OKLAHOMA GEOLOGICAL SURVEY
Charles J. Mankin, *Director*

GEOLOGIC ASSESSMENT OF RADON-222 POTENTIAL IN OKLAHOMA

JAMES R. FLOOD
TOM B. THOMAS
NEIL H. SUNESON
KENNETH V. LUZA

(Text to accompany GM-32, Radon-Potential Map of Oklahoma)

Prepared for
Oklahoma State Department of Health
under contract No. 21286

The University of Oklahoma
Norman

1990

CONTENTS

FIGURES

TABLES

MAP SHEET

(Separate, in envelope)

Geologic Assessment of Radon-222 Potential in Oklahoma

James R. Flood
Tom B. Thomas
Neil H. Suneson
Kenneth V. Luza

Oklahoma Geological Survey
Norman, Oklahoma

INTRODUCTION

Radon is a naturally occurring radioactive gas formed by the spontaneous decay of isotopically unstable uranium to stable lead. Uranium is found in all rocks and soils and radon generated in the top 10–20 ft of the ground either decays to a solid in the ground or escapes to the air. In air, the radon is generally diluted to very low concentrations before decaying. However, in buildings and houses radon can accumulate to concentrations considered to represent a health hazard. The U.S. Environmental Protection Agency currently recommends remedial action for levels above 4 pico-Curies per liter (pCi/L). In general, radon concentrations decrease as the floor level becomes higher above ground level.

When radon decays inside a building, the radioactive progeny adhere to dust and other aerosols. When breathed into the lungs, these materials can lodge in lung tissues and the ensuing radioactive decay of the radon progeny can cause cell damage which may ultimately cause lung cancer. Alternatively, radon can be inhaled directly and if it decays while in the lungs, its solid progeny can become embedded in the lung tissue. Alpha-emitting polonium isotopes are considered to be the most damaging. Health hazards resulting from exposure to and inhalation of above-normal levels of indoor radon, radon detection, recommended safety levels, and remedial methods are summarized in publications issued by the U.S. Environmental Protection Agency (1986,1987).

The relationship between indoor radon and radon in the ground (soil-gas radon) has been studied by Tanner (1986). Four factors determine how much soil-gas radon may enter a home:

1) Radium (the immediate precursor of radon) must be present in the soil and/or bedrock in close proximity to the home. High concentrations of radium result in higher concentrations of soil-gas radon when other geological and soil formation variables are equal.

2) About 90% of radon decays to polonium in 13 days; therefore, soil-gas radon must be able to rapidly migrate through pore spaces in the rock or soil and subsequently into the building.

3) For soil-gas radon to enter a building, the structure must have openings (such as cracks) below ground level in the building materials.

4) Low internal air pressure within a building creates a pressure differential across the ground/structure interface; this produces a "pumping" effect on the soil gases, including radon, and draws them into the building.

The Oklahoma Geological Survey in cooperation with the Oklahoma State Department of Health evaluated and rated the near-surface geological conditions in Oklahoma for radon potential. The study, which included a report and map showing radon potential in Oklahoma (scale 1:750,000), was intended to assist the Oklahoma State Department of Health in planning site-specific indoor-radon surveys. The study considered only factor 1) above and did not address other significant variables, such as soil characteristics, ground-water hydrology, precipitation and other atmospheric conditions, and types and conditions of building structures. Consideration of these variables is critical for determining site-specific radon potentials. Tanner (1986, p. 2) clearly stated the limitations of a map based only on geologic criteria: "No matter how accurate and detailed a radon map may be it represents only one of the four major factors that determine whether an indoor hazard exists in a house."

This study is a reconnaissance-level investigation based on existing geologic literature. Quantitative concentrations or radiometric measurements of indoor or soil-gas radon were not available for this study.

SOURCES AND CHARACTERISTICS OF RADON

Radon is formed by the radioactive decay of two naturally occurring radioactive elements—uranium and thorium. Although thorium is four times as abundant in the Earth's crust as uranium, it is less important for environmental considerations because it contributes less radioactivity on a weight basis than uranium, and it is much less mobile in the near-surface environment than uranium. Most (99.3%) uranium is ^{238}U. The spontaneous emission of alpha and beta particles and gamma radiation from the radioactive isotopes shown in Table 1 causes ^{238}U eventually to decay into a number of daughter products including radium (^{226}Ra) and its immediate progeny, radon (^{222}Rn). (Hereafter, the terms *radon, radium,* and *uranium* refer to these isotopes.) Therefore, radon can be concentrated to above-average values only in structures built on bedrock and/or soil that contains radium.

Radon in the ground migrates by diffusion and is transported by moving fluids (Tanner, 1980). Diffusion occurs when radon moves with respect to the fluid that contains it. Transport occurs when the fluid itself moves and carries the radon along with it. Either or both mechanisms may be important, but, in general, diffusion is more important in rocks and soils with small pore spaces. Moving fluids are more likely to be the dominant migration mechanism in rocks and soils with large pore spaces.

Tanner (1980) identifies several factors that control the rate of radon release from the source, migration and transportation through the bedrock or soil, and emanation from the ground. These factors include:

1) *Grain-size of radium-bearing mineral.* It is easier for radon atoms to escape from the solid in which they are produced if that solid has a large ratio of surface area to volume (e.g., fine-grained rocks and soils).

2) *Size and amount of pore space.* If the amount of pore space in a rock is small, radon atoms that do escape from their source grains are more likely to be absorbed into adjacent grains.

3) *The fluid in the pore space.* Pore water effectively traps radon and tends to inhibit radon migration.

TABLE 1.—URANIUM-238 DECAY SERIES

Isotope	Half-life*	Principal decay modes
^{238}U	4.5×10^9 yr	α,γ
^{234}Th	24.1 day	β,γ
^{234}Pa	6.75 hr	β,γ
^{234}U	2.48×10^5 yr	α,γ
^{230}Th	8.0×10^4 yr	α,γ
^{226}Ra	1,622 yr	α,γ
^{222}Rn	3.82 day	α
^{218}Po	3.05 min	α
^{214}Pb	26.8 min	β
^{214}Bi	19.7 min	α,β,γ
^{214}Po	1.6×10^{-4} sec	α
^{210}Pb	22.0 yr	β,γ
^{210}Bi	5.01 day	β
^{210}Po	138.4 day	α
^{206}Pb	stable	α

Source: Bowie and Plant (1983).
*Half-life: The time required for the decay of half the atoms of a radioactive substance.

Conversely, low water saturation above the groundwater table facilitates diffusion of radon to the air.

4) *Permeability of the rock or soil.* Radon migration is partly dependent on the mass transport of the fluid or gaseous medium that contains it. Radon migration is more likely to occur in permeable rocks and soils than in those that are relatively impermeable. Fractures, faults, and joints commonly increase rock permeability.

5) *Atmospheric conditions.* The pressure differential across the air/ground interface is influenced by changes in barometric pressure and wind speed; a decrease in the barometric pressure and higher wind speeds favor upward movement of soil gases, including radon. Frozen ground and heavy rains tend to suppress radon migration.

Radon dissolved in ground water can be quickly transported to the surface by pumping water wells. It can then come out of solution in a building and be inhaled or remain in solution and be ingested. Radon associated with ground water and water wells is discussed by Bailey and Childers (1977), Hall (1986), and Tanner (1986), but is not addressed in this study.

To summarize, the release of radon from its source and migration to the atmosphere is enhanced in rocks and soils that (1) are fine-grained, (2) are porous, (3) have pore spaces filled with air, and (4) are permeable. Radon emanation from the ground to the atmosphere is enhanced (5) in well-drained soils and (6) in temperate climates with moderate rainfall.

GEOLOGICAL AND GEOCHEMICAL CHARACTERISTICS OF URANIUM AND RADIUM

This report uses uranium, the ultimate source of radon, as a mappable indicator for radon. Uranium has been studied in great detail because of its economic and strategic importance. The relationship between uranium and radon was used by Hasenmueller (1988) in Indiana and by Sprinkel (1988) in Utah to produce radon-potential maps of those states.

The Earth's crust contains an average of 2.5 parts per million (ppm) uranium (Bowie and Plant, 1983). However, the uranium is not distributed equally among all rocks in the crust (Table 2). Uranium is initially concentrated in the Earth's crust in silicic igneous rocks, such as granite and associated late-stage intrusives, particularly pegmatites. Granitic rocks and the sediments derived from them average 4 ppm uranium.

Most uranium complexes are soluble in water under oxidizing geochemical conditions (Bowie and Plant, 1983; Bowen, 1988), and rainwater is generally oxidizing. Therefore, in the surface and near-surface environment, uranium compounds are removed from weathered soils and bedrock and dissolved in the ground water. Oxygen-rich ground water will carry uranium in solution until it enters a reducing geochemical environment (usually an environment with abundant organic matter). Under reducing conditions, uranium minerals will precipitate within a host rock or sediments. The distance from the site of dissolution to the site of precipitation can vary greatly.

TABLE 2.—AVERAGES AND RANGES OF URANIUM CONTENTS (ppm) FOR COMMON ROCK TYPES

Rock type	Mean	Range
Igneous		
gabbro, basalt	0.8	0.1–3.5
diorite, quartz diorite	2.5	0.5–12
granite, rhyolite	4.0	1.0–22
Sedimentary		
orthoquartzite	0.5	0.2–0.6
sandstone	1.5	0.5–4
carbonate	1.6	0.1–10
shale	3.0	1.0–15
black shale		3.0–1,250
lignite		10.0–2,500
phosphorite		50.0–2,500

Source: Modified from Bowie and Plant (1983).

Some uranium associated with dark, organic-rich or phosphatic shales was probably leached under subaerial conditions and precipitated in sediments deposited in a restricted (anaerobic) marine environment. Some uranium associated with similar shales may have been dissolved in ground water and was precipitated when the geochemistry of the ground water changed as it passed through the shales.

The rate and degree of uranium dissolution and leaching depends on the porosity and permeability of the bedrock and soil and the amount of rainfall. In areas with moderate rainfall, uranium will be leached from highly porous and permeable near-surface sandstones, conglomerates, and porous carbonates and fractured rocks. Less-permeable soils and bedrock composed of clay, shale, siltstone, and dense, unfractured rocks will be leached to a lesser degree. Highly weathered residual soil will generally be leached to a greater degree than the underlying bedrock. As a result, indirect calculations of uranium concentration made from airborne radiometric surveys, which analyze only the top few inches of soil, are probably low relative to the underlying, less-weathered bedrock.

Unlike uranium, radium is more soluble in a reducing environment and is precipitated under oxidizing conditions (Moore, 1972; Bloch, 1979; Bloch and Craig, 1981). Near-surface radium is not likely to be significantly dissolved and subsequently concentrated by ground water. Very little information exists about radium in Oklahoma's ground water. However, radium in above-normal concentrations is present in some highly reduced spring waters and oil-field brines (Bloch, 1979; Bloch and others, 1982; Eutsler and others, 1982). These brines are deep-seated and unrelated to potential near-surface radon unless they come in contact with near-surface rocks and ground water by natural artesian flow or leakage from oil wells.

GEOLOGIC SETTING

Throughout geologic time, shallow seas have periodically covered large areas of Oklahoma and surrounding states. Thick layers of mud, sand, and calcareous sediment were deposited in the seas; these layers were subsequently changed to shale, sandstone, and limestone, respectively, by compaction and cementation. Alluvial and deltaic deposits formed on land areas near the ancient seas. When certain areas were later raised above sea level, earlier-deposited sediments and rocks were exposed and eroded. Uplift occurred either by gentle arching of broad areas such as in the Ozark region or by formation of mountains where rocks are intensely folded, faulted, and thrust upward (Johnson and others, 1979).

Three mountain belts, Ouachita, Arbuckle, and Wichita, occur in the southern third of the State (Fig. 1). These mountain belts were formed by folding, faulting, and uplifting during the Pennsylvanian Period, about 300 million years ago. Thick sequences of Paleozoic sedimentary rocks, some igneous rocks (granite, rhyolite, and gabbro), and a variety of structural features (faults and folds) are exposed in these mountain belts. Major sedimentary basins—Anadarko, Arkoma, Ardmore, Marietta, and Hollis (Fig. 1)—occur north of and adjacent to the mountain uplifts. These basins subsided more rapidly than adjacent areas and contain 10,000 to 40,000 ft of sedimentary rocks (Johnson and others, 1979).

The present distribution of rock units in Oklahoma is shown in a generalized geologic map with cross sections (Fig. 2). Rocks of every geologic system are present in Oklahoma (Fig. 2). Nearly 99% of the State's surface is underlain by sedimentary rocks; the remainder is underlain mostly by igneous rocks in the Wichita and Arbuckle Mountains, and there is a smaller area of slightly metamorphosed rocks in the Ouachita Mountains (Johnson, 1971).

URANIUM OCCURRENCES

Oklahoma presently has no known economic uranium deposits. However, generation of indoor-radon concentrations in excess of the EPA standard (>4 pCi/L of air) does not require ore-grade uranium (>500 ppm). Under favorable conditions, rocks and residual soils containing much lower uranium contents are capable of generating above-normal radon levels.

In Oklahoma, uranium is associated with many different rock types and geologic environments. Uranium occurrences in the State are divided into seven types based on the mode of uranium enrichment and size, distribution, and geologic continuity of the occurrence:

Type 1.—*Uranium associated with granitic rocks and their late-stage intrusives (dikes and sills).* A typical granite will average about 4 ppm uranium. Much higher uranium concentrations can occur in localized, late-stage intrusions and hydrothermal deposits. During the latter stages of crystallization, the magma's most volatile phase is typically enriched in uranium, thorium, and rare earths. The best example is in the Wichita Mountains, where granites

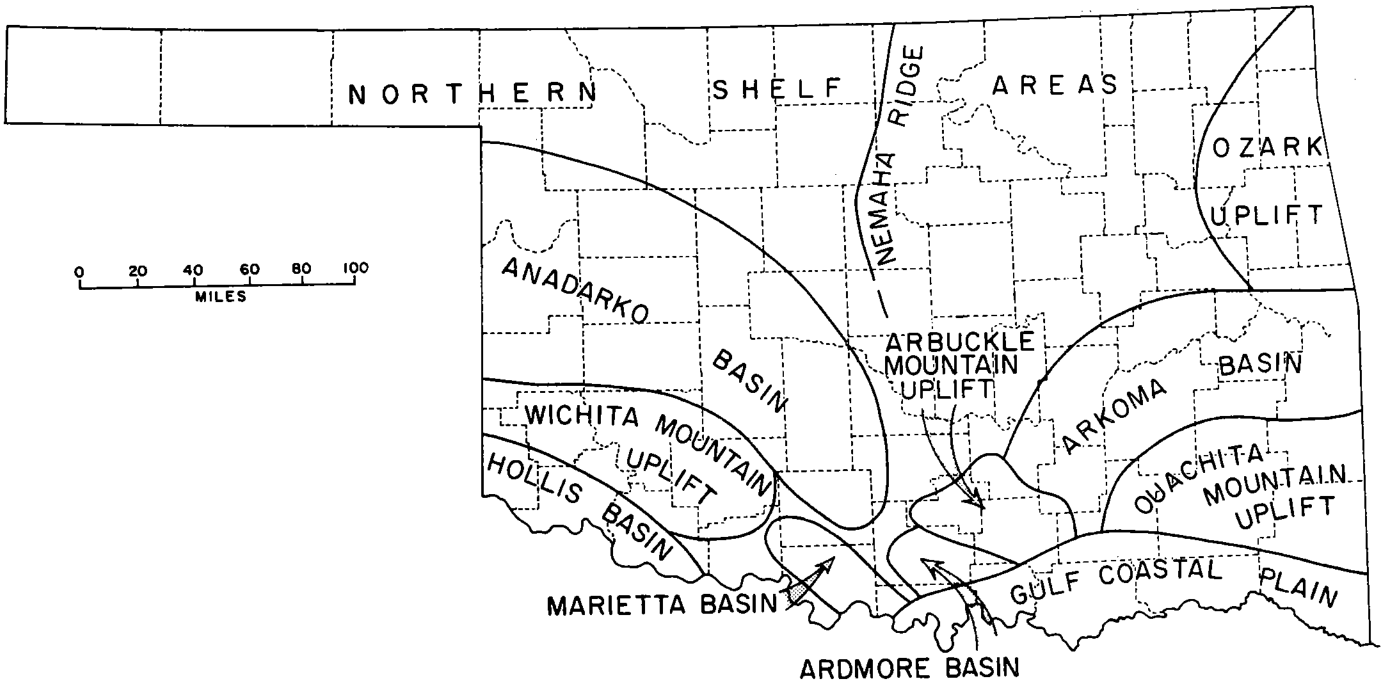

Figure 1. Tectonic-province map of Oklahoma (after Johnson and others, 1979).

contain 4.6–11 ppm uranium and certain dikes average 153 ppm uranium (Al-Shaieb and others, 1982).

Type 2.—*Uranium associated with arkosic sediments (weathered granite).* Uranium is found in conglomerate, sandstone, and siltstone derived from erosion of granitic rocks. These sediments generally contain uranium concentrations similar to those of the parent rock, less any uranium lost by groundwater leaching. Locally, small areas within the arkosic sediments are enriched in uranium by secondary precipitation of uranium minerals. The best example is found immediately south of the Wichita Mountains in the granite facies of the Post Oak Conglomerate, which ranges from 1 to 126 ppm uranium (Al-Shaieb and others, 1982).

Type 3.—*Uranium associated with dark, organic-rich shales.* Most marine shales have uranium contents of 1–4 ppm. Black shales, usually marine, contain moderately high amounts of disseminated organic material and generally have above-average uranium concentrations. Disseminated organic compounds trapped in fine-grained sediments can precipitate and concentrate uranium from seawater and formation water. The Pennsylvanian black shales of east-central and northeastern Oklahoma contain 10–20 ppm uranium (Hyden and Danilchik, 1962). Worldwide, uranium contents of black shale range from 3 to 250 ppm and average 8–20 ppm (Swanson, 1961).

Type 4.—*Uranium associated with phosphatic black shales.* Phosphate nodules, concretions, and thin, discontinuous layers in black shales significantly elevate their uranium content. Uranium dissolved in seawater is readily incorporated in the phosphate crystal structure. Uranium concentration in phosphate nodules can range from 10 to 1,000 ppm and is proportional to the phosphate content, usually 10–35% of the nodule (Swanson, 1961). The best examples occur in northeastern Oklahoma, where phosphate nodules contain 20–600 ppm uranium (Hyden and Danilchik, 1962). These black shales contain as much as 5% nodules, average 20–50 ppm uranium (Coveney and others, 1988; Hyden and Danilchik, 1962), and represent the State's most laterally persistent uranium-rich rock units. Although these units are very thin (about 3 ft thick), some formations in northeastern Oklahoma contain multiple phosphate-rich black-shale beds separated by thin sandstone layers, which significantly increases the total thickness. The shale is easily eroded, and a phosphate-nodule lag deposit often occurs on the surface.

Type 5.—*Uranium associated with lignite and bituminous coal beds.* Organic compounds in lignite and coal are capable of uranium precipitation and concentration as in black shale (Type 3). Lignite is particularly effective in concentrating uranium and has measured uranium concentrations worldwide of 10–2,500 ppm (Vine, 1962). Some thin lignite beds occur in southern Oklahoma, but the uranium contents are unknown. Samples of three northeastern Oklahoma coal beds contain 10–40 ppm uranium (Hyden and Danilchik, 1962).

Type 6.—*Uranium associated with local point sources.* Uranium enrichments of the point-source type are common and widespread across the State, but generally have very limited areal extent. These occurrences were formed where mobile, oxygenated, uranium-bearing ground water has come in contact with local, subsurface, reducing chemical environments. The reducing chemical environment may be associated with plant fragments and/or oil fields. In

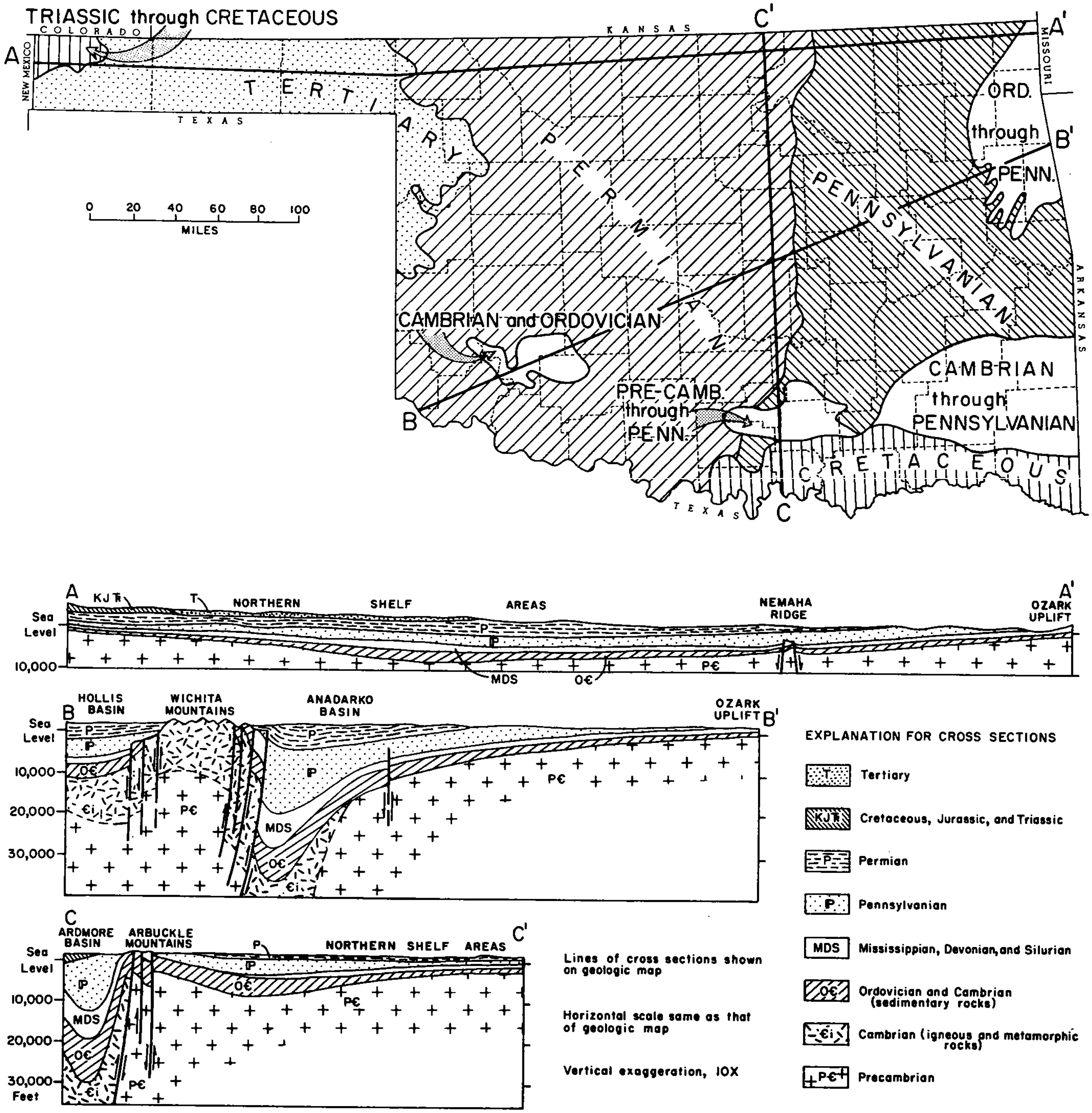

Figure 2. Generalized geologic map and geologic cross sections of Oklahoma (from Johnson, 1971).

the Cement area, southwestern Oklahoma, the largest known point-source occurrence in the State is associated with an oil field. Uranium ore was mined at Cement in 1957 and contained as much as 20,460 ppm uranium (Totten and Fay, 1982).

Type 7.—*Uranium associated with stratiform bodies.* Rocks with above-average, but highly variable (60–16,100 ppm) uranium concentrations are confined to certain stratigraphic units in Permian red beds of western and southwestern Oklahoma. The origin of the uranium is not well understood.

CLASSIFICATION OF ROCKS INTO RADON-POTENTIAL CATEGORIES

Methods and Sources of Information

Radium-226, and ultimately uranium-238, are the precursors of radon-222. At present, little is known about the concentration and distribution of radon and radium in Oklahoma rocks and soils. More is known about the distribution of uranium in various geologic formations because uranium is used in the nuclear and defense industries. Thus, uranium is utilized in this assessment as a mappable indicator of the potential presence of radon.

The interpretation of radon potential across the State is based exclusively on a review of existing literature. Geologic maps at a scale of 1:250,000 in the Oklahoma Geological Survey's Hydrologic Atlas series (Marcher, 1969; Marcher and Bingham, 1971; Hart, 1974; Bingham and Moore, 1975; Carr and Bergman, 1976; Havens, 1977; Bingham and Bergman, 1980; Morton, 1981; Marcher and Bergman, 1983) and the Texas Bureau of Economic Geology's Texas Atlas series (Barnes, 1970,1984) provided the basic outcrop information for the assessment. Additional geologic information in numerous county reports, published articles, and unpublished student theses aided in the evaluation.

Several private and government reports describe uranium occurrences by chemical and radiometric analyses, rock type, and origin. Totten and Fay's (1982) statewide study and the U.S. Department of Energy's National Uranium Resource Evaluation (NURE) quadrangle folio reports for the Enid, Oklahoma City, Sherman, Clinton, Lawton, and Dalhart Quadrangles were essential to this study (Hobday and Rose, 1982; Derby and others, 1982; Eutsler and others, 1982; Al-Shaieb and others, 1982; Bloch and others, 1982; Consulting Professionals, 1982). Sample locations and uranium-concentration information are shown on the accompanying Radon-Potential Map.

Statewide airborne radiometric surveys, which measured ground surface gamma-ray intensity, were conducted for each 1° × 2° quadrangle (scale 1:250,000) during the NURE program, 1975 to 1983 (EG&G geoMetrics, 1980; Geodata International, 1976,1980a,b; Geo-Life, 1979; Texas Instruments, 1977,1978,1979). Except for the McAlester Quadrangle, the east–west flightlines were spaced 3–6 mi apart, and the north–south tie lines were spaced 12–24 mi apart. In the McAlester Quadrangle, north–south flightlines were spaced 6 mi apart, and the east–west tie lines were spaced 24 mi apart. The NURE gamma-ray surveys measured the gamma-ray flux produced by radioactive decay of potassium-40, uranium-238, and thorium-232 in the top few inches of rock and/or soil (Duval, 1989). Equivalent uranium (eU) was measured by bismuth-214. Bismuth-214 is a daughter product of radon-222 in the uranium-238 decay series (Table 1). Therefore, the radiation values recorded by the survey are believed to be approximately proportional to near-surface radon concentrations in the soil. The NURE reports provided extensive data on equivalent-uranium (eU) concentrations across the State. The U.S. Geological Survey reprocessed the radiometric survey data and produced a computer-generated National Equivalent Uranium Map (Duval, 1989). Preliminary copies of this map and report were very useful in delineating areas of radon potential in the State.

Radon-Potential Categories

Several factors were used to evaluate the near-surface radon potential of the State's bedrock units. Uranium analyses and airborne radiometric surveys were the two most important rating factors in the evaluation. Rock type, the number of samples analyzed, and the type of uranium occurrence were the next-most-important factors considered. Topography, structure, and the radon potential of similar rocks outside Oklahoma were additional factors. It should be noted that many of the rock-sample analyses plotted on the Radon-Potential Map are in areas with known uranium-enriched bedrock, and do not indicate the average uranium content of the entire geologic formation.

Based on these factors and considerations, five radon-potential categories were developed: *generally very low, generally low, locally low to moderate, locally moderate,* and *locally moderate to high.* Twenty-six areas in the State were outlined, numbered, and assigned a radon-potential rating (Fig. 3; Radon-Potential Map). For organization and discussion, each area was assigned to one of the following four regions: northeast, southeast, southwest, and northwest (Fig. 4). The modifiers *generally* and *locally* are used because the designated potential rating may not necessarily be equally distributed throughout an area. Local sub-areas within an area may have radon potentials different from that assigned to the entire area. It should be noted that a large part of the State was not assigned to one of the 26 areas. The potential for radon in the near-surface environment in the unassigned parts of the State is probably very low, except over small, point-source concentrations of uranium.

REGIONAL ANALYSIS

Northeast Region

The northeast region includes Ottawa, Craig, Mayes, Delaware, Rogers, Nowata, Washington, Tulsa, Wagoner, Cherokee, Adair, Okmulgee, Muskogee, Sequoyah, McIntosh, Haskell, and parts of Le Flore, Latimer, Pittsburg, Coal, Hughes, Okfuskee, Creek, Pawnee, and Osage Counties (Fig. 4). The Ozark uplift, Arkoma basin, and the eastern part of the northern shelf are the principal geological provinces found in this region. The northeast region contains Areas 1–8. These areas have radon-potential categories that range from generally low to locally moderate to high. Parts of this region, particularly in the east and northwest, have generally very low radon potentials.

Area 1

Some deeply eroded valleys of the western Ozark uplift contain several narrow, discontinuous exposures of Area 1 rock units in parts of Delaware, Mayes, Cherokee, Adair, and Sequoyah Counties. These units are Mississippian to Ordovician and include, in descending order, the Chattanooga Formation, Fernvale Formation, Fite Formation, Tyner Formation, Burgen Sandstone, and Cotter Formation. Of these formations, the Upper Devonian to Lower Mississippian Chattanooga is the principal uranium-bearing formation. The uranium is associated with dark, organic-rich shale, and phosphate nodules in-

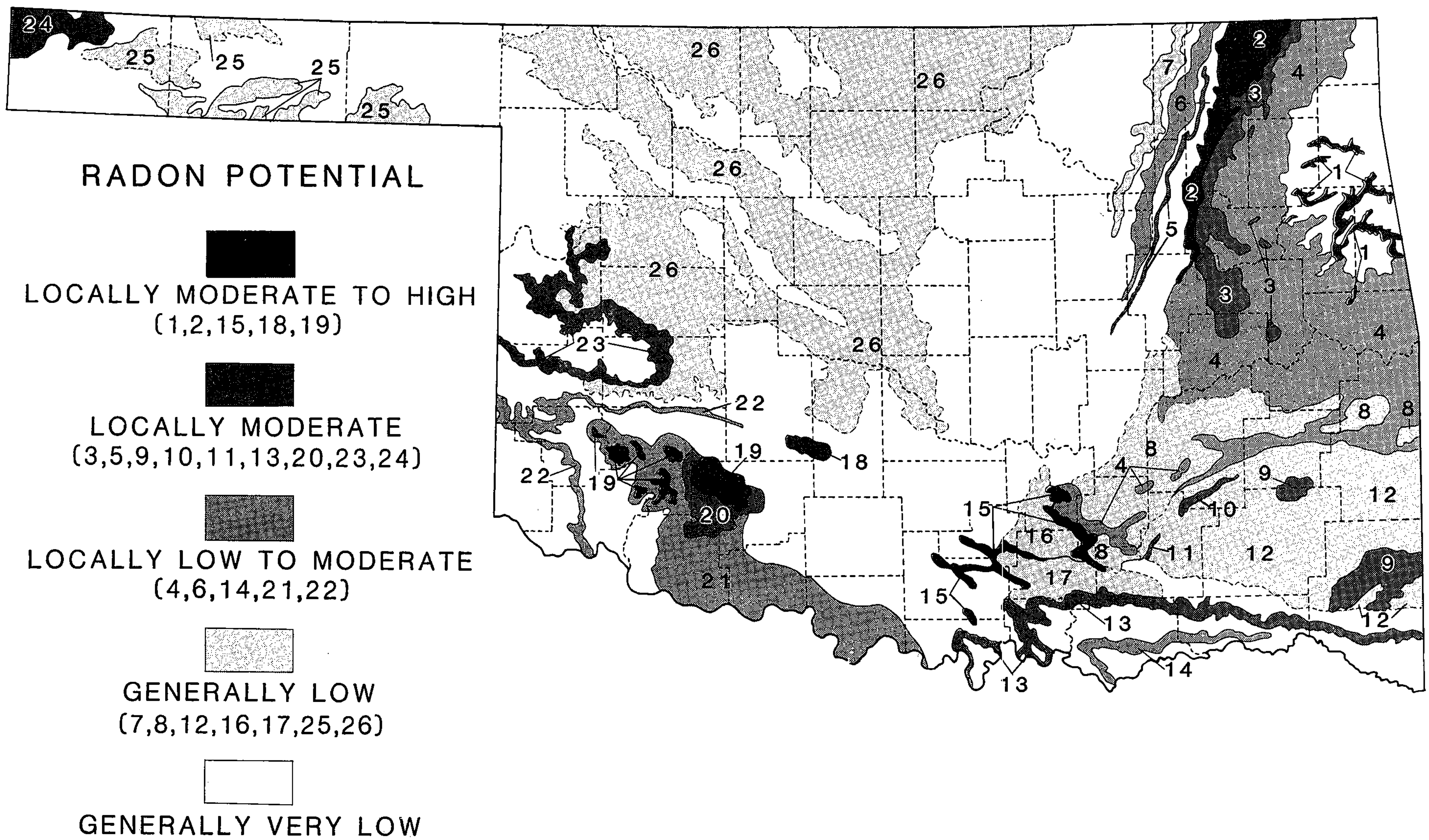

Figure 3. Radon potential in Oklahoma. (See also accompanying large-scale Radon-Potential Map of Oklahoma.)

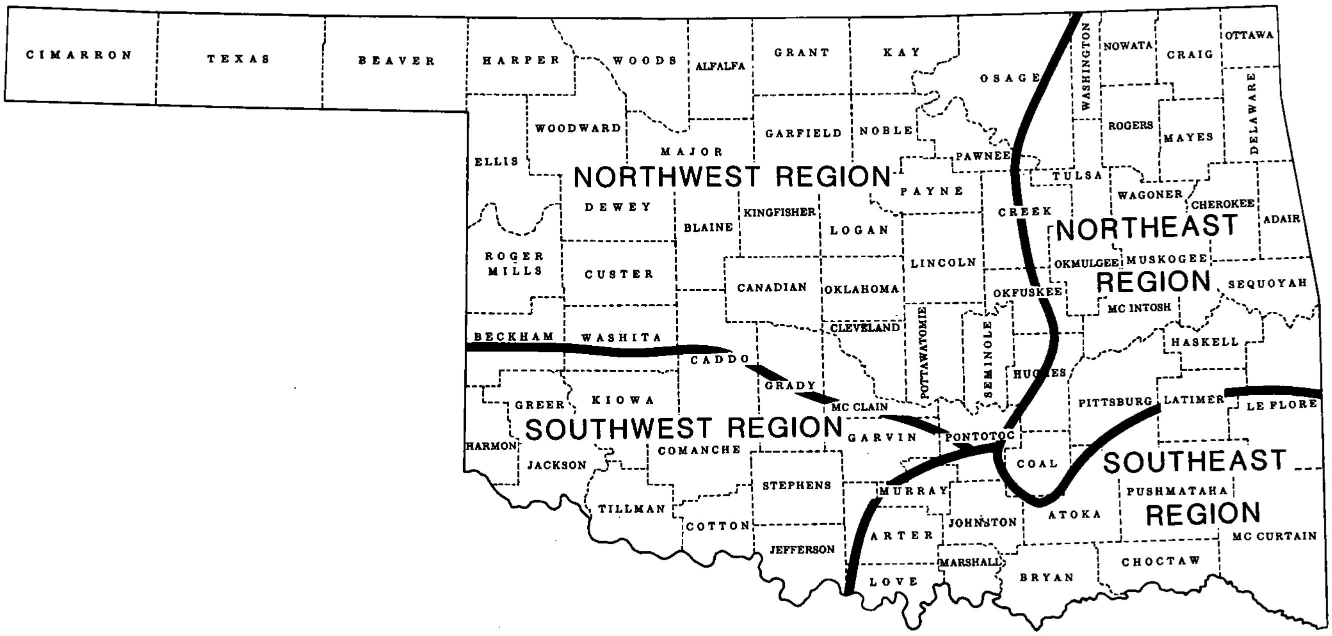

Figure 4. Four regions used to discuss area radon potentials.

cluded within the shale (Type 3 and minor Type 4 occurrences). The Chattanooga Formation ranges from 40 to 80 ft thick and is equivalent to the Woodford Shale of southern Oklahoma. The uranium content ranges from 10 to 70 ppm (Landis, 1962).

Similar Devonian black shales elsewhere in the United States have above-average concentrations of uranium. For example, the uranium content of the Marcellus Shale in the vicinity of Syracuse, New York, averages 34 ppm (Hand and Banikowski, 1988). Swanson (1961) reported that the Chattanooga Formation and its lithostratigraphic equivalents average 50 ppm uranium in Tennessee, Alabama, Kentucky, and Arkansas.

The radon potential for Area 1 is locally moderate to high, based on the high uranium content of the Chattanooga Formation. Furthermore, the overlying Mississippian limestones are well jointed, fractured, and locally cavernous. Some joint systems and fractures could provide pathways for radon to migrate away from the Chattanooga Formation and concentrate in the overlying limestones.

References on the geology include Huffman and others (1958,1966), Marcher and Bingham (1971), and Marcher (1969).

Area 2

Parts of Craig, Nowata, Rogers, Okmulgee, Tulsa, and Wagoner Counties are contained in Area 2. Area 2 occurs in a 100-mi-long zone that extends from central Okmulgee County northward to Nowata and Craig Counties. This zone is approximately 20 mi wide at the Kansas border, narrows southwestward to an average width of about 6 mi in Rogers County, and thins to zero in central Okmulgee County. Pennsylvanian rock units of the upper Senora Formation, Fort Scott Limestone, and Oologah Formation are exposed in Area 2. These formations contain numerous thin, uraniferous, black, phosphatic shale members (Type 3 and 4 occurrences). Important shale members include the Excello, Little Osage, Anna, Bandera, and Lake Neosho; these shale members are as much as 10 ft thick, and the uranium content ranges from 20 to 50 ppm. The uranium content in individual phosphate nodules ranges from 20 to 600 ppm and averages about 160 ppm. Phosphate nodules can make up as much as 5% of the rock volume; this further increases the shale's uranium content (Hyden and Danilchik, 1962). Differential erosion of the phosphate-rich shale may produce soils enriched in phosphate nodules.

The radon potential for Area 2 is locally moderate to high. Highly jointed limestone beds, such as those in the Fort Scott Formation, may be favorable sites for secondary uranium mineralization. Some fracture systems in the limestone could provide pathways for radon migration. The airborne radiometric survey shows that the highest gamma-ray intensities occur along the eastern edge of Area 2 (Texas Instruments, 1978). Airborne radiometric surveys show elevated gamma-ray intensities for the Excello and Little Osage Shale Members, beneath and within the Fort Scott Formation.

References on the geology include Branson and others (1965), Bennison and others (1972), Marcher and Bingham (1971), Oakes and others (1952), Oakes (1963), and Marcher (1969).

Area 3

Area 3 is located in parts of Craig, Nowata, Rogers, Mayes, Tulsa, Wagoner, Okmulgee, Muskogee, and McIntosh Counties. This area is a 110-mi-long zone that extends from northern McIntosh County to the north edge of Craig County. This zone is approximately 6 mi wide from Craig County through Rogers County and widens to as much as 14 mi in Muskogee County. Pennsylvanian rocks of the Senora Formation are exposed in the northern and central parts of Area 3. Parts of the Boggy Formation occupy the southern end of this area. These formations contain numerous thin, black shales, black phosphatic shales, and bituminous coal beds (Type 3, 4, and 5 occurrences). Some of the black shale beds have a uranium content of 10–30 ppm (Hyden and Danilchik, 1962). The uranium content of phosphate nodules is as much as 190 ppm and averages 110 ppm. The Tebo coal in the Senora Formation locally contains 40 ppm uranium.

The radon potential for Area 3 is locally moderate. This assessment is based on the presence of uraniferous rock types within the formations. Analytical data suggest that the uranium content of some of the key beds is lower than that of similar units in Area 2. Airborne radiometric surveys show that the southern part of Area 3 has a slightly higher uranium content than the central and northern parts (EG&G geoMetrics, 1980; Texas Instruments, 1978; Duval, 1989). The apparent increase in uranium content may be due to the presence of dark-gray to black shale, phosphatic shale beds associated with the Inola Limestone, and thin coal beds of the Boggy Formation in this area.

References on the geology include Branson and others (1965), Oakes (1967,1977), Marcher (1969), and Marcher and Bingham (1971).

Area 4

Area 4 is a broad region that surrounds the Ozark uplift and occupies most of the Arkoma basin. This area covers parts of Ottawa, Craig, Delaware, Mayes, Rogers, Wagoner, Cherokee, Adair, Muskogee, Okmulgee, McIntosh, Sequoyah, Haskell, Le Flore, Latimer, and Pittsburg Counties. Pennsylvanian rock units of the Boggy, Savanna, McAlester, Hartshorne, and Atoka Formations dominate Area 4. These formations contain numerous beds of dark-gray to black, carbonaceous shale; thin bituminous coal; and some carbonaceous sandstone (Type 3 and 5 occurrences). Phosphate nodules are generally absent. The eastern boundary of Area 4 includes the Mississippian Fayetteville Formation, a black shale and thin limestone. Uranium analyses of rock samples are sparse in this area. Black-shale beds in the northern part of Area 4 generally contain 10–20 ppm uranium. One bituminous coal sample contained 20 ppm uranium (Hyden and Danilchik, 1962).

The radon potential for Area 4 is locally low to moderate, but probably varies widely across this large region. Airborne radiometric surveys indicate that Area 4 is underlain by strata with above-average uranium contents (EG&G geoMetrics, 1980; Texas Instruments, 1978; Duval, 1989). Highest radon potentials probably occur in those few outcrops that contain black, phosphatic shale.

References on the geology include Reed and others (1955), Branson and others (1965), Huffman and others (1958), Oakes (1963,1967,1977), Hendricks (1937, 1939), Russell (1960), Marcher and Bergman (1983), Marcher and Bingham (1971), Marcher (1969), and Hart (1974).

Area 5

Area 5 consists of a 100-mi-long, very narrow exposure of Pennsylvanian black shale and coal. This area extends northward from Okfuskee County across parts of Okmulgee, Tulsa, Rogers, and Nowata Counties. The outcrop belt contains the Dawson coal and overlying Nuyaka Creek Black Shale Bed of the Seminole Formation (named by Dott and Bennison, 1981). The Dawson (Type 5 occurrence) is a thin, bituminous coal bed as much as 2.5 ft thick. The Nuyaka Creek (Type 4 occurrence) is a black, phosphatic shale, 5–13 ft thick. The uranium content of the shale at one locality ranges from 40 to 130 ppm (Totten and Fay, 1982).

The radon potential for Area 5 is locally moderate. Area 5 contains rock types similar to those found in Areas 2 and 3. The Dawson coal was mined extensively in Tulsa County (Knight, 1972). The outcrop belt now contains reclaimed lands and abandoned coal-mine sites.

References on the geology include Oakes and others (1952), Oakes (1963), Bennison and others (1972), Marcher (1969), Marcher and Bingham (1971), Bingham and Moore (1975), Ries (1954), and Hemish (1987).

Area 6

Area 6 is an outcrop belt of Pennsylvanian units, approximately 100 mi long by 4–6 mi wide, that extends northward from Okmulgee County through parts of Creek, Tulsa, Washington, Rogers, and Nowata Counties. Pennsylvanian rocks of the Checkerboard Limestone and Coffeyville and Hogshooter Formations are exposed in this area. The basal Coffeyville Formation, which rests on the Checkerboard Limestone, consists of 10–35 ft of black shale (Type 3). Phosphate nodules occur in the lower 4 ft of this unit (Type 4). Samples from the phosphate-rich zones have uranium contents that range from 10 to 900 ppm (Totten and Fay, 1982). The Winterset Limestone Member of the Hogshooter Formation is carbonaceous and phosphatic in the basal 1 ft and overlies 3–10 ft of black shale. No uranium analyses are available for the Hogshooter Formation.

The radon potential for Area 6 is locally low to moderate. Airborne radiometric surveys indicate low gamma-ray intensities over Area 6 (EG&G geoMetrics, 1980; Texas Instruments, 1978; Duval, 1989). Higher radon potentials may coincide with exposures of thick black-shale members of the Coffeyville Formation, which crop out along the eastern half of the area. The well-jointed Winterset and Checkerboard Limestones may be favorable sites for secondary enrichment. Some of the fracture systems in the limestone could provide pathways for radon migration.

References on the geology include Oakes and others (1952), Oakes (1963), Bingham and Moore (1975), and Marcher and Bingham (1971).

Area 7

Area 7 is an outcrop belt of three Pennsylvanian units, the Dewey Limestone, Chanute Formation, and

Iola Limestone (Type 3, 4, and 5 occurrences), and is 80 mi long by 4–10 mi wide. The outcrop belt trends through parts of Creek, Tulsa, Osage, and Washington Counties. The Dewey Limestone contains some thin, black, phosphatic shale beds (Oakes, 1940). The Chanute Formation locally contains thin coal beds. The basal Muncie Creek Shale Member of the Iola Limestone contains dark-gray shale beds that are locally phosphatic at the base (Oakes, 1940; Oakes and others, 1952). No uranium analyses of these strata in Oklahoma are available. However, Coveney and others (1988) reported that the Muncie Creek Shale in Kansas contains 50 ppm uranium.

The radon potential for Area 7 is generally low. The uranium-bearing rock units are thin and generally very localized. Airborne radiometric surveys indicate elevated gamma-ray intensities over Area 7 units in Washington County (Texas Instruments, 1978); elsewhere in Area 7, low gamma-ray intensities occur.

References on the geology include Bennison and others (1972), Oakes (1940), Marcher and Bingham (1971), Bingham and Bergman (1980), Oakes and others (1952), Tanner (1956), and Bingham and Moore (1975).

Area 8

A large part of the southern Arkoma basin, which includes parts of McIntosh, Okfuskee, Hughes, Pittsburg, Haskell, Le Flore, Coal, Atoka, and Pontotoc Counties, is included in Area 8. Pennsylvanian rock units exposed in Area 8 include the Savanna, Boggy, Thurman, Stuart, and Senora Formations. These formations, which also crop out in Area 4, contain more sandstone and siltstone beds and fewer dark-gray, brown, and black, carbonaceous shale and coal beds (Type 3 and 5 occurrences). Area 8 lacks phosphatic shales. No rock-sample uranium analyses are available in Area 8; however, the uranium content of the uranium-bearing rocks is probably somewhat less than in Area 4.

The radon potential for Area 8 is generally low. The airborne radiometric surveys show low gamma-ray intensities for Area 8 (Geo-Life, 1979; Duval, 1989). The low potential is due to an increase in sandstones and lighter-colored shales and a decrease in carbonaceous shales and coal beds, compared to the same formations in Area 4.

References on the geology include Marcher (1969), Marcher and Bergman (1983), Hart (1974), and Bingham and Moore (1975).

Southeast Region

The southeast region includes Pushmataha, McCurtain, Choctaw, Bryan, Marshall, and parts of Le Flore, Latimer, Pittsburg, Atoka, Coal, Pontotoc, Murray, Carter, Johnston, and Love Counties (Fig. 4). The Ouachita Mountains uplift, Arbuckle Mountains uplift, Ardmore basin, and Gulf Coastal Plain are the principal geologic provinces in this region (Fig. 1). The southeast region contains Areas 9–17; these areas have radon potentials that range from generally low to locally moderate to high. However, parts of the region, particularly in the south, have a generally very low radon potential.

Area 9

Area 9 is in central McCurtain, northern Pushmataha, and southern Latimer Counties and includes the Broken Bow uplift and Potato Hills. The Broken Bow uplift is about 35 mi long and 18 mi wide. It extends from near Wright City to the Arkansas state line and is entirely in McCurtain County. The Potato Hills are about 12 mi long by 8 mi wide and straddle the Pushmataha–Latimer county line. Both areas are characterized by irregular topography and steep hills and expose some of the oldest rocks in the Ouachita Mountains. These rocks range in age from Ordovician to Mississippian. Exposed formations include the Collier Shale, Crystal Mountain Sandstone, Mazarn Shale, Blakely Sandstone, Womble Shale, Bigfork Chert, Polk Creek Shale, Blaylock Sandstone, Missouri Mountain Shale, Arkansas Novaculite, and the lower parts of the Stanley Group. The principal uranium-bearing formation is the Devonian–Mississippian Arkansas Novaculite, which contains about 10–20 ppm uranium (Landis, 1962), and the basal part of the Mississippian Stanley Group, which contains about 10 ppm uranium. Strata in the Broken Bow uplift are slightly metamorphosed, intensely folded and faulted, and locally mineralized with quartz, lead, and zinc. Strata in the Potato Hills are not metamorphosed or mineralized but are intensely folded and faulted.

The potential for radon in the near-surface environment is locally moderate. The measured uranium contents of selected formations would seem to justify a slightly lower rating. However, the abundance of dark, relatively organic-rich shales (Type 3 occurrence) and the highly mineralized (Broken Bow uplift) nature of the rocks may have resulted in local areas of higher uranium concentrations. This, and the fractured nature of these rocks, may contribute to a greater amount of radon migration. In addition, airborne radiometric surveys of the Broken Bow uplift area indicate elevated gamma-ray intensities over most of the area (Geo-Life, 1979; Duval, 1989).

References on the geology of Area 9 include Honess (1923), Pitt and others (1982), and Marcher and Bergman (1983).

Area 10

Area 10 is a narrow, elongate area in the northwestern part of the Ouachita Mountains in southern Pittsburg County and a small part of northern Atoka County. The area is characterized by broad valleys and low hills. The formations with above-average uranium contents in this area range in age from Devonian to Mississippian and include, in ascending order, the Woodford Shale (equivalent to the Chattanooga Shale in northeastern Oklahoma), the Delaware Creek (Caney) Shale, and the Goddard (Springer) Shale. The Woodford Shale contains 5–70 ppm uranium, and the Delaware Creek 10–24 ppm uranium (Landis, 1962). The Goddard has not been analyzed, but probably contains >3 ppm uranium, because it is lithologically similar to the Delaware Creek. The strata in Area 10 are steeply tilted, faulted, and fractured, but are not metamorphosed.

The potential for near-surface radon in Area 10 is locally moderate because black and organic-rich phosphatic shales (Type 3 and 4 occurrences), such as the Woodford and Delaware Creek, are an important part of the exposed section. The rocks are fractured, and some fractures could provide pathways for radon migration. The area was not rated higher because the strata are steeply tilted, and the outcrop widths of the uraniferous formations are small. Also, airborne radiometric surveys do not indicate above-average gamma-ray intensities for Area 10 (Geo-Life, 1979; Duval, 1989).

References on the geology include Hendricks and others (1947) and Marcher and Bergman (1983).

Area 11

Area 11 is a narrow, elongate area about 1 mi wide by 11 mi long, in the extreme western part of the Ouachita Mountains. The area is known as Black Knob Ridge and extends from the town of Atoka to immediately north of Stringtown in north-central Atoka County. It is similar in many respects to Area 9: It is characterized by irregular topography and steep, knobby hills underlain by strata that range in age from Ordovician to Devonian. Formations exposed on the surface include, in ascending order, the Womble Shale, Bigfork Chert, Polk Creek Shale, Missouri Mountain Shale, and Arkansas Novaculite. The principal uranium-bearing formation is the Arkansas Novaculite, which contains 10–30 ppm uranium (Landis, 1962).

The potential for near-surface radon based on geological considerations is locally moderate; reasons for this rating are similar to those given for Area 9 and include slightly uraniferous rocks, organic-rich shales (Type 3 occurrence), and the highly fractured and folded character of the strata exposed along the ridge. The area does not appear to contain strata with above-average uranium contents, based on airborne radiometric surveys (Geo-Life, 1979; Duval, 1989), but the presence of fractured, potentially uraniferous rocks precluded a lower rating.

References on the geology include Hendricks and others (1937), Hendricks and others (1947), and Marcher and Bergman (1983).

Area 12

Area 12 includes most of the Ouachita Mountains region (with the exception of Areas 9, 10, and 11) and extends from Atoka on the west, to Wilburton and immediately south of Heavener on the north, to the Arkansas state line on the east, to Antlers and immediately north of Broken Bow on the south. It is located in northeastern Atoka, southeastern Pittsburg, southern Latimer, southern Le Flore, northern McCurtain, extreme northeastern Choctaw, and most of Pushmataha Counties. The topography varies from elongate, relatively narrow valleys and ridges in the north to ridges separated by wide, gently rolling valleys to the south. The strata exposed at the surface are Mississippian–Pennsylvanian; the most common rock types are shale and sandstone. However, in the extreme northern and western parts of the area, ridges of Wapanucka Limestone are separated by valleys underlain by Limestone Gap Shale. The principal units that constitute most of the Ouachita Mountains are the Stanley Group, Jackfork Group, Johns Valley Shale, and Lynn Mountain (Atoka) Formation. With the exception of several small asphaltite deposits, there are no published uranium analyses of rocks in Area 12.

The potential for near-surface radon is generally low; this is based on rock type and airborne radiometric surveys (Geo-Life, 1979; Duval, 1989), which show low levels of gamma radiation throughout this part of the Ouachita Mountains. Most of the shales (Type 3 occurrence) contain little organic carbon. The area was not rated lower, because the strata are folded, faulted, and locally fractured; this increases the possibility that uranium mineralization and/or increased radon mobility has occurred in some places.

References on the geology include Hendricks and others (1947), Pitt and others (1982), and Marcher and Bergman (1983).

Area 13

Area 13 is in the Gulf Coastal Plain in extreme southern and southeastern Oklahoma. It is a long, relatively narrow area south and southwest of the Ouachita Mountains, extending from the Arkansas state line west to Madill and near Marietta. The area is in southern McCurtain, Choctaw, northern Bryan, southern Atoka, Marshall, southern Johnston, and eastern Love Counties. The northern boundary of the area is typically marked by a low to moderately high, north-facing escarpment; most of Area 13 is nearly flat. The escarpment is formed by differential erosion of the relatively resistant Cretaceous Goodland Limestone; the flat area to the south is underlain by the slightly younger Cretaceous Kiamichi Shale. In the western part of Area 13, the Goodland Limestone is underlain by the Walnut Clay. One sample of Goodland Limestone from the western end of its outcrop band contains 5.7 ppm uranium (Hobday and Rose, 1982); the Walnut Clay from two locations nearby contains 1.8 and 5.5 ppm uranium.

The potential for radon in the near-surface environment is believed to be locally moderate despite the low uranium contents of the three samples studied. Several factors suggest that Area 13 may be underlain by more-uranium-rich strata than indicated by available data: (1) The Kiamichi Shale is a dark, relatively organic-rich shale (Type 3 occurrence). (2) The Goodland Limestone is highly jointed, increasing the possibility that ground water enriched in uranium from the overlying Kiamichi Shale percolated through the limestone and deposited the uranium. (3) The outcrop belt of the Goodland and Kiamichi is evident on airborne radiometric profiles of southeastern Oklahoma (Geo-Life, 1979; Texas Instruments, 1977; Duval, 1989).

References on the geology include Marcher and Bergman (1983), Hart (1974), Davis (1960), and Huffman and others (1975,1978,1987).

Area 14

Area 14 parallels and is south of Area 13 in extreme southeastern Oklahoma immediately north of the Red River. The area is narrow, elongate, and extends from south of Hugo to south of Durant in southern Choctaw and southern Bryan Counties. Area 14 marks the outcrop band of parts of the Cretaceous Woodbine Formation and, in particular, the Red Branch Member, which erodes to a low, north-facing escarpment. The Red Branch Member consists of sandstone, shale, carbonaceous claystone, and bedded lignite coal deposits (Type 5 occurrence). The claystone and lignite may contain above-average concentrations of uranium; however, no published uranium analyses of the unit are available.

The potential for near-surface radon is locally low to moderate, based on rock type (organic-rich shale and lignite coal; Type 3 and 5 occurrences, respectively), and the fact that the outcrop band can be recognized on airborne radiometric surveys (Geo-Life, 1979; Duval, 1989).

References on the geology include Marcher and Bergman (1983), Hart (1974), and Huffman and others (1975,1978).

Area 15

Area 15 is narrow, irregularly shaped, and covers a small part of a relatively large area surrounding and northeast of the Arbuckle Mountains and in the Criner Hills in central and southern Pontotoc, southwestern Coal, western Atoka, northern and southwestern Johnston, southern Murray, and northern and south-central Carter Counties. The topography varies from gently rolling hills in the northeast to steep, elongate ridges separating narrow valleys near the Arbuckle Mountains. Area 15 outlines the outcrop pattern of the Devonian–Mississippian Woodford Shale (equivalent to the Chattanooga Shale in northeastern Oklahoma) and the Mississippian Delaware Creek (Caney) and Goddard (Springer) Shales. The uranium content of the Woodford Shale in Area 15 ranges from 8 to 127 ppm (Totten and Fay, 1982), and one sample from the Delaware Creek contained 10 ppm uranium (Landis, 1962). Both of these units are black, phosphatic shales (Type 4 occurrence) and have above-average uranium contents throughout Oklahoma. The Goddard Shale is not phosphatic; however, it may locally be rich in organic material (Type 3 occurrence).

The potential for near-surface radon in Area 15 is locally moderate to high, based on the known association of uranium with phosphatic shales, and the measured above-average uranium contents of some samples of those shales. In addition, the strata are locally complexly faulted and fractured, which would allow for increased permeability to ground-water movement and possible local uranium precipitation and concentration.

References on the geology include Hart (1974), Ham (1968), Ham and McKinley (1954), and Kempf (1957).

Area 16

Area 16 is in that part of the Arbuckle Mountains uplift region known as the Hunton anticline; it also includes a small part of the northern shelf geologic province (Fig. 1). It includes central Pontotoc, eastern Murray, and northern Johnston Counties. The area marks the surface exposure of a relatively thick sequence of Ordovician to Devonian limestones and subordinate dolomites, sandstones, and shales. In ascending order, the rock units include the McKenzie Hill, Cool Creek, Kindblade, and West Spring Creek (upper Arbuckle Group), Joins, Oil Creek, McLish, Tulip Creek, and Bromide (Simpson Group), Viola and Fernvale (Viola Group), Sylvan Shale, and Hunton Group. Uranium contents of these units in this area are unknown. However, the units are not believed to contain above-average concentrations of uranium. Several analyses in the northern part of Area 16 indicate minor, low-level uranium enrichment of asphaltic sandstones in the Pennsylvanian Ada Formation (Type 6 occurrence).

The potential for near-surface radon in Area 16 is generally low. The uranium content of most of the bedrock is probably very low; however, the Ordovician to Devonian rocks are highly faulted and fractured. It is possible that ground water may have leached uranium from nearby sources in the Woodford Shale (Area 15) and precipitated that uranium in fractures and shear zones in the carbonates. A similar process was described by Hand and Banikowski (1988) in New York. The fractures would also increase permeability and facilitate radon migration to the surface. Airborne radiometric surveys indicate low gamma-ray intensities over Area 16 (Texas Instruments, 1977; Duval, 1989).

References on the geology include Hart (1974), Ham and McKinley (1954), and Morgan (1924).

Area 17

Area 17 is in southwestern Atoka, southern Johnston, northwestern Marshall, and southeastern Murray Counties, in the southeastern part of the Arbuckle Mountains uplift region. The topography varies from nearly flat to gently rolling. The principal formations that underlie the area are the Precambrian Tishomingo and Troy Granites (Type 1 occurrence) and that part of the Cretaceous Antlers Sandstone that contains arkosic sediments derived from the granites (Type 2 occurrence). No published uranium analyses of the granites or sandstone are available; a single occurrence of carbonized wood in the Antlers Sandstone contains 7,670 ppm uranium (Totten and Fay, 1982).

The radon potential for Area 17 is generally low, based on rock type. Airborne radiometric surveys over the area (Texas Instruments, 1977; Duval, 1989) do not indicate above-average gamma-ray intensities; therefore, it appears that the Tishomingo and Troy

Granites (and sediments derived from them) contain less uranium than more "typical" granites, such as those that crop out in the Wichita Mountains (Area 19).

References on the geology include Hart (1974), Ham and McKinley (1954), and Ham and others (1964).

Southwest Region

The southwest region includes Harmon, Greer, Jackson, Kiowa, Tillman, Comanche, Cotton, Stephens, Jefferson, and parts of Love, Carter, Garvin, Grady, Caddo, Washita, and Beckham Counties (Fig. 4). The Wichita Mountains uplift, Hollis basin, Marietta basin, and southern part of the Anadarko basin are the principal geological provinces in this region (Fig. 1). The southwest region contains Areas 18–22. These areas have radon-potential categories that range from locally low to moderate to locally moderate to high. Parts of the region, particularly in the east and southwest, have generally very low radon potentials.

Area 18

An 18-mi-long by 6-mi-wide region in parts of Caddo and Grady Counties constitutes Area 18. Area 18 contains Oklahoma's most concentrated, localized uranium occurrence, and the only known uranium mine. The orebody, located within the town of Cement, occurred along a 150-ft-long fracture in the Permian Rush Springs Sandstone near the crest of the Cement anticline. Prior to removal, the orebody measured as much as 5 ft wide and 6 ft high along the fracture. Rock samples assayed as high as 20,460 ppm (2.046%) uranium (Totten and Fay, 1982). Mining ceased in 1957 because of limited ore volume, distance to mill, and price. Uranium concentrations as high as 43 ppm still exist near the mine site (Al-Shaieb and other, 1982).

Secondary uranium enrichment in the Rush Springs Sandstone is believed to be the result of interaction of oxygenated, uranium-bearing ground water coming in contact with a localized reducing chemical environment (Type 6 occurrence). Hydrogen-sulfide-bearing natural gas, escaping along fractures from the deep-seated Cement oil field, is thought to be the reductant initiating uranium precipitation (Al-Shaieb and others, 1982).

The radon potential for Area 18 is locally moderate to high. This assessment is based on the presence of uranium and above-normal uranium anomalies in soil and ground-water samples and radon-survey data (Al-Shaieb and others, 1982). The flightline spacings for the airborne radiometric survey were too large to show elevated gamma-ray intensities over Area 18 (Geodata International, 1976; Duval, 1989).

References on the geology include Havens (1977), Davis (1955), and Tanaka and Davis (1963).

Area 19

Outcrops of Cambrian granite, rhyolite, and associated late-stage dikes in the Wichita Mountains constitute Area 19. Parts of Comanche, Kiowa, Jackson, Greer, and Tillman Counties contain Area 19 exposures. The Quanah Granite, which crops out northwest of Lawton, is the youngest and most uraniferous of the Wichita Granite Group. The Quanah constitutes about 20% of the outcrop area and contains 2.6–104 ppm uranium. The average uranium content of the Quanah is approximately 11 ppm. Other granites in the group, the Mount Scott and Lugert, have average uranium contents of 4.6 ppm and 4.8 ppm, respectively. The Carlton Rhyolite, composed of lava flows and pyroclastics derived from silicic magmas, contains 4–9 ppm uranium and averages 5 ppm uranium (Totten and Fay, 1982). Numerous late-stage dikes associated with the Quanah Granite have uranium concentrations that range from 2.7 to 1,815 ppm and average 138 ppm. The exposures of the dikes are small.

The radon potential for Area 19 is locally moderate to high. This area contains rock types with known above-average uranium contents, in particular the Quanah Granite and associated dikes (Type 1 occurrence). Airborne radiometric surveys indicate elevated gamma-ray intensities over Area 19 (Geodata International, 1976; Duval, 1989). The higher potentials within Area 19 should occur over dikes and in valleys filled with weathered, porous and permeable granitic debris.

References on the geology include Gilbert and Donovan (1982), Powell and others (1980), Havens (1977), Merritt (1958), Ham and others (1964), and Al-Shaieb (1978).

Area 20

Parts of Comanche, Kiowa, and Tillman Counties are contained in Area 20. Area 20 contains outcrops of Permian Post Oak Conglomerate (granite facies) exposed on the south flank of the Wichita Mountains. In this area, the Post Oak Conglomerate is composed of coarse-grained sandstone, conglomerate, and shale beds derived from the Wichita Mountains. The uranium content of the Post Oak is highly variable because of the depositional environment of the unit. Locally, small areas within the Post Oak are enriched in uranium by secondary precipitation of uranium minerals (Type 2 occurrence). The rock-sample analyses show a range of 1–126 ppm uranium, with an average of 4 ppm uranium for Area 20 (Al-Shaieb and others, 1982). Some samples associated with Permian stream-channel deposits average >30 ppm uranium.

The radon potential for Area 20 is locally moderate. The rock-sample analytical data indicate that numerous samples contain 3 ppm or more uranium. Many of the samples contained >20 ppm uranium. Airborne radiometric surveys indicate low gamma-ray intensities over Area 20 (Geodata International, 1976; Duval, 1989). Individual radiometric profiles (Geodata International, 1976) show some increase in gamma-ray intensity over those parts of the Post Oak with above-average uranium contents.

References on the geology include Havens (1977) and Chase (1954).

Area 21

Area 21 is in parts of Tillman, Comanche, Cotton, Jefferson, Love, Kiowa, Greer, and Jackson Counties. Point-source uranium occurs within cross-bedded channel-sandstone deposits of limited areal extent in the Permian Hennessey Group, Garber Sandstone, and Wellington Formation, and the Pennsylvanian Oscar Group. These point-source deposits generally result when uranium-bearing, oxygenated ground water comes in contact with localized reducing environments established in and around carbonaceous plant remains and asphalt-rich zones (Type 6 occurrence). Copper minerals, pyrite, and galena typically occur in association with the uranium minerals. Chemical analyses of selected rock samples range from 5.5 to 15,000 ppm uranium (Al-Shaieb and others, 1982; Totten and Fay, 1982). These deposits are small because the sandstone beds have limited areal extent and lack significant amounts of carbonaceous material. An occurrence along the Red River in extreme southern Cotton County is one of the largest in Area 21. The mineralized zone, associated with abundant woody, carbonaceous material, occurs in the basal 10 ft of a 25-ft-thick, 300-ft-wide, 600-ft-long ancient stream channel in the Garber Sandstone.

The radon potential for Area 21 is locally low to moderate, based on the abundance of known point-source uranium deposits. The flightline spacings for the airborne radiometric survey were too large to identify most point-source occurrences. Individual flightline radiometric profiles (Geodata International, 1976) exhibit rare, minor increases in gamma-ray intensity.

References on the geology include Havens (1977).

Area 22

Area 22 consists of a 150-mi-long by 1- to 3-mi-wide exposure of Permian Flowerpot Shale. This area extends northward from Jackson County through parts of Greer and Beckham Counties, and eastward through parts of Washita, Kiowa, and Caddo Counties. Uranium is concentrated in two or more thin, stratigraphically continuous, copper-bearing, silty shale beds (Type 7 occurrence). Two of these beds, the Prewitt and Meadows copper shales, were prospected for copper in the Creta and Mangum Districts, respectively (Johnson, 1976). The Prewitt copper shale was mined from 1965 to the mid-1970s. Uranium contents range from 70 to 100 ppm in the Prewitt and 80 to 100 ppm in the Meadows (Lockwood, 1976).

The radon potential for Area 22 is locally low to moderate. Uranium-bearing beds, which are continuous over long distances, are very thin, generally <1 ft thick. Higher potentials occur over outcrop exposures and debris derived from the uranium-bearing beds. Individual flightline radiometric profiles show elevated gamma-ray intensities in the vicinity of the Flowerpot Shale in Area 22 (Geodata International, 1976; Duval, 1989).

References on the geology include Havens (1977), Carr and Bergman (1976), and Johnson and Croy (1977).

Northwest Region

The northwest region includes the Oklahoma Panhandle, northwest Oklahoma, and a large part of central Oklahoma. The region includes Kay, Noble, Grant, Garfield, Alfalfa, Major, Woods, Woodward, Harper, Ellis, Payne, Lincoln, Logan, Oklahoma, Kingfisher, Canadian, Blaine, Dewey, Custer, Roger Mills, Seminole, Pottawatomie, Cleveland, and parts of Osage, Pawnee, Creek, Okfuskee, Hughes, Pontotoc, McClain, Grady, Caddo, Washita, and Beckham Counties (Fig. 4). Almost the entire region is within the northern shelf or Anadarko basin tectonic provinces (Fig. 1). The northwest region contains Areas 23–26. The radon potential of these areas ranges from generally low to locally moderate. However, most of the region, and particularly the eastern part, has a generally very low radon potential.

Area 23

Area 23 is a relatively large, curved area in Beckham, Washita, southwestern Custer, Roger Mills, extreme southwestern Dewey, and extreme southeastern Ellis Counties in western Oklahoma. The curved shape of the area results from the outcrop pattern of the lower part of the Doxey Shale and upper part of the Cloud Chief Formation on the flanks of the gently west-plunging Anadarko basin (Fig. 1). Both units are Permian and mostly composed of reddish-brown siltstone and shale. The basal 10 ft of the Doxey Shale is greenish-gray and has unusually high uranium contents (Type 7 occurrence). Radiometric surveys indicate that surface gamma radiation 4–5 times background is typical; locally, similar surveys have recorded gamma radiation 30–40 times background (Totten and Fay, 1982). The uranium content of 11 samples from the basal Doxey Shale ranges from 23 to 1,770 ppm and averages 243 ppm (Bloch and others, 1982).

The potential for near-surface radon in Area 23 is locally moderate, based on rock type and radiometric surveys. Chemical analyses, airborne radiometric surveys (Geodata International, 1976; Duval, 1989), and ground radiometric surveys indicate that the basal part of the Doxey Shale is unusually rich in uranium. Despite widespread agreement on the character of the Doxey Shale, the origin of the uranium is unknown. Area 23 also includes the upper part of the Cloud Chief Formation, because it may be slightly enriched in uranium due to ground-water leaching of the overlying Doxey Shale.

References on the geology include Fay and Hart (1978) and Carr and Bergman (1976).

Area 24

Area 24 is in the northwestern corner of the Oklahoma Panhandle, in the northwestern part of Cimarron County. The area extends from about 15 mi north of Boise City north to the Kansas state line and west to the Colorado state line. The topography varies from nearly flat, to gently rolling, to relatively steep-walled canyons and mesas. Area 24 is underlain by Mesozoic rocks exposed in the Cimarron River Valley and its tributaries; the bedrock units consist of the Triassic Dockum Group, the Jurassic Exeter Sandstone and Morrison Formation, and the Cretaceous Kiowa Shale, Dakota Sandstone, and Graneros–Greenhorn Group. The only formation known to contain uranium is the Morrison; single sample analyses range from 8 to 2,600 ppm uranium (Abbott, 1979; Consulting Professionals, 1982). The uranium in the Morrison is associated with carbonaceous material in sandstones, conglomerates, and gray-green shales (Type 3 and 6 occurrences).

The potential for near-surface radon in Area 24 is locally moderate, based on rock type. The Morrison Formation is known to contain above-average concentrations of uranium throughout the western United States. In addition, significant parts of the Kiowa and Graneros are composed of dark-gray to black shale; these are likely to be rich in organic material and may contain above-average amounts of uranium (Type 3 occurrence). The Dakota Sandstone also contains a significant amount of dark shale (Type 3 occurrence); in addition, its middle member contains bedded lignite (Type 5 occurrence). Airborne radiometric surveys (Texas Instruments, 1979; Duval, 1989) indicate that Area 24 is underlain by strata with above-average uranium contents.

References on the geology include Barnes (1984) and Schoff and Stovall (1943).

Area 25

Area 25 is in the central part of the Oklahoma Panhandle in Cimarron, Texas, and southwestern Beaver Counties. The area is large, extending from immediately north of Boise City about 120 mi east, to south of Beaver; but it is discontinuous, consisting of seven sub-areas. The area is extremely flat and is part of the undissected high plains. The principal geologic unit is Quaternary and consists of (1) a surface deposit composed of caliche-cemented detritus derived from the underlying Pliocene Ogallala Formation, (2) playa deposits, and (3) windblown sand and silt. The uranium content of the Quaternary deposits is unknown.

The potential for near-surface radon in Area 25 is generally low, based entirely on airborne radiometric surveys (Geodata International, 1980a; Texas Instruments, 1979; Duval, 1989). In general, these surveys indicate more gamma radiation over the undissected Quaternary surface deposits than over the underlying Ogallala Formation exposed in valleys. The origin of the higher gamma radiation is unknown, but may include one or more of the following: (1) uraniferous volcanic ash in the windblown sediments; (2) above-average uranium contents in the caliche; (3) above-average uranium contents in the soil caused by the long-term use of slightly uraniferous phosphate fertilizers (Area 26); and (4) above-average uranium content in silicified rocks of the Ogallala Formation, as in Clark and Meade Counties, Kansas (Berendsen and Hathaway, 1981).

References on the geology include Barnes (1970,1984), Schoff (1939), Schoff and Stovall (1943), and Marine and Schoff (1962).

Area 26

Area 26 is a large area in northwestern Oklahoma, excluding the Panhandle. It extends from near Ponca City on the northeast, to Norman on the southeast, to Cordell on the southwest, to Buffalo on the northwest. Most or parts of the following counties are included in Area 26: Osage, Kay, Grant, Alfalfa, Woods, Harper, Noble, Garfield, Major, Woodward, Logan, Kingfisher, Blaine, Dewey, Ellis, Oklahoma, Canadian, Custer, Roger Mills, Cleveland, McClain, Grady, and Washita. The area is mostly flat to gently rolling. The bedrock formations consist of Permian sandstones, siltstones, and shales and thin limestone, dolomite, and gypsum beds of the northern shelf and margin of the Anadarko basin. These formations constitute Oklahoma's red bed sequence. With the exception of small, point-source concentrations of uranium associated with carbonaceous material, the uranium content of the red beds is low; this is consistent with the oxidized nature of the sediments. Most chemical analyses of bedrock samples show <4 ppm uranium; the highest concentration is 8 ppm uranium (Eutsler and others, 1982; Derby and others, 1982; Bloch and others, 1982).

Despite the apparent absence of any significant occurrences of uranium-rich rocks in Area 26, there appears to be some potential for near-surface radon. As a result, the area is believed to be generally low in radon potential, as opposed to generally very low. Airborne radiometric surveys (Geodata International, 1976,1980b; Texas Instruments, 1977,1978; Duval, 1989) indicate slightly above-average uranium contents in the surficial rocks and soils. The elevated gamma-ray intensities that characterize Area 26 contrast with several northwest-trending areas of low intensities that correspond to the alluvium-filled valleys of the Canadian, North Canadian, Cimarron, and Salt Fork Rivers.

The origin of the uranium in the soil and surface rocks of Area 26 is unknown. The Permian bedrock appears to contain only localized point-source accumulations of uranium that show relatively low concentrations. This observation is consistent with the oxidized nature and published chemical analyses of the rocks. In addition, the pattern of elevated gamma-ray intensities does not coincide with geologic formations. However, Area 26 closely coincides with Oklahoma's wheat belt. It is possible that the soils in Area 26 are slightly enriched in uranium due to the long-term application of uraniferous phosphate fertilizers. Phosphate fertilizers typically contain 50–200 ppm uranium (Wakefield, 1980; Tucker and others, 1988).

References on the geology include Bingham and Bergman (1980), Morton (1981), Bingham and Moore (1975), and Carr and Bergman (1976).

SUMMARY

Four fundamental factors determine how much radon in the ground enters a building: (1) the amount of radium (uranium) in the soil and/or bedrock, (2) the amount of pore space in the rock or soil, (3) the number of openings (pores, cracks) below ground level in a building, and (4) the pressure differential across the ground/structure interface (Tanner, 1986). This study only addresses the distribution and concentration of uranium in Oklahoma's soils and/or bedrock; this represents only one of the four factors that determine whether an indoor-radon hazard may exist.

This report uses uranium as a mappable indicator for radon. Uranium has been studied in great detail because of its economic and strategic importance. In Oklahoma, uranium is associated with many different rock types and geologic environments. The principal Oklahoma uranium occurrences are associated with (1) granite and sediments derived from the erosion of granitic rocks; (2) dark, organic-rich shale; (3) phosphatic black shale; and (4) coal beds.

Analytical data, airborne radiometric surveys, and uranium occurrence were the principal factors used to evaluate the bedrock formations for radon potential. Five radon-potential categories were developed: *generally very low*, *generally low*, *locally low to moderate*, *locally moderate*, and *locally moderate to high*. The modifiers *generally* and *locally* are used because the rating for a given area may not be uniformly distributed. A summary of the principal rating factors used to identify and classify geologic formations and/or units for radon potential is given in Table 3.

Twenty-six areas in the State were outlined, numbered, and assigned a radon-potential category (Radon-Potential Map). The boundary lines are approximate; the map scale is too small to accurately portray individual beds within a formation. For organization and discussion, each area was assigned to one of four regions. The northeast region contains Areas 1–8; the southeast region contains Areas 9–17; the southwest region contains Areas 18–22; and the northwest region contains Areas 23–26. Areas underlain by formations with uranium contents equal to or less than the crustal average (2.5 ppm) are rated generally very low or generally low. Approximately 80% of the State is included in these two categories (Table 4). About 7% of the State's land area has a locally moderate to locally moderate to high radon-potential rating. The rest of the State, 13%, is included in the locally low to moderate radon-potential category (Table 4).

This study is a reconnaissance-level investigation based on existing geologic literature. The report and map are intended to assist the Oklahoma State Department of Health in planning site-specific indoor-radon surveys. The map scale, limited analytical data, time constraints, and lateral lithologic variations in rock units precluded a site-by-site analysis.

This map does not predict indoor-radon levels. Climate, rock/soil permeability, ground-water saturation and movement, and building construction and usage strongly affect indoor-radon levels. The low–moderate–high radon-potential rating scheme only compares the distribution of uranium-bearing rocks from one outlined area to another. Bedrock and soils with above-average uranium contents are more likely to produce above-average concentrations of soil-gas radon (Tanner, 1986). Higher soil-gas radon concentrations may result in higher indoor-radon concentrations when other variables are equal.

ACKNOWLEDGMENTS

This report is based on work completed in fulfillment of Contract No. 21286 between the Oklahoma Geological Survey and the Oklahoma State Department of Health. We thank Jim Chaplin, LeRoy Hemish, Ken Johnson, and Larry Stout (all with the Oklahoma Geological Survey), and Pieter Berendsen (Kansas Geological Survey) for their thoughtful reviews of the report and map. We are especially grateful to Joseph Duval (U.S. Geological Survey) for his review and for providing us with a preliminary copy of his equivalent-uranium map.

Table 3.—Summary of Principal Rating Factors Used to Classify and Identify Geologic Formations and/or Units for Radon Potential

Area (by region)	Radon potential	Uranium occurrence (type[a])	Number of uranium analyses	Radiometric-intensity correlation[b]	Confidence factor[c]	Principal geologic formations and/or units	Remarks
NORTHEAST							
1	locally moderate to high	3,4	low	poor	3	Chattanooga Shale	Very limited exposures; uranium contents 10–70 ppm
2	locally moderate to high	3,4	high	good	4	Excello, Little Osage, Anna, Bandera, Lake Neosho Shales	Uranium contents of black phosphatic shales 20–50 ppm
3	locally moderate	3,4,5	moderate	fair	4	Senora and Boggy Formations; Inola Limestone	Numerous black phosphatic shales, black shales, and coal beds; uranium contents 10–30 ppm
4	locally low to moderate	3,5	low	good	4	Boggy, Savanna, McAlester, Hartshorne, and Atoka Formations; Fayetteville Shale	Black-shale beds lack phosphate enrichment; uranium contents 10–20 ppm
5	locally moderate	4,5	low	poor	3	Dawson coal and Nuyaka Creek Shale of Seminole Formation	Thin coal bed and phosphatic black shale; estimated uranium content in shale 40–130 ppm
6	locally low to moderate	3,4	low	fair	4	Checkerboard Limestone; Coffeyville and Hogshooter Formations	Uranium contents 10–900 ppm in phosphate-rich zones in the Coffeyville Formation
7	generally low	3,4,5	low	fair	3	Dewey, Chanute, and Iola Limestones	Uranium-rich zones thin; some correlation with airborne radiometric survey in northern end of area
8	generally low	3,5	none	poor	3	Savanna, Senora, and Boggy Formations; Stuart Shale; Thurman Sandstone	Formations contain more sand and fewer dark-gray, brown, and black carbonaceous shales than in Area 4
SOUTHEAST							
9	locally moderate	3	low	fair	4	Mazarn, Womble, Polk Creek, and Stanley Shales; Bigfork Chert; Missouri Mountain Formation; Arkansas Novaculite	Uranium contents of Arkansas Novaculite and basal Stanley Shale 10–20 ppm

TABLE 3.—*Continued*

Area (by region)	Radon potential	Uranium occurrence (type[a])	Number of uranium analyses	Radiometric-intensity correlation[b]	Confidence factor[c]	Principal geologic formations and/or units	Remarks
10	locally moderate	3,4	low	poor	4	Woodford, Delaware Creek, and Goddard Shales	Uranium contents of Woodford and Delaware Creek 5–70 and 10–24 ppm, respectively
11	locally moderate	3	low	poor	4	Womble, Polk Creek, Missouri Mountain, and Delaware Creek Shales; Bigfork Chert; Arkansas Novaculite	Uranium contents of Arkansas Novaculite 10–30 ppm
12	generally low	3	very low	poor	3	Stanley and Jackfork Groups; Johns Valley and Limestone Gap Shales; Lynn Mountain Formation	Formations appear low in organic contents, light-colored, and probably low in uranium
13	locally moderate	3	very low	good	4	Kiamichi Shale; Goodland Limestone; Walnut Clay	Uranium contents 1.8–5.7 ppm in Goodland Limestone and Walnut Clay
14	locally low to moderate	3,5	none	fair	2	Red Branch Member of Woodbine Formation	Parts of the Woodbine, particularly the Red Ranch, contain carbonaceous clay, lignite fragments, and lignite beds
15	locally moderate to high	3,4	high	good	5	Woodford, Delaware Creek, and Goddard Shales	Uranium contents of the Woodford and Delaware Creek Shales 8–127 ppm
16	generally low	6	low to moderate	fair to poor	3	Ada Formation (northern part of Area 16)	Local asphaltic sandstones in Ada Formation
17	generally low	1,2	none	poor	2	Tishomingo and Troy Granites; Antlers Sandstone	No published uranium analyses of the granites and sandstone
SOUTHWEST							
18	locally moderate to high	6	high	fair	5	Rush Springs Sandstone	Site of Oklahoma's most concentrated, localized uranium occurrence and only known mined uranium deposit
19	locally moderate to high	1	high	good	5	Wichita Granite Group, Quanah Granite and dikes; Carlton Rhyolite	Uranium contents of Quanah 2.6–104 ppm; other granites have average uranium contents of 4–5 ppm; uranium contents of dikes 3–1,815 ppm

20	locally moderate	2	high	fair to poor	4	Post Oak Conglomerate (granite facies)	Uranium contents 1–126 ppm; average uranium content 4 ppm
21	locally low to moderate	6	high	fair to poor	3	Garber and Wellington Formations; Oscar and Hennessey Groups	Point-source occurrences; uranium contents 5.5–15,000 ppm
22	locally low to moderate	7	moderate	fair to poor	4	Prewitt and Meadows Beds of Flowerpot Shale	Uranium associated with two areas of significant copper mineralization; uranium contents 70–100 ppm
NORTHWEST							
23	locally moderate	7	high	good	5	Basal Doxey Shale and upper Cloud Chief	Uranium contents of the Doxy 23–1,770 ppm; upper part of Cloud Chief may be enriched in uranium from ground-water leaching of the overlying Doxey
24	locally moderate	3,5,6	moderate	fair	3	Morrison Formation; Kiowa Shale; Dakota and Exeter Sandstones; Graneros–Greenhorn and Dockum Groups	Uranium contents of the Morrison 8–2,600 ppm
25	generally low	?	none	fair	2	High Plains caliche caprock and overlying soil veneer	Area of above-average airborne-radiometric-intensity values
26	generally low	?	high	fair	2	Numerous Permian red-bed formations	Area of above-average airborne-radiometric-intensity values; no apparent geologic control

[a]Uranium occurrences in the State were divided into seven types based on the mode of uranium enrichment and size, distribution, and geologic continunity of the occurrence. See map and/or report for detailed discussion.

[b]Correlation with gamma-ray-intensity measurements from airborne radiometric surveys.

[c]The radon-potential category for each area was rated on a confidence-factor scale ranging from 1 to 5; 1 represents the lowest confidence factor, and 5 the highest. The confidence factor is based on uranium occurrence (type), analytical data, and correlation with airborne-radiometric-survey data.

Table 4.—Estimated Percentage of Land Area in the Five Radon-Potential Categories, by County

County	Area* (sq. mi)	Radon Potential (percent of county area)				
		Generally very low	Generally low	Locally low to moderate	Locally moderate	Locally moderate to high
Adair	577	64		23		13
Alfalfa	864	39	61			
Atoka	980	17	75	2	5	1
Beaver	1,808	87	13			
Beckham	904	70	3	12	15	
Blaine	920	34	66			
Bryan	902	78		14	8	
Caddo	1,286	93	3	<1		4
Canadian	902	21	79			
Carter	827	92				8
Cherokee	748	41		46		13
Choctaw	763	70		9	21	
Cimarron	1,842	63	19		18	
Cleveland	529	66	34			
Coal	520		70	24		6
Comanche	1,076	52		8	21	19
Cotton	656	25		75		
Craig	763	6		48	19	27
Creek	930	90	2	8	<1	
Custer	981	7	79		14	
Delaware	720	94				6
Dewey	1,007	24	74		2	
Ellis	1,232	93	5		2	
Garfield	1,060	3	97			
Garvin	813	100				
Grady	1,106	66	31			3
Grant	1,004	13	87			
Greer	638	65		32		3
Harmon	537	98		2		
Harper	1,039	39	61			
Haskell	570		10	90		
Hughes	805	62	38			
Jackson	817	91		9		<1
Jefferson	769	36		64		
Johnston	639	1	86		6	7
Kay	921		100			
Kingfisher	906	29	71			
Kiowa	1,019	45		33	4	18
Latimer	728		71	23	6	
Le Flore	1,585		60	40		
Lincoln	964	100				
Logan	748	47	53			
Love	519	77		9	14	<1

TABLE 4.—*Continued*

County	Area* (sq. mi)	Radon Potential (percent of county area) Generally very low	Generally low	Locally low to moderate	Locally moderate	Locally moderate to high
Major	958	47	53			
Marshall	372	51	5		44	
Mayes	644	36		60	2	2
McClain	581	80	20			
McCurtain	1,826	39	35		26	
McIntosh	599		12	78	10	
Murray	420	66	17			17
Muskogee	815		69	31		<1
Noble	736	50	50			
Nowata	541	34	2	21	3	40
Okfuskee	628	94	5		1	
Oklahoma	708	56	44			
Okmulgee	698	63	3	31	2	1
Osage	2,264	78	20	2		
Ottawa	465	51		49		
Pawnee	551	100				
Payne	691	99	1			
Pittsburg	1,251		76	21	3	
Pontotoc	717	50	32	10		8
Pottawatomie	783	100				
Pushmataha	1,417	7	91		2	
Roger Mills	1,146	53	18		29	
Rogers	683	18		33	29	20
Seminole	639	100				
Sequoyah	678			99		1
Stephens	885	100				
Texas	2,040	69	31			
Tillman	904	32		65	3	<1
Tulsa	571	62	3	20	7	8
Wagoner	559			62	36	2
Washington	423	37	40	23		
Washita	1,006	49	35	1	15	
Woods	1,291	35	65			
Woodward	1,242	56	44			
Percent of total area		50	30	13	5	2

*Directory of Oklahoma, State Almanac—1989–1990 (Oklahoma Department of Libraries, 1989).

REFERENCES

Abbott, M. M., 1979, A basic evaluation of the uranium potential of the Morrison Formation of northwestern Cimarron County, Oklahoma, and adjoining areas of New Mexico and Colorado: Oklahoma State University unpublished M.S. thesis, 41 p.

Al-Shaieb, Z. F., 1978, Guidebook to uranium mineralization in sedimentary and igneous rocks of Wichita Mountains region, southwestern Oklahoma: Oklahoma City Geological Society, 73 p.

Al-Shaieb, Z. F.; Thomas, R. G.; and Stewart, G. F., 1982, National uranium resource evaluation, Lawton Quadrangle, Oklahoma and Texas: U.S. Department of Energy Open-File Report GJQ-017(82), 48 p.

Bailey, R. V.; and Childers, M. O., 1977, Applied mineral exploration with special reference to uranium: Westview Press, Inc., Boulder, Colorado, p. 84–85, 126.

Barnes, V. E. (project director), 1970, Geologic atlas of Texas, Perryton sheet: Texas Bureau of Economic Geology, Map, scale 1:250,000, 1 sheet.

______1984, Geologic atlas of Texas, Dalhart sheet: Texas Bureau of Economic Geology Map, scale 1:250,000, 1 sheet.

Bennison, A. P.; Knight, W. V.; Creath, W. B.; Dott R. H.; and Hayes, C. L. (eds.), 1972, Tulsa's physical environment: Tulsa Geological Society Digest, v. 37, 489 p.

Berendsen, Pieter; and Hathaway, L. R., 1981, Uranium in unconsolidated aquifers of western Kansas: Kansas Geological Survey Mineral Resources Series 9, 43 p.

Bingham, R. H.; and Bergman, D. L., 1980, Reconnaissance of the water resources of the Enid Quadrangle, north-central Oklahoma: Oklahoma Geological Survey Hydrologic Atlas 7, scale 1:250,000, 4 sheets.

Bingham, R. H.; and Moore, R. L., 1975, Reconnaissance of the water resources of the Oklahoma City Quadrangle, central Oklahoma: Oklahoma Geological Survey Hydrologic Atlas 4, scale 1:250,000, 4 sheets.

Bloch, Salman, 1979, Origin of radium-rich oil-field brines—a hypothesis: Oklahoma Geology Notes, v. 39, p. 177–182.

Bloch, Salman; and Craig, R. L., 1981, Radioactive springs in the watershed of a proposed reservoir in Sequoyah County, Oklahoma: origin and environmental effect: Geology, v. 9, p. 195–199.

Bloch, Salman; Johnson, K. S.; Eutsler, R. L.; and Myers, J. J., 1982, National uranium resource evaluation, Clinton Quadrangle, Oklahoma: U.S. Department of Energy Open-File Report PGJ/F-096(82), 36 p.

Bowen, Robert, 1988, Isotopes in the earth sciences: Elsevier, London, 647 p.

Bowie, S. H. U.; and Plant, J. A., 1983, Natural radioactivity in the environment, *in* Thorton, I. (ed.), Applied environmental geochemistry: Academic Press, London, p. 481–494.

Branson, C. C.; Huffman, G. G.; and Strong, D. M., 1965, Geology and oil and gas resources of Craig County, Oklahoma: Oklahoma Geological Survey Bulletin 99, 109 p.

Carr, J. E.; and Bergman, D. L., 1976, Reconnaissance of the water resources of the Clinton Quadrangle, west-central Oklahoma: Oklahoma Geological Survey Hydrologic Atlas 5, scale 1:250,000, 4 sheets.

Chase, G. W., 1954, Permian conglomerate around Wichita Mountains, Oklahoma: American Association of Petroleum Geologists Bulletin, v. 31, p. 2028–2035.

Consulting Professionals, Inc., 1982, National uranium resource evaluation, Dalhart Quadrangle, Texas, New Mexico, Oklahoma, Colorado, and Kansas: U.S. Department of Energy Open-File Report PGJ/F-081(82), 41 p.

Coveney, R. M., Jr.; Hilpman, P. L.; Allen, A. V.; and Glascock, M. D., 1988, Radionuclides in Pennsylvanian black shales of the midwestern United States, *in* Marikos, M. A.; and Hansman, R. H. (eds.), Geological causes of natural radionuclide anomalies: proceedings of the Georad Conference: Missouri Department of Natural Resources, Division of Geology and Land Survey, Special Publication 4, p. 25–42.

Davis, L. V., 1955, Geology and ground-water resources of Grady and northern Stephens Counties, Oklahoma: Oklahoma Geological Survey Bulletin 73, 184 p.

______1960, Geology and ground-water resources of southern McCurtain County, Oklahoma: Oklahoma Geological Bulletin 86, 108 p.

Derby, J. R.; Upshaw, L. P.; Carter, E. O.; Roach, L. F.; and Roach, D. G., 1982, National uranium resource evaluation, Oklahoma City Quadrangle, Oklahoma: U.S. Department of Energy Open-File Report PGJ/F-091(82), 23 p.

Dott, Robert, Sr.; and Bennison, A. P., 1981, Road log, *in* Dott, Robert, Sr. (ed.), A guidebook to the type areas of the Holdenville and Seminole Formations, western Arkoma basin: American Association of Petroleum Geologists Mid-Continent Regional Convention, Field Trip No. 2, p. 11–30.

Duval, J. S., 1989, Equivalent uranium map, conterminous United States: U.S. Geological Survey Open-File Report 89-478, 13 p.

EG&G geoMetrics, Inc., 1980, Aerial gamma ray and magnetic survey, Fort Smith Quadrangle, Oklahoma and Arkansas: U.S. Department of Energy Open-File Report GJBX-200(80), 137 p.

Eutsler, R. L.; Bloch, Salman; and Johnson, K. S., 1982, National uranium resource evaluation, Enid Quadrangle, Oklahoma and Kansas: U.S. Department of Energy Open-File Report PGJ/F-095(82), 39 p.

Fay, R. O.; and Hart, D. L., Jr., 1978, Geology and mineral resources (exclusive of petroleum) of Custer County, Oklahoma: Oklahoma Geological Survey Bulletin 114, 88 p.

Geodata International, Inc., 1976, Aerial radiometric and magnetic survey, Clinton, Oklahoma City, and Lawton national topographic map: U.S. Department of Energy Open-File Report GJBX-34(76).

______1980a, Aerial radiometric and magnetic survey, Perryton national topographic map, Texas/Oklahoma/Kansas, West Texas Project: U.S. Department of Energy Open-File Report GJBX-229(80), 100 p.

______1980b, Aerial radiometric and magnetic survey, Woodward national topographic map, Oklahoma: U.S. Department of Energy Open-File Report GJBX-251(80), 100 p.

Geo-Life, Inc., 1979, Aerial radiometric and magnetic survey, McAlester national topographic map, Oklahoma/Arkansas: U.S. Department of Energy Open-File Report GJBX-174(79), 117 p.

Gilbert, M. C.; and Donovan, R. N. (eds.), 1982, Geology of the eastern Wichita Mountains, southwestern Oklahoma: Oklahoma Geological Survey Guidebook 21, 160 p.

Hall, F. R., 1986, Geologic controls on radon in groundwater, *in* Mahotske, W. J.; and Edelstein, M. R. (eds.), Radon and the environment: Institute for Environmental Studies, Ramapo College of New Jersey, Mahwah, New York, p. 48–55.

Ham, W. E., 1968, Regional geology of the Arbuckle Mountains, Oklahoma: Oklahoma Geological Survey Guidebook 17, 52 p.

Ham, W. E.; and McKinley, M. E., 1954, Geologic map and sections of the Arbuckle Mountains, Oklahoma: Oklahoma Geological Survey Map A-2, scale 1:72,000.

Ham, W. E.; Denison, R. E.; and Merritt, C. A., 1964, Basement rocks and structural evolution of southern Oklahoma: Oklahoma Geological Survey Bulletin 95, p. 126–140.

Hand, B. M.; and Banikowski, J. E., 1988, Radon in Onodaga County, New York: paleohydrogeology and the redistribution of uranium in Paleozoic sedimentary rocks: Geology, v. 16, p. 775–778.

Hart, D. L., Jr., 1974, Reconnaissance of the water resources of the Ardmore and Sherman Quadrangles, southern Oklahoma: Oklahoma Geological Survey Hydrologic Atlas 3, scale 1:250,000, 4 sheets.

Hasenmueller, N. R., 1988, Preliminary geologic characterization of Indiana for radon survey: Indiana Geological Survey Report of Progress 32, 7 p.

Havens, J. S., 1977, Reconnaissance of the water resources of the Lawton Quadrangle, southwestern Oklahoma: Oklahoma Geological Survey Hydrologic Atlas 6, scale 1:250,000, 4 sheets.

Hemish, L. A., 1987, Coal geology of Craig County and eastern Nowata County, Oklahoma: Oklahoma Geological Survey Bulletin 140, 131 p.

Hendricks, T. A., 1937, The McAlester district, *pt. 1 of* Geology and fuel resources of the southern part of the Oklahoma coal field: U.S. Geological Survey Bulletin 874-A, p. 1–90.

______ 1939, The Howe–Wilburton district, Latimer and Le Flore Counties, *pt. 4 of* Geology and fuel resources of the southern part of the Oklahoma coal field: U.S. Geological Survey Bulletin 874-D, p. 255–300.

Hendricks, T. A.; Knechtel, M. M.; and Bridge, J., 1937, Geology of Black Knob Ridge, Oklahoma: American Association of Petroleum Geologists Bulletin, v. 21, p. 1–29.

Hendricks, T. A.; Gardner, L. S.; Knechtel, M. M.; and Averitt, P., 1947, Geology of the western part of the Ouachita Mountains of Oklahoma: U.S. Geological Survey Oil and Gas Investigation Preliminary Map 66, scale 1:42,240, 3 sheets.

Hobday, D. K.; and Rose, F. G., Jr., 1982, National uranium resource evaluation, Sherman Quadrangle, Texas and Oklahoma: U.S. Department of Energy Open-File Report PGJ/F-089(82), 30 p.

Honess, C. W., 1923, Geology of the southern Ouachita Mountains of Oklahoma: Oklahoma Geological Survey Bulletin 32, 355 p.

Huffman, G. G.; and others, 1958, Geology of the flanks of the Ozark uplift, northeastern Oklahoma: Oklahoma Geological Survey Bulletin 77, 281 p.

Huffman, G. G.; Langston, J. M.; and Hancock, J. M., Jr., 1966, Geology of northern Adair County, Oklahoma: Oklahoma Geological Survey Circular 68, 50 p.

Huffman, G. G.; Alfonsi, P. P.; Dalton, R. C.; Duarte-Vivas, A.; and Jeffries, E. L., 1975, Geology and mineral resources of Choctaw County, Oklahoma: Oklahoma Geological Survey Bulletin 120, 39 p.

Huffman, G. G.; Hart, T. A.; Olson, L. J.; Currier, J. D.; and Ganser, R. W., 1978, Geology and mineral resources of Bryan County, Oklahoma: Oklahoma Geological Survey Bulletin 126, 108 p.

Huffman, G. G.; Bridges, K. F.; Ganser, R. W.; Holtzman, A. M., Jr.; and Merritt, M. L., 1987, Geology and mineral resources of Marshall County, Oklahoma: Oklahoma Geological Survey Bulletin 142, 126 p.

Hyden, H. J.; and Danilchik, Walter, 1962, Uranium in some rocks of Pennsylvanian age in Oklahoma, Kansas, and Missouri: U.S. Geological Survey Bulletin 1147-B, p. B1–B82.

Johnson, K. S., 1971, Guidebook for geologic field trips in Oklahoma: Oklahoma Geological Survey Educational Publication 2, 15 p.

______ 1976, Permian copper shales of southwestern Oklahoma, *in* Johnson, K. S.; and Croy R. L. (eds.), Stratiform copper deposits in the Midcontinent region, a symposium: Oklahoma Geological Survey Circular 77, p. 3–14.

Johnson, K. S.; and Croy, R. L. (eds.), 1977, Stratiform copper deposits of the Midcontinent region, a symposium: Oklahoma Geological Survey Circular 77, 99 p.

Johnson, K. S.; Branson, C. C.; Curtis, N. M., Jr.; Ham, W. E.; Harrison, W. E.; Marcher, M. V.; and Roberts, J. F., 1979, Geology and earth resources of Oklahoma—an atlas of maps and cross sections: Oklahoma Geological Survey Educational Publication 1, 8 p.

Kempf, J. H. (ed.), 1957, Criner Hills field conference, Lake Murray area, southern Oklahoma: Ardmore Geological Society Guidebook, 79 p.

Knight, W. V., 1972, Coal and coal mining in the Tulsa area, *in* Bennison, A. P.; Knight, W. V.; Creath, W. B.; Dott, R. H.; and Hayes, C. L. (eds.), Tulsa's physical environment: Tulsa Geological Society Digest, v. 37, p. 243–251.

Landis, E. R., 1962, Uranium and other trace elements in Devonian and Mississippian black shales in the central Midcontinent area: U.S. Geological Survey Bulletin 1107-E, p. 289–334.

Lockwood, R. S., 1976, Geochemistry and petrology of some Oklahoma red-bed copper occurrences, *in* Johnson, K. S.; and Croy, R. L. (eds.), Stratiform copper deposits of the Midcontinent region, a symposium: Oklahoma Geological Survey Circular 77, p. 61–68.

Marcher, M. V., 1969, Reconnaissance of the water resources of the Fort Smith Quadrangle, east-central Oklahoma: Oklahoma Geological Survey Hydrologic Atlas 1, scale 1:250,000, 4 sheets.

Marcher, M. V.; and Bergman, D. L., 1983, Reconnaissance of the water resources of the McAlester and Texarkana Quadrangles, southeastern Oklahoma: Oklahoma Geological Survey Hydrologic Atlas 9, scale 1:250,000, 4 sheets.

Marcher, M. V.; and Bingham, R. H., 1971, Reconnaissance of the water resources of the Tulsa Quadrangle, northeastern Oklahoma: Oklahoma Geological Survey Hydrologic Atlas 2, scale 1:250,000, 4 sheets.

Marine, I. W.; and Schoff, S. L., 1962, Ground-water resources of Beaver County, Oklahoma: Oklahoma Geological Survey Bulletin 97, 74 p.

Merritt, C. A., 1958, Igneous geology of the Lake Altus area, Oklahoma: Oklahoma Geological Survey Bulletin 76, 70 p.

Moore, W. S., 1972, Radium: element and geochemistry, *in* Fairbridge, R. W. (ed.), The encyclopedia of geochemistry and environmental sciences: Van Nostrand Reinhold Company, New York, p. 1006–1007.

Morgan, G. D., 1924, Geology of the Stonewall Quadrangle, Oklahoma: Oklahoma Bureau of Geology Bulletin 2, 248 p.

Morton, R. B., 1981, Reconnaissance of the water resources of the Woodward Quadrangle, northwestern Oklahoma: Oklahoma Geological Survey Hydrologic Atlas 8, scale 1:250,000, 4 sheets.

Oakes, M. C., 1940, Geology and mineral resources of Washington County, Oklahoma: Oklahoma Geological Survey Bulletin 62, 208 p.

______ 1963, Geology of Oklmulgee County, *part 1 of* Geology and water resources of Okmulgee County, Oklahoma: Oklahoma Geological Survey Bulletin 91, p. 4–80.

______ 1967, Geology and mineral resources of McIntosh

County, *part 1 of* Geology and petroleum of McIntosh County, Oklahoma: Oklahoma Geological Survey Bulletin 111, p. 4–49.

______ 1977, Geology and mineral resources (exclusive of petroleum) of Muskogee County, Oklahoma: Oklahoma Geological Survey Bulletin 122, 78 p.

Oakes, M. C.; Dille, G. S.; and Warren, J. H., 1952, Geology and mineral resources of Tulsa County, Oklahoma: Oklahoma Geological Survey Bulletin 69, 234 p.

Oklahoma Department of Libraries, 1989, Directory of Oklahoma—State almanac, 1989–1990, 756 p.

Pitt, W. D.; Fay, R. O.; Wilson, L. R.; and Curiale, J. A., 1982, Geology of Pushmataha County, Oklahoma: Eastern New Mexico University Studies in Natural Sciences Special Publication No. 2, 101 p.

Powell, B. N.; Gilbert, M. C.; and Fisher, J. F., 1980, Lithostratigraphic classification of basement rocks of the Wichita province, Oklahoma: Geological Society of America Bulletin, pt. 2, v. 91, p. 1875–1994.

Reed, E. W.; Schoff, S. L.; and Branson, C. C., 1955, Ground-water resources of Ottawa County, Oklahoma: Oklahoma Geological Survey Bulletin 72, 203 p.

Ries, E. R., 1954, Geology and mineral resources of Okfuskee County, Oklahoma: Oklahoma Geological Survey Bulletin 71, 120 p.

Russell, D. T., 1960, Geology of northern Latimer County, Oklahoma: Oklahoma Geological Survey Circular 50, 57 p.

Schoff, S. L., 1939, Geology and ground water resources of Texas County, Oklahoma: Oklahoma Geological Survey Bulletin 59, 248 p.

Schoff, S. L.; and Stovall, J. W., 1943, Geology and ground water resources of Cimarron County, Oklahoma: Oklahoma Geological Survey Bulletin 64, 317 p.

Sprinkel, D. A., 1988, Assessing the radon hazard in Utah: Utah Geological and Mineral Survey, Survey Notes, v. 22, no. 4, 12 p.

Swanson, V. F., 1961, Geology and geochemistry of uranium in marine black shales: a review: U.S. Geological Survey Professional Paper 356-C, p. 67–112.

Tanaka, H. H.; and Davis, L. V., 1963, Ground-water resources of the Rush Springs Sandstone in the Caddo County area, Oklahoma: Oklahoma Geological Survey Circular 61, 63 p.

Tanner, A. B., 1980, Radon migration in the ground: a supplemental review: National Radiation Environment III, v. 1, U.S. Department of Energy Symposium, Series 51, ONF-780422, 30 p.

______ 1986, Indoor radon and its sources in the ground: U.S. Geological Survey Open-File Report 86-222, 5 p.

Tanner, W. F., 1956, Geology of northeastern Osage County, Oklahoma: Oklahoma Geological Survey Circular 40, 76 p.

Texas Instruments, Inc., 1977, Aerial gamma-ray and magnetic survey of the Red River area—block C, Texas and Oklahoma: U.S. Department of Energy Open-File Report GJBX-17(77), 85 p.

______ 1978, Aerial radiometric and magnetic reconnaissance survey of portions of the Great Plains and central Lowlands, Tulsa and Enid Quadrangles: U.S. Department of Energy Open-File Report GJBX-100(78).

______ 1979, Aerial radiometric and magnetic reconnaissance survey of portions of New Mexico, Oklahoma, and Texas, Dalhart Quadrangle: U.S. Department of Energy Open-File Report GJBX-46(80), 154 p.

Totten, M. W.; and Fay, R. O., 1982, Map of Oklahoma showing localities of reported uranium and radioactivity values: Oklahoma Geological Survey Map GM-25, scale 1:750,000, 1 sheet, with text, 16 p.

Tucker, B. B.; Westerman, R. L.; and Johnson, G. V., 1988, Sequoyah Fuels Corporation fertilizer development program, 1973–1986: Oklahoma State University Publication A-88-5.

U.S. Environmental Protection Agency, 1987, Radon reduction methods: a homeowner's guide [2nd edition]: U.S. Environmental Protection Agency Report OPA-87-010, 20 p.

U.S. Environmental Protection Agency and U.S. Centers for Disease Control, 1986, A citizen's guide to radon: U.S. Environmental Protection Agency Report OPA-86-004, 13 p.

Vine, J. D., 1962, Geology of uranium in coaly carbonaceous rocks: U.S. Geological Survey Professional Paper 356-D, p. 113–170.

Wakefield, Z. T., 1980, Distribution of calcium and selected heavy metals in phosphate fertilizer processing: National Fertilizer Development Center Bulletin Y-159, Tennessee Valley Authority, 12 p.