, moderate to high radioactivity in the central portion, and low in the north. Many of the uranium occurrences seem to be concentrated in the southern and central parts of the Green Mountains.

The Taconic Mountains are also moderate in radon potential. Radioactivity is generally moderate to high, and several rock types appear to have elevated levels of uranium, especially the carbonaceous sedimentary rocks of the Pawlet Formation. Elevated concentrations of uranium in the black to gray phyllites and slates are probably the principal radon sources in this terrain. Soils generally have moderate to locally low permeability.

The Vermont Piedmont has moderate but variable geologic radon potential. Much of the area is underlain by mafic rocks, such as amphibolites, with low radon potential. Granites, granitic gneiss and schist, and carbonaceous or graphitic slate and phyllite have the potential for moderate to high radon. Radioactivity in the Piedmont is low to moderate with a few highs. Soils have moderate permeability with some low and high permeabilities. The Northeastern Highlands have moderate radon potential. Plutonic igneous rocks are abundant in this area and in the northern half of the Vermont Piedmont, but only a few of the plutons have distinct radiometric anomalies associated with them. Further, indoor radon for counties underlain by these rocks is moderate with the exception of Caledonia County. It has one high indoor radon measurement of 41.8 pCi/L. Eleven of the 51 measurements in the county are greater than 4 pCi/L.

SUMMARY

For the purpose of this assessment, Vermont has been divided into six geologic radon potential areas and each area assigned a Radon Index (RI) and a Confidence Index (CI) score (Table 2). The RI is a semi-quantitative measure of radon potential based on geology, soils, radioactivity, architecture, and indoor radon. The CI is a measure of the relative confidence of the RI assessment based on the quality and quantity of the data used to assess geologic radon potential (see the Introduction chapter to this regional booklet for more information).

The radon potential of Vermont is generally moderate but certain rock types appear to be associated with both high and low radon potential throughout the State. Rocks in Vermont with locally high geologic radon potential include granitic and micaceous metamorphic rocks in parts of the Green Mountains, Vermont Piedmont, and Northeastern Highlands, some granite plutons in the Northeastern Highlands and Vermont Piedmont, carbonaceous and graphitic phyllites, slates, and schists in parts of the Taconic Mountains, Green Mountains, and Vermont Piedmont and some clastic and carbonate sedimentary rocks in the Green Mountains, Vermont Valley, and Champlain Lowlands, including the Cheshire quartzite, Clarendon Springs, Dunham Dolomite, and related black shales. Low geologic radon potential is associated with mafic igneous and metamorphic rocks including amphibolite, hornblende gneiss, gabbro, and serpentinite found throughout the State, especially in the Green Mountains, Vermont Piedmont, and Northeastern Highlands.

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

TABLE 2. RI and CI scores for geologic radon potential areas of Vermont.

	Champlain Lowlands		Taconic Mountains		Vermont Valley	
FACTOR	RI	CI	RI	CI	RI	CI
INDOOR RADON	1	3	2	3	2	3
RADIOACTIVITY	1	3	2	3	2	3
GEOLOGY	2	2	2	3	2	3
SOIL PERM.	1	3	2	3	2	3
ARCHITECTURE	3	-	3	-	3	-
GFE POINTS	0	-	0	-	0	-
TOTAL	8	11	11	12	11	12
	Low	High	Mod	High	Mod	High

	Green Mountains		Piedmont		NE Highlands	
FACTOR	RI	CI	RI	CI	RI	CI
INDOOR RADON	2	3	2	3	2	3
RADIOACTIVITY	2	3	2	3	2	3
GEOLOGY	2	3	2	3	2	3
SOIL PERM.	2	3	2	3	2	3
ARCHITECTURE	3	-	3	-	3	-
GFE POINTS	0	-	0	-	0	-
TOTAL	11	12	11	12	11	12
	Mod	High	Mod	High	Mod	High

RADON INDEX SCORING:

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

Possible range of points = 3 to 17

CONFIDENCE INDEX SCORING:

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

Possible range of points = 4 to 12

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