RADON-HAZARD POTENTIAL OF BEAVER BASIN AREA, BEAVER COUNTY, UTAH

by
Charles E. Bishop
Utah Geological Survey

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SPECIAL STUDY 94
UTAH GEOLOGICAL SURVEY
a division of
UTAH DEPARTMENT OF NATURAL RESOURCES
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U.S. ENVIRONMENTAL PROTECTION AGENCY

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SIXTH-YEAR GEOLOGIC STUDIES FOR THE U.S. ENVIRONMENTAL PROTECTION AGENCY STATE INDOOR RADON GRANT PROGRAM

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Cover photo: *View to west of Beaver basin; northern Mineral Mountains in background..*
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CONTENTS

FIGURES

TABLES

APPENDIX

THE RADON-HAZARD POTENTIAL OF THE BEAVER BASIN AREA, BEAVER COUNTY, UTAH

by
Charles E. Bishop

ABSTRACT

Indoor-radon levels in the Beaver basin of southwestern Utah are the highest recorded to date in Utah. Measured indoor-radon concentrations range from 17.5 to 495 pCi/L. These levels are well above those considered a health risk by the U.S. Environmental Protection Agency. Both geologic (uranium content of soil, depth to ground water, soil permeability) and non-geologic (weather, home construction, lifestyle) factors affect indoor-radon levels. In this study, geologic factors are quantified and used to produce a radon-hazard-potential map of the Beaver basin area. The map helps prioritize radon testing and evaluation of the need for radon-resistant construction.

The Beaver basin is a topographic and structural depression filled with uraniferous sediments derived from volcanic and intrusive rocks. Benches and alluvial-fan deposits along the range front of the Tushar Mountains commonly contain the highest uranium levels, although the west side near the Mineral Mountains also contains high levels. Basin-fill deposits generally have moderate to high permeability. Ground water depth is greater then 10 feet in most of the basin, but shallow ground water occurs along most of the major streams.

High uranium concentrations, deep ground water, and highly permeable soils combine to yield a high radon-hazard potential in much of the area. South and west of the city of Beaver, areas of shallow ground water contribute to a moderate hazard potential. Soil-gas-radon and indoor-radon concentrations broadly correlate with hazard potential, particularly in areas of high potential. The correlation is imperfect because of the affects of non-geologic and other factors.

INTRODUCTION

In response to a growing national concern over radon gas, Congress amended the Toxic Substances Control Act in 1988 and enacted Title III of the Indoor Radon Abatement Act (IRAA). The IRAA's intent was to reduce public-health risks by rendering indoor air almost as free of radon as outdoor air (U.S. Environmental Protection Agency, 1989). Section 306 of the IRAA authorizes the State Indoor Radon Grants (SIRG) program, providing grants for states to develop and continue radon assessment and mitigation programs. The knowledge that sufficiently high levels of radon causes lung cancer, and concerns with unknown associated health effects of radon, encouraged these state programs. Identifying and studying areas of Utah with a high potential for indoor radon is the Utah Geological Survey's (UGS) principal activity under the SIRG program.

The UGS identified the Beaver basin area for study based on preliminary data that suggested a potential radon hazard. A 1988 statewide indoor-radon survey conducted by the Utah Division of Radiation Control (UDRC), Department of Environmental Quality, measured one high indoor-radon concentration in the city of Beaver (Sprinkel and Solomon, 1990). Indoor-radon measurements in Beaver after the initial survey found additional high levels, including the highest level yet recorded in the state. Also, using regional geologic data, Black (1993) delineated areas of high radon-hazard potential in most of the Beaver basin. Black based his evaluation on high uranium concentrations in the surrounding mountains and other favorable geological factors. Based on this information, I conducted a detailed investigation of geologic factors controlling radon levels in the Beaver basin. The investigation designates areas where additional indoor-radon testing and radon-resistant new construction should be considered.

The Beaver basin is a small fault-bounded basin in the transition zone between the Colorado Plateau and the Basin and Range physiographic provinces (figure 1) (Stokes, 1977). The Beaver basin encompasses about 160 square miles (414 km^2) in eastern Beaver County, southwestern Utah. It is about 15 miles (24 km) long north to south, and 9 to 14 miles (14-23 km) wide. The basin is bounded on the east by the foothills of the Tushar Mountains, on the west by the Mineral Mountains, on the north by the Gillies Hill area, and on the south by the Greenville Bench/Black Mountains (figure 2). The Tushar Mountains rise to over 12,000 feet (3,658 m) on the east side of the basin. The lowest point is in the southeast

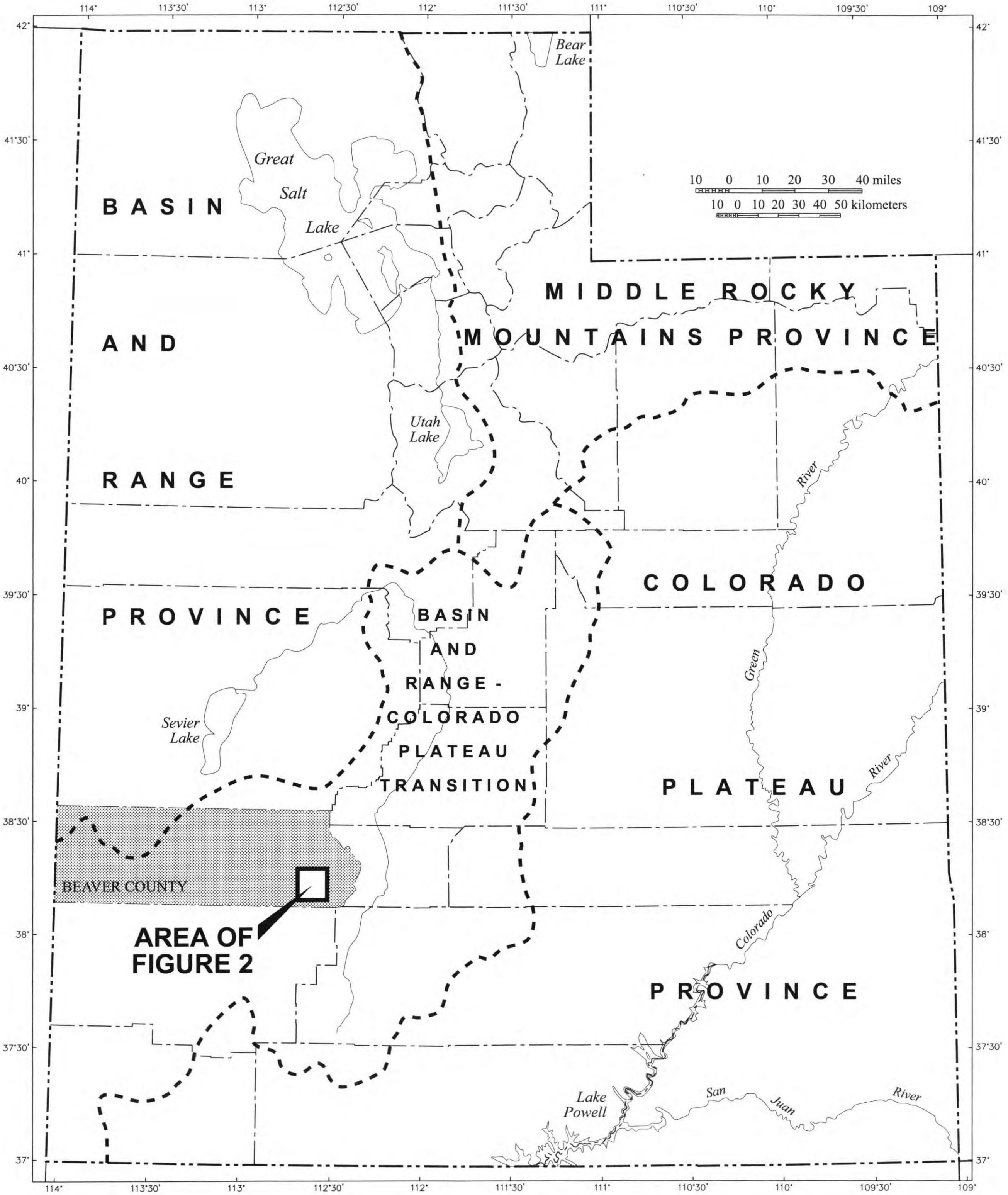


Figure 1. Major physiographic subdivisions of Utah and location of the Beaver basin study area (Stokes, 1977).

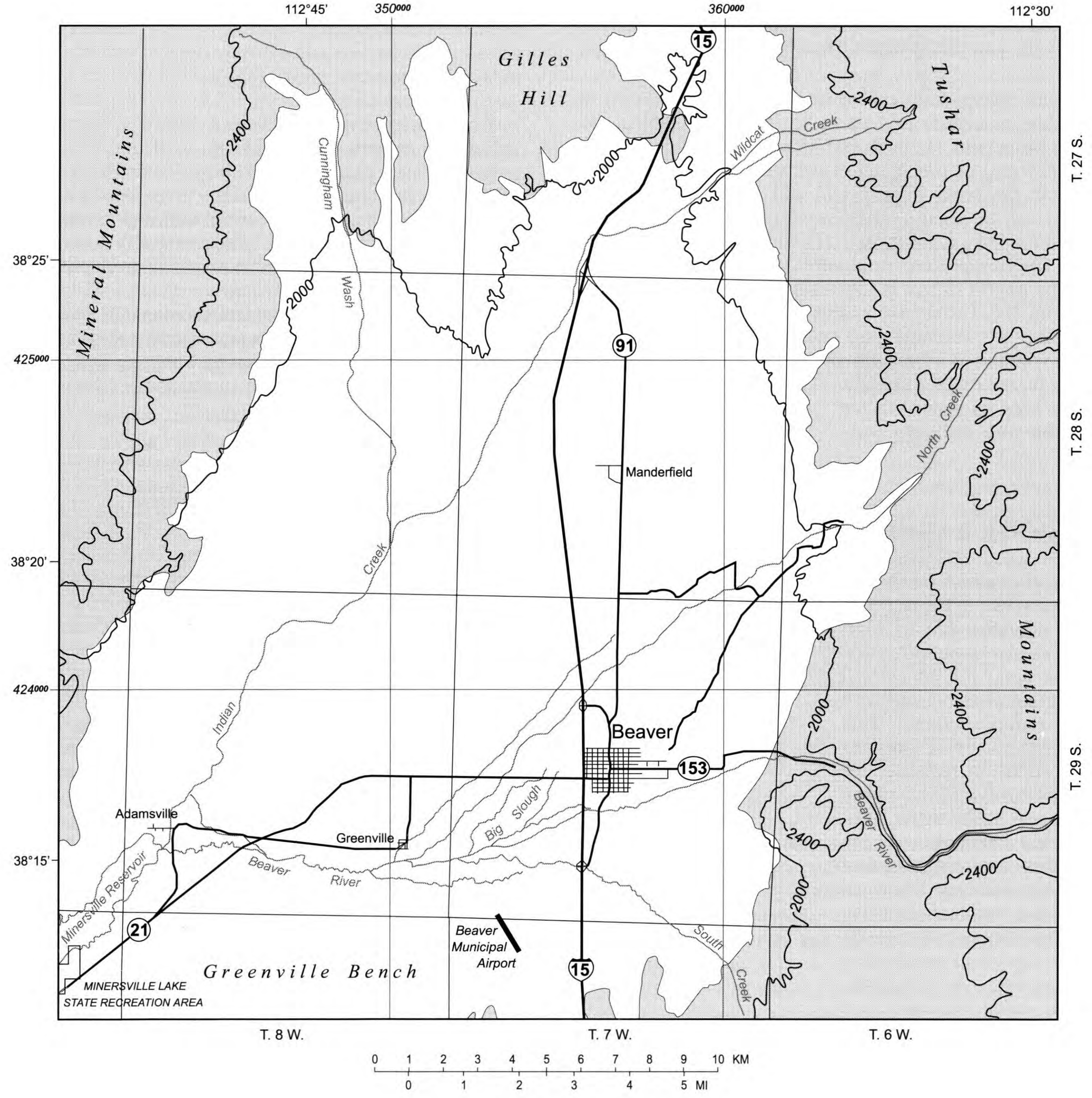


Figure 2. *The Beaver basin area.*

corner of the basin along the Beaver River at about 5,500 feet (1,676 m). The study area includes the communities of Beaver, Greenville, Adamsville, and Manderfield. Most of the area is sparsely populated with a total population of approximately 2,000 in 1990, and an expected population of over 2,200 by the year 2000 (Utah Office of Planning and Budget, 1991).

Annual precipitation can be over 40 inches (102 cm) in the Tushar Mountains and up to 25 inches (63 cm) in the Mineral Mountains. In the lower areas of the basin about 10 inches (25 cm) of precipitation per year is common. The climate in the basin is semi-arid and annual precipitation amounts can be highly variable; wetter years may receive three times that of drier years (Division of Water Rights, 1995). The Beaver River originates in the Tushar Mountains and is the largest stream in the basin. Other principal drainages from the Tushar Mountains are Wildcat, North, and Indian Creeks. Perennial and intermittent streams produce smaller volumes of water from the Mineral Mountains on the western boundary of the basin. The basin is rural, and the primary uses of water are for irrigation and culinary purposes.

INDOOR RADON

Concerns about indoor radon have arisen in the last couple of decades due to high indoor-radon concentrations found in areas not considered radon prone or associated with known radon sources. This problem is receiving growing public attention because, for many people, indoor radon poses a real health threat. Report radon concentrations are sometimes confusing because of the measurement units and the various ways of reporting the measurements, due to the many assumptions involved in acquiring data. In this study, reported radon concentrations are in picocuries per liter (pCi/L) of air; one pCi (3.7 x 10^{-2} Becquerels [Bq]) represents a decay of about 2 radon atoms per minute. Whatever the units used, the common-sense assertion that higher levels are more dangerous than lower levels of radon still stands. Outdoor-radon concentrations in air average about 0.35 pCi/L, whereas indoor-radon concentrations can vary over several orders of magnitude and are typically much higher. To effectively control indoor radon, a knowledge of the relative importance of various sources of radon and factors that influence indoor concentrations is necessary.

Sources

Radon is a colorless, odorless, tasteless, water-soluble radioactive element that is difficult to detect. An almost chemically inert gas, and the only gas in the decay series of uranium or thorium, radon easily moves into air. Indoor radon originates by the decay of uranium and thorium in soil and rock beneath a structure. Three naturally occurring isotopes of radon form as intermediate decay products of either uranium or thorium.

The term radon generally refers to radon-222 and its decay products. Radon-222 forms as part of the natural radioactive decay of uranium-238 by alpha- and beta-particle emission (figure 3). Alpha particles are small, heavy, energetic sub-

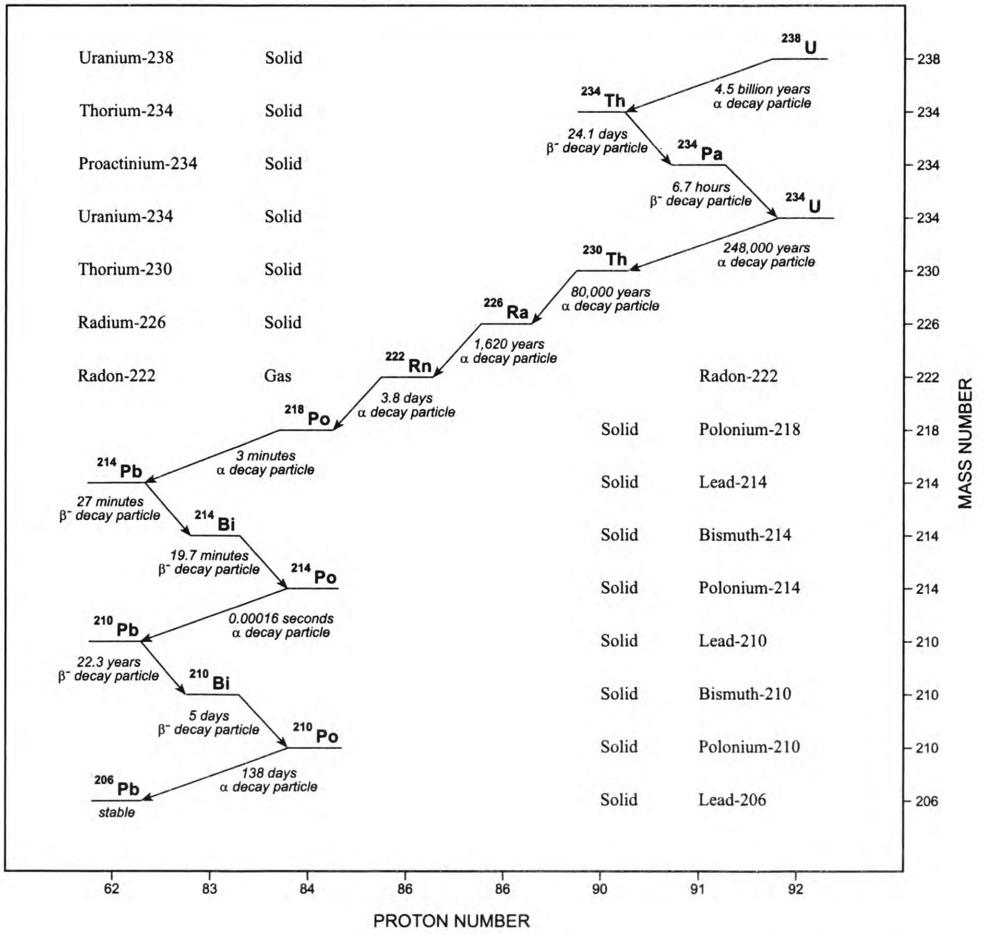


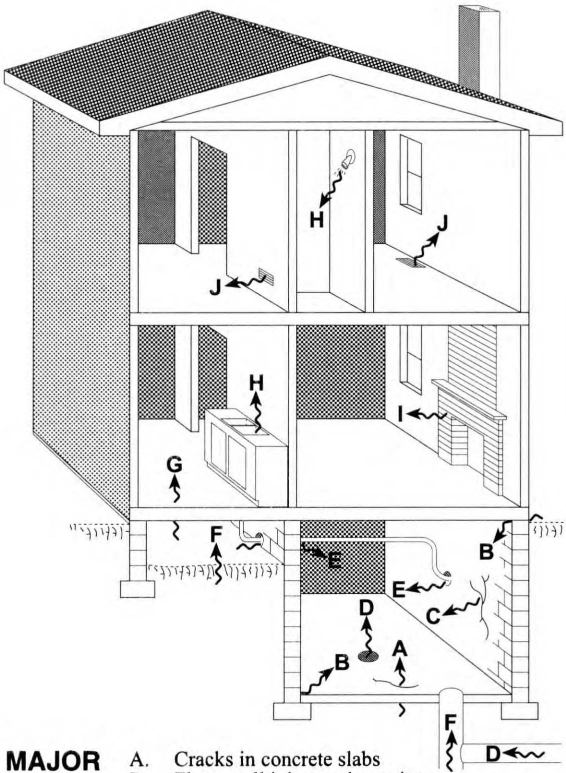
Figure 3. *Schematic plot of a generalized uranium-238 decay series showing half-lives of isotopes, modes of decay, and their physical states. Alpha decays are branches to the left and beta decays are branches to the right. The horizontal scale is the number of protons in the nucleus, and the vertical scale is the mass number. Radon-222, the only gas in the series, is nearly inert and free to move through soil, air, and water without entering into chemical reactions.*

atomic particles consisting of two protons and two neutrons. Alpha decay is the emission of an alpha particle, which has a relatively large mass and energy release, from the nucleus of a parent atom. Alpha particles are more dangerous to human health than other types of radiation. Radon itself decays and produces a series of short-lived radioactive products, called radon progeny or daughters. This series continues until stable products form. Radon-222 is the most abundant radon isotope and usually the most significant contributor to indoor radon. Radon's half-life of 3.83 days allows a substantial travel distance before decay, but it remains near its source. The abundance of radon-222 is due to the abundance of its natural uranium parent element; uranium-238 is 138 times more common than uranium-235, the next most common isotope (Nielson and others, 1990). Naturally occurring uranium is 99.28 percent uranium-238 and only 0.17 percent uranium-235. Because of this, the analysis for total uranium yields a value closely approximating that of uranium-238.

Radon-220 forms by the decay of thorium-232. Radon-220 is almost as common as radon-222, but has a half-life of only 55.65 seconds. Thorium-enriched rock and soil can affect indoor-radon levels, and contribute significantly in areas with high thorium-232 concentrations (Stranden, 1984). Since only a few studies address indoor-radon hazards from thorium, the contribution of thorium-enriched geologic materials to indoor-radon levels is unknown. However, in sufficient concentrations, radon-220 can be a significant contributor to indoor radon (Durrance, 1986). Radon-219, with a half-life of 3.96 seconds, forms from the decay of uranium-235. Radon-219 does not contribute significantly to indoor radon because of its short half-life and rarity. Radon-220 and radon-219 are commonly called thoron and actinon, respectively.

Radon concentrations in outside air never reach dangerous levels because air movement dissipates the gas. However, in buildings in contact with the ground we typically find high radon concentrations in places without significant air movement such as basements or low crawl spaces (Fleischer and others, 1982). Indoor radon originates from soil gas that enters through cracks or openings in foundations; around poorly sealed floors and slab-to-foundation wall joints; and through floor drains, sumps, and cracks in floors (figure 4). Ground water and building materials may also contain radon, and contribute radon to indoor air. The possible public health effect of radon in drinking water has not received much attention, but could be important (Cothern, 1987). Of the three primary contributors to indoor radon (soil gas, ground water, and building materials), soil gas is the most important source.

Factors that influence the accumulation of radon in a building complicate the prediction of indoor-radon levels. Buildings constructed before the 1973 oil embargo commonly did not use energy-efficient construction methods, allowing indoor air to escape through above-grade joints, uninsulated walls, and attics. Since 1973, energy-efficient construction practices conserving non-renewable energy resources have contributed to building energy efficiency by preventing the loss of indoor air. Relatively little exchange between outside and indoor air causes an accumulation and concentration of indoor-air pollutants, such as radon. Studies have shown that energy-efficient buildings with inadequate ventilation systems generally have higher indoor-radon levels than conventional buildings (Fleischer and others, 1982; Nero, 1986).



MAJOR RADON ENTRY ROUTES

A. Cracks in concrete slabs
B. Floor-wall joints and openings
C. Pores and cracks in foundations, concrete block, concrete walls, and mortar joints
D. Floor drains, and drains to open sumps
E. Loose-fitting pipe penetrations
F. Exposed soil, as in a sump or crawlspace
G. Cracks in floors over a crawlspace
H. Water supplies (from private well)
I. Building materials, such as some rocks
J. Around and through heat ducts from furnace

Figure 4. *Various pathways for radon to enter a home. Most entry routes are in the basement because this part of the house has the greatest surface area in contact with the surrounding soil (modified from U.S. Environmental Protection Agency, 1992).*

The U.S. Environmental Protection Agency (EPA) (1992) recommends action when indoor-radon levels exceed 4 pCi/L (148 Becquerels per cubic meter [Bq/m^3]). The EPA based its recommended action level on early radon studies of uranium miners, making some adjustments for background radon and incorporating recent information. Radon concentrations in some buildings in the United States can pose a significant health hazard to occupants, but most buildings have concentrations less than 3 pCi/L (111 Bq/m^3) (Nero, 1986). The national average for indoor radon is 1.6 pCi/L (59 Bq/m^3), and Utah has an average of about 2.7 pCi/L (100 Bq/m^3) (Sprinkel and Solomon, 1990).

Radon is highly soluble in ground water and does not interact strongly with soil or rock once the gas is dissolved in the water. The uranium and thorium content of the rock and soil control the initial abundances and constantly provide additional radon to ground water. The dominant ground-water transporting mechanism of radon is ground-water flow, but ground-water flow is still slow compared with radon decay rates (Wanty and Schoen, 1991). The increased velocity of ground water towards a pumping well increases the distance radon travels. Radon content of water diminishes rapidly with turbulent flow, but because most ground-water flow is not turbulent, radon content remains constant in ground water.

Ground water used in homes can release radon when the occupants are taking a shower, doing laundry, or washing dishes. Nationally, radon concentrations in drinking water range from less than 10 pCi/L (370 Bq/m^3) in some surface waters to a reported high of 2,000,000 pCi/L (74 million Bq/m^3) in well water (Aieta and others, 1987). Estimates of the contribution of radon in water to airborne radon range from 1 to 2.5 pCi/L (37-92.5 Bq/m^3) in air for every 10,000 pCi/L (3.7×10^5 Bq/m^3) in water (Wanty and Schoen, 1991). Private ground-water systems usually have higher concentrations of radon in water than public systems. Small private distribution systems, with low capacity wells, allow minimal time for decay and less aeration of the water. The EPA has proposed a 300 pCi/L (11,100 Bq/m^3) action level for radon in drinking water.

Radon is generally in very low concentrations in surface water because of losses from radioactive decay and atmospheric exposure. Thus, radon concentrations in surface water are generally several orders of magnitude lower than those in ground water. Major sources of radon in surface water are:

1. weathering of source rocks,
2. in situ decay of dissolved parent, and
3. ground-water discharge into the surface water.

Building materials containing high concentrations of uranium or radon parent materials can be used either in a building or its foundation and be a source of indoor radon.

Health Effects

Unlike most geologic hazards that adversely affect both life and property, radon is a hazard only to living things. The increased risk of lung cancer to some individuals breathing elevated levels of radon over time is well documented. Studies in the 1950s and early 1960s of uranium miners exposed to high levels of radon over long periods of time indicated an increased risk of radon-related lung cancer. These types of studies led to the classification of radon as a known human carcinogen (National Council on Radiation Protection and Measurements, 1984b). The EPA estimated that radon is the second leading cause of lung cancer (Jacobi and Eisfeld, 1982; National Council on Radiation Protection and Measurements, 1984a, 1984b; Samet, 1989). They estimate that long-term radon inhalation causes 8,000 to 40,000 deaths from lung cancer in the U. S. each year (Schmidt and others, 1990).

Because radon gas is almost inert, it does not easily attach to lung tissue and thus is not thought to be the primary source of internal cancer-causing radiation. Additionally, inhaled radon is exhaled before radon can decay and emit dangerous alpha particles in the lungs. Radioactive progenies from radon decay that are not inert and attach to dust or smoke in the air are of more concern. Once inhaled, the particles with radon progeny move into the upper respiratory system and find their way to the bronchial tissue where direct bombardment by energetic alpha particles from radioactive decay causes damage to sensitive lung tissue. If an alpha particle strikes a living cell, it can alter the way the cell proliferates. Anything that increases the number of airborne particles to which radon progeny can become attached and inhaled into the lungs increases the risk. Like breathing radon, the ingestion of radon dissolved in water may contribute to development of some types of cancer. It's uncertain whether radon in water poses a direct health threat, but there is concern over high levels of radon in ground water contributing to radon in indoor air. Household use of this water releases radon gas into the air where it can be inhaled.

Factors Affecting Indoor-Radon Levels

Four principal factors contribute to elevated indoor-radon levels (Tanner, 1986):

1. elevated uranium levels in the soil or rock on which a structure lies,
2. soil and ground-water conditions that do not restrict the movement of radon,
3. porous building materials or foundation openings near or below the ground surface, and
4. lower atmospheric pressure inside a building than outside.

Factors (1) and (2) are geologic factors influencing indoor-radon levels by controlling the local concentration and transport of radon. Combining these factors with factors (3) and (4) in an enclosed structure can result in elevated indoor-radon levels. Factors (3) and (4) are non-geologic factors that are difficult to measure; the importance of their effects is variable and fluctuates with the weather, types of construction, and occupant lifestyle. Although geologic factors may suggest similar radon-hazard potentials in adjacent structures, indoor-radon levels can vary from one structure to the next because of these non-geologic factors.

The effectiveness of supplying radon for transport to the atmosphere depends not only on the concentration of parent atoms present, but also on the fraction of radon atoms that escape from the grain into the pore space. This transfer of radon from a grain is called emanation, and the fraction of radon atoms that escape from a grain is known as the emanating power of the grain. Factors affecting emanating power include structure of the material, grain size, pore size, porosity, and moisture content. Materials with smaller grains generally have a higher emanating power; grain size and emanating power are inversely related (Tanner, 1980). Radon atoms produced in grains larger than one micron (4 x 10^{-5} inches) are unlikely to escape into pores unless they are on or near the grain's surface. When pore spaces are dry, some escaping radon atoms may pass through and become embedded in adjacent grains. Moisture occupying the space between grains traps a higher percentage of radon atoms within the pore space. High uranium content in soils may not always cause high radon releases. The uranium may be in a rigid or tight-structured mineral in the soil such as zircon, monazite, apatite, sphene, and others where bonding is so strong that emanation of radon from the uranium is very small (Durrance, 1986).

A combination of diffusion and convection causes the movement of radon gas through soils (Tanner, 1980). Diffusion, the least important, is the movement of radon atoms by natural chemical gradients through the pore space in soils, which may be occupied by air, water, or both. Because of molecular spacing in air, the coefficient of diffusion of gases in air is larger than in water. However, even in air, radon can travel by diffusion only a few feet before decay. Convection or pressure-driven flow is a more significant mechanism of transport. Convection is due to a pressure differential of separate air masses at different temperatures or barometric pressures. During cold seasons, heating causes a net inward pressure through walls and floors. Pressure differences causing convection can be within the soil, between the soil and atmosphere, or between the soil and air in a structure. Flow driven by convection can move radon over tens of feet (Baretto, 1975). Convection dominates in larger pores and travel distances can be high, whereas diffusion dominates in intergranular channels, capillaries, and smaller pores and travel distances are small (Tanner, 1980). Only a small fraction of soil gas containing radon needs to be drawn from soils to account for the observed amounts of radon found in most buildings.

Factors such as shallow ground water and soil permeability affect the ability of radon to migrate to the surface. Although water provides an effective means for dissolved radon migration, ground water inhibits upward soil-gas migration by reducing diffusion and blocking upward gas flow (Tanner, 1980). Seasonally changing ground-water levels can cause temporal effects on radon concentrations. The size and configuration of pore spaces and the permeability controls transport of radon through soils. In highly permeable soil, radon is easily released from a grain and the soils provide excellent pathways for radon migration, whereas impermeable soils (which often contain clay) inhibit the flow of soil gas (Tanner, 1980; McLemore and others, 1991). Studies have shown a correlation between permeable soils and elevated radon levels (Tanner, 1980; Schery and Siegel, 1986; Otton and Duval, 1990).

Measurement of Indoor-Radon Levels

The concentrations of soil-gas radon in pores and the permeability of the soil for transport (geologic factors) affect indoor-radon levels. But non-geologic factors also influence indoor-radon levels. As a result, indoor-radon levels fluctuate and measurements in each building are necessary to decide if a problem exists. Radon-testing devices are either active (external power required) or passive (external power not required). Tests by professionals use both passive and active devices to measure indoor radon, but devices typically used by homeowners are passive.

Indoor-radon concentrations can vary by more than an order of magnitude annually. These variations are due to changes in soil-moisture content and precipitation; fluctuations in temperature, wind, barometric pressure, and other atmospheric conditions; ventilation of buildings; and occupant lifestyles. These factors directly or indirectly affect indoor-radon levels by modifying radon migration and influencing the need for indoor heating, cooling, and ventilation, thereby modifying the relative proportions of indoor air and outdoor air. Because of these effects, indoor-radon levels fluctuate daily, weekly, monthly, and seasonally.

Radon-testing devices measure indoor-radon levels during specific intervals of time. Short-term measurements, usually conducted for less than three months, provide quick and accurate results for the testing period, but do not reflect fluctuations in indoor-radon levels during longer intervals. Long-term measurements, usually conducted for three or more months, reflect long-term variations and provide a more realistic picture of radon exposure during a lifetime.

Standard methods for measuring radon should meet EPA-established protocols to assure accuracy and consistency of indoor-test data. The protocols balance the need for quick results with the need for measurements that reflect long-term indoor-radon levels (U.S. Environmental Protection Agency, 1993a). To accurately detect yearly average indoor-radon levels, the EPA recommends long-term monitoring. Conducting short-term screening measurements that follow EPA protocol (closed-house conditions) in the lowest living area can help determine the need for long-term monitoring (U.S. Environmental Protection Agency, 1992).

The EPA protocols emphasize follow-up testing in homes with screening measurements of 4 pCi/L (148 Bq/m^3) or more; a higher screening level indicates a greater urgency for retesting. If long-term follow-up tests measure 4 pCi/L (148 Bq/m^3) or more, EPA recommends reducing indoor-radon levels. If a short-term follow-up test measures 4 pCi/L (148 Bq/m^3) or more, EPA recommends radon-reduction measures if the average of the first and second short-term tests is 4 pCi/L (148 Bq/m^3) or more. If a short-term screening measurement is less than 4 pCi/L (148 Bq/m^3), EPA recommends no additional testing.

Low-cost "do it yourself" kits for measuring radon levels indoors are available through the mail, hardware stores, and other retail outlets. Charcoal canisters and alpha-track detectors are used most commonly for short-term and long-term measurements, respectively. To ensure accuracy, a test kit should have passed the EPA's testing program and display the phrase "Meets EPA Requirements." To do the testing, a trained contractor listed in EPA's Radon Measurement Proficiency (RMP) program can be hired. RMP program participants have shown their ability to make accurate tests, follow quality assurances, and meet EPA test guidelines. The Utah Division of Radiation Control (UDRC) can provide information on the advantages and disadvantages of radon detectors, EPA-approved test kits, and RMP-qualified companies and individuals.

No measured problem with airborne radon in a home indicates generally no need to test household water for radon. Radon entering homes through water and released into the air during household use is generally less than 10 percent of household radon, and not a substantial hazard by itself (Cothern, 1987). However, if indoor radon levels are high, it may be necessary to test household water to identify the source of indoor radon. Low-cost water test kits are available from commercial laboratories.

Hazard Reduction

To reduce elevated indoor-radon levels, several procedures are available. Selecting a radon-reduction method requires testing to define entry routes and select the most effective method. These fall into four categories:

1. preventing radon from entering (figure 4),
2. removing radon (or decay products) after entry,
3. removing sources of radon, and
4. modifying lifestyle to minimize radon effects.

The specific method chosen to reduce indoor-radon levels depends on the initial radon concentration, and house design and construction. Methods of permanent radon reduction must take these into account and include one or more of the following (U.S. Environmental Protection Agency, 1993b):

1. increasing ventilation with ventilators,
2. restricting entry of radon into a house by sealing soil-gas entry routes,
3. ventilating soil to withdraw radon-contaminated soil gas and divert it away from a house,
4. restricting flow of soil gas into a house by altering pressure differentials between the house and soil, and
5. cleaning air to remove solid radon-decay products.

Once appropriate radon-reduction methods are chosen and carried out, retesting is necessary to ensure reduced radon levels. In existing buildings, restricting radon entry may be difficult, but new structures may restrict radon entry by minimizing soil-gas entry pathways and indoor-outdoor pressure differences (Clarkin and Brennan, 1991). Preventing radon entry is often the best approach because it has a high probability of success, even in locations with high radon-hazard potential.

Reducing elevated indoor-radon levels often requires professional assistance. Without the proper equipment and technical knowledge, radon levels may actually increase or other hazards may be created. When using a radon contractor, choose one listed in the EPA's Radon Contractor Proficiency (RCP) program. RCP contractors must pass a comprehensive exam, and agree to follow standards developed to ensure effective radon reduction. The UDRC maintains a list of RCP contractors.

If the contribution of water-borne radon to indoor air is significant, this radon may be removed from the water before it reaches the indoor air or from the air after it has left the water (U.S. Environmental Protection Agency, 1987). Often, good ventilation of bathrooms, laundry rooms, and the kitchen, particularly during periods of water use, may be adequate, though impractical during cold weather. Storing the water for several days before use allows the radon to decay and lowers the radon concentration. Home aeration systems remove radon by spraying the water through an air-filled chamber and using a fan to move the contaminated air out of the house. These devices are not readily available or widely used. Devices that use granular activated charcoal to remove radon from water are presently the least costly for a home using its own well. To date, these are the most extensively tested and used radon-reduction techniques for water.

Generally, building materials are not implicated as a major source of indoor radon. However, materials with elevated uranium content and high emanation ratios can significantly contribute radon to indoor air. Radon can be emitted from wallboard, concrete containing shale or fly ash, and building blocks and bricks (Durrance, 1986). Where building materials contribute significantly to indoor radon, the contribution may be reduced by physical removal of the materials emitting the radon or sealing of the surfaces to block radon emission. Sealing is less desirable because it requires maintenance.

Some immediate lifestyle modifications with minimal expense can be made to reduce radon exposure (U.S. Environmental Protection Agency, 1988). Discouraging smoking inside a house reduces the risk of developing lung cancer not only from smoking but also from radon exposure. Spending less time in areas of higher radon concentration, such as a basement and other low areas, will also reduce the risk. Opening windows and turning on fans improve ventilation, but are not always practical during cold winter months.

SAMPLING METHODS

I conducted two types of ground radiometric surveys for this study: (1) gamma-ray spectrometry, and (2) radon emanometry. Gamma-ray spectrometry measures the concentration of selected radioactive elements in surficial materials. By measuring the intensity and energy of gamma radiation, spectrometry differentiates between uranium, thorium, and potassium and determines the concentration of radioactive materials available to decay into radon. Radon emanometry is the measurement of soil-gas radon in the pore spaces of soils which can migrate into structures. Radiometric data collected for this survey indicate the areal distribution of the measured parameters at or near the ground surface. The survey does not adjust for vertical inhomogeneities, temporal variations due to meteorologic effects, or radioactive decay imbalances.

I used an Exploranium GR-256 portable gamma-ray spectrometer to measure concentrations of selected gamma-emitting elements in the soil. Concentrations of total gamma, potassium-40 (K), equivalent uranium-238 (eU), and equivalent thorium-232 (eTh) were measured. The detector assembly in the Exploranium GR-256 contains a 3 x 3 inch (7.5 x 7.5 cm) sodium-iodide crystal and an integral bi-alkali photomultiplier tube. The instrument used peak energy levels of 1.46 million electron volts (MeV) for K (which has only one emission line), 1.76 MeV for eU (corresponding to bismuth-214), and 2.62 MeV for eTh (corresponding to thallium-208). The spectrometer was calibrated at the factory using calibration pads. The detector was held at a height of about 2 feet (0.6 m) to correct for the influence of local topography and non-homogeneous materials.

I used a RDA-200 portable alpha-sensitive scintillometer manufactured by EDA instruments to measure concentrations of radon in soil gas. Soil gas was pumped into a scintillator cell that is then placed in the scintillometer to measure radon concentration. A phosphor coating inside of the scintillator cells is sensitive to alpha particles in the 5.5 MeV range, the range emitted by the decay of radon. To determine the efficiency of the phosphor coating material, Geotech, Inc. calibrated the cells in an alpha-track chamber. The factory calibrated the scintillometer, and I used a standard scintillator cell of a known count rate to check sensitivity of the instrument.

The soil-gas sampling tool consists of a 0.5-inch (1.3-cm) diameter hollow steel probe 26 inches (66 cm) long, perforated in the lower 6 inches (15 cm). To make a hole of the same diameter as the sampling tool I forced a solid steel rod into the ground. After removing the steel rod, the probe was then inserted into the hole to a depth of roughly 26 inches (65 cm). After inserting the probe, the ground around the hole was compacted to restrict atmospheric air from entering the probe. The probe perforations are generally below the root zone for most grasses, within the lower B and upper C soil horizons, and close to sampling depths which provided consistent and reproducible data to other researchers (Reimer and Bowles, 1979; Hesselbom, 1985; Reimer and Gundersen, 1989). To purge the probe of ambient air and pump soil gas into the scintillator cells through the probe I used a hand-held evacuation pump. Figure 5 shows the apparatus used to obtain and measure soil-gas samples. I collected soil-gas samples from about 60 percent of the spectrometer measurement stations, but the spacing between soil-gas sample sites is irregular because of difficulties in sampling. Dense clayey or gravelly soils restricted the insertion of the probe and dry sandy soils collapsed before inserting the probe.

DATA AND DISCUSSION

General Geology

The geology of the sharply defined topographic and structural Beaver basin reflects Miocene to Pleistocene faulting, uplifting, and volcanism (figure 6). Up to 6,000 feet (2,000 m) of lake and open-basin sediments accumulated in the basin during this time (Machette, 1985). Volcanic rocks of the Tushar Mountains to the east and the plutonic rocks of the

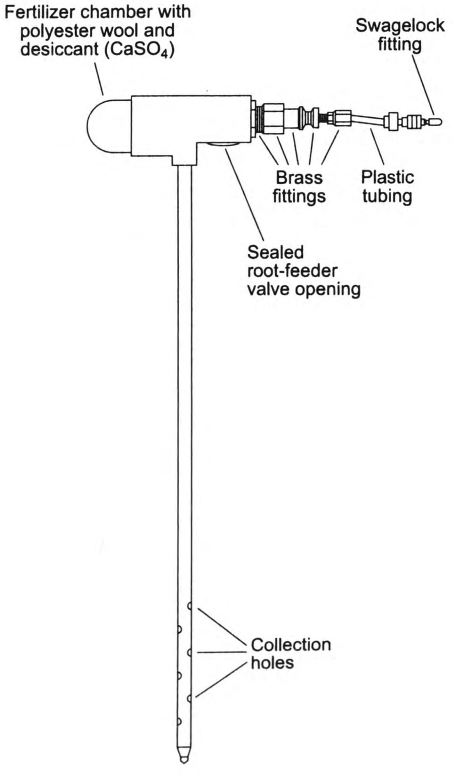


Figure 5. *Portable instrumentation and equipment used in the soil-gas extraction technique. Soil-gas probe (to right) is inserted into the ground and is modified from Ross Root Feeder Model 102, manufactured by Ross Daniel, Inc.*

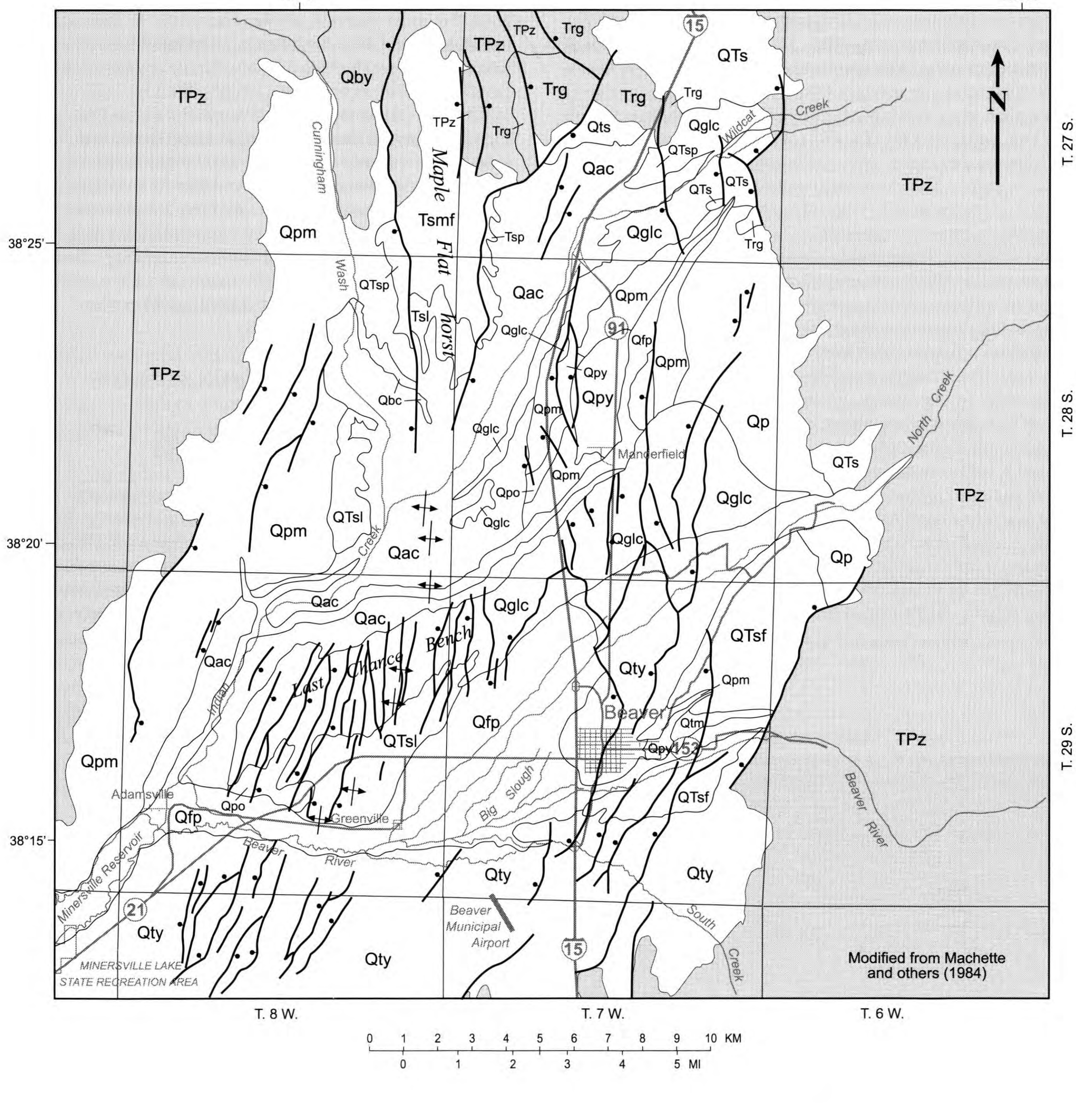
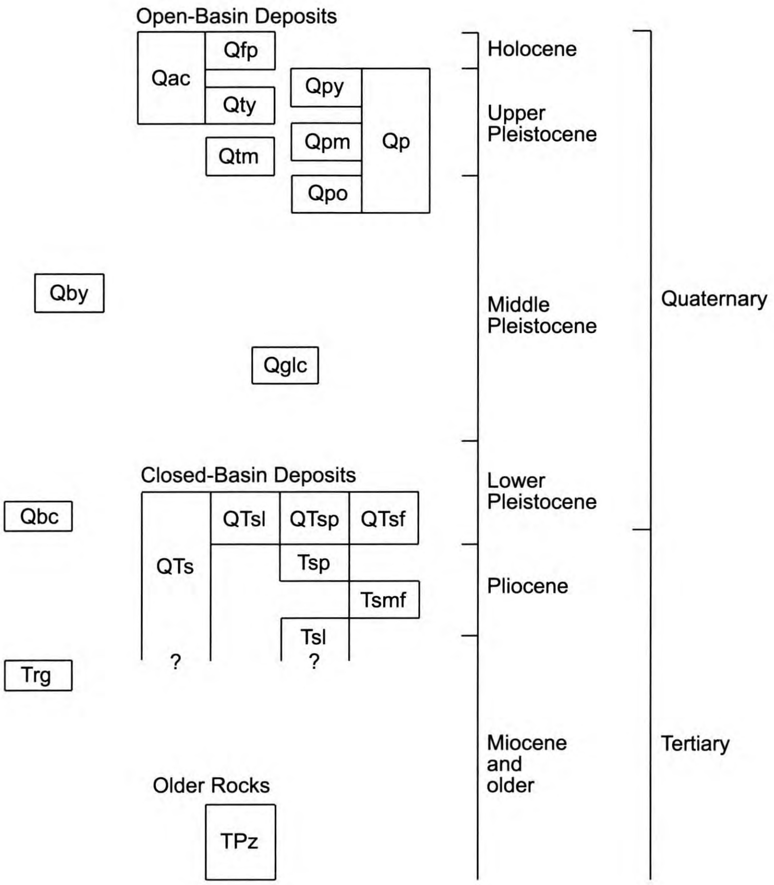


***Figure 6.** Generalized geologic map of the Beaver basin area (modified from Machette and others, 1984; and Machette, 1995).*

Figure 6 *(continued)*

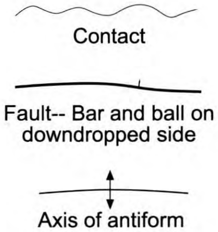
CORRELATION OF MAP UNITS



DESCRIPTION OF MAP UNITS

Qac	Undivided alluvium
Qfp	Floodplain alluvium
Qty	Young terrace alluvium
Qtm	Middle terrace alluvium
Qp	Undivided piedmont-slope
Qpy	Young piedmont-slope
Qpm	Middle piedmont-slope
Qpo	Old piedmont-slope
Qby	Basalts of Red Knoll and Crater Knoll
Qglc	Gravel of Last Chance Bench
Qbc	Basalt of Cunningham Hill
QTs	Closed-basin deposits undivided
QTsl	Lacustrine facies
QTsp	Piedmont facies
QTsf	Fanglomerate facies
Tsp	Upper piedmont member
Tsmf	Conglomerate of Maple Flats
Tsl	Lower Piedmont member
Trg	Rhyolite
TPz	Older rocks-- volcanic, sedimentary, and intrusive

MAP SYMBOLS


Contact

Fault-- Bar and ball on downdropped side

Axis of antiform

Mineral Mountains to the west confined and provided much of the material that filled the basin. At the north end of the basin are low hills of rhyolite domes and flows in the Gillies Hill area (Evans and Steven, 1982). Volcanic rocks of the Black Mountains (out of the study area) form the south end of the basin. Exposed sediments within the Beaver basin consist of unconsolidated and semi-consolidated closed-basin deposits covered by a locally thin mantle of younger alluvium.

A perennial lake occupied the Beaver basin almost continuously from latest Miocene (6.5 Ma) until early Pleistocene (1.6 Ma) time. The lake, informally called Lake Beaver by Machette (1985), existed until about 750,000 years ago. By 500,000 years ago a pediment surface developed across most of the basin. Since then, the basin has undergone periodic downcutting and minor sedimentation related largely to climatic changes (Machette, 1985). Moderately oxidized, calcareous, fine-grained, and slightly indurated deposits that crop out in the northern part of the basin are the oldest and most poorly exposed deposits. Other surficial deposits include widespread middle Pleistocene to Holocene gravel-capped pediments and terraces and latest Pleistocene to Holocene coarse-grained (sand and gravel) alluvial-fan deposits and stream alluvium.

In late Oligocene to early Miocene (32-21 Ma) time, a composite volcanic center in the Tushar Mountains blanketed the region with volcanics consisting of intermediate-composition calc-alkaline rocks and a later bimodal assemblage of mafic and high-silica alkali-rhyolitic rocks (Lanigan and Anderson, 1987). A multi-phase pluton consisting of granitic rocks, diorite stocks, and several types of mafic dikes formed the Mineral Mountains in Eocene time (Sibbett and Nielson, 1980). Faulting has placed Paleozoic and Mesozoic sedimentary rocks against the younger intrusive rocks in the southern Mineral Mountains (Price and Bartley, 1990). These rocks could be the intrusive equivalents of volcanics in the Tushar Mountains (Aleinikoff and others, 1986). In late Miocene (9 Ma) time, volcanic activity began and continued episodically into the Pleistocene, erupting rhyolite domes and flows in the Gillies Hill area. Miocene volcanics forming the Black Mountains are viscous lava flows, volcanic domes, and minor pyroclastics generally younger than the volcanics in the Tushar Mountains. Faults localized these Late Miocene volcanic rocks in the area between the volcanics to the east and the intrusive rocks to the west (Steven and others, 1981; Evans and Steven, 1982).

Late Pliocene to Pleistocene deformation of the Beaver basin is represented by two structural systems (figure 6). The first system consists of the Maple Flats horst and the Last Chance Bench antiform. The Maple Flats horst consists of older exposed sediments bounded by north-trending faults in the north-central parts of the basin. The possible coeval Last Chance Bench antiform is a broad south-plunging antiform in the central part of the basin that deformed younger sediments. Closely spaced north-northeast-trending normal faults traverse the antiform and are probably related to its formation. The other structural system is represented by faulting along the east side of the basin, which could be the boundary between the Basin and Range and the Colorado Plateau (Machette, 1985). Additional Pleistocene and younger faulting is found throughout the basin.

Progressive concentration during separation of the magma responsible for the igneous rocks that surround the Beaver basin accounts for the abundance of uranium and thorium in the rocks. During separation within a magma, uranium and thorium become concentrated in the late-stage silica-rich liquid phases. Principal uranium-bearing rocks in the surrounding mountains are typical of these later liquid phases and consist of the Mount Belknap Volcanics, rhyolite of Gillies Hill, and granite, quartz monzonite, and diorite from the Mineral Mountains pluton. Uranium deposits are widespread in the surrounding areas and are typically associated with Miocene or younger rhyolites (Steven and Morris, 1984). Average concentrations of uranium and thorium in granitic rocks (plutonic rock) range from 15 to 120 ppm, and from 30 to 170 ppm, respectively. The volcanic rocks usually contain 1.5 to 2 times as much uranium as the plutonic rocks of equivalent composition (Durrance, 1986). Flowing streams transported uranium and thorium, mobilized by leaching and weathering, from the volcanic and plutonic rocks in the surrounding mountains onto alluvial fans and floodplains in the Beaver basin.

Mapping Methods

To map radon-hazard potential in the Beaver basin, I used a method that recognized geologic factors influencing indoor-radon levels. Methods of hazard-potential mapping developed in previous studies used many methods. Solomon and others (1991) developed a land-type hazard-classification scheme for specific geologic settings and assigned hazard potentials that reflected radon emanation and migration in mapped geologic units. Solomon (1992) mapped hazard potential irrespective of geologic contacts, and recognized that geologic factors are not necessarily uniform within each geologic unit. The classification scheme of Solomon (1992) is applicable to a wide range of settings, and Black and Solomon (1996) used this approach. The method of Black and Solomon (1996), used in this study, uses three factors to evaluate radon-hazard potential:

1. uranium concentration,
2. soil permeability, and
3. depth to ground water.

Uranium concentrations were sampled at field sites spaced roughly 1 mile (1.6 km) apart, depending on access, except around the towns of Beaver, Manderfield, Greenville, and Adamsville (figure 7) where station spacing was about 0.5 mile (0.8 km). I sampled during September 1994, the same time of year as earlier radon surveys throughout Utah. When possible, measurements were taken in vacant lots or undeveloped, non-irrigated lands to minimize cultural influence and measure the characteristics of native soil. I avoided measurements on roadbeds to reduce the possibility of masking because of foreign materials. The sample grid is unevenly spaced because of limited access in heavily developed, farm-

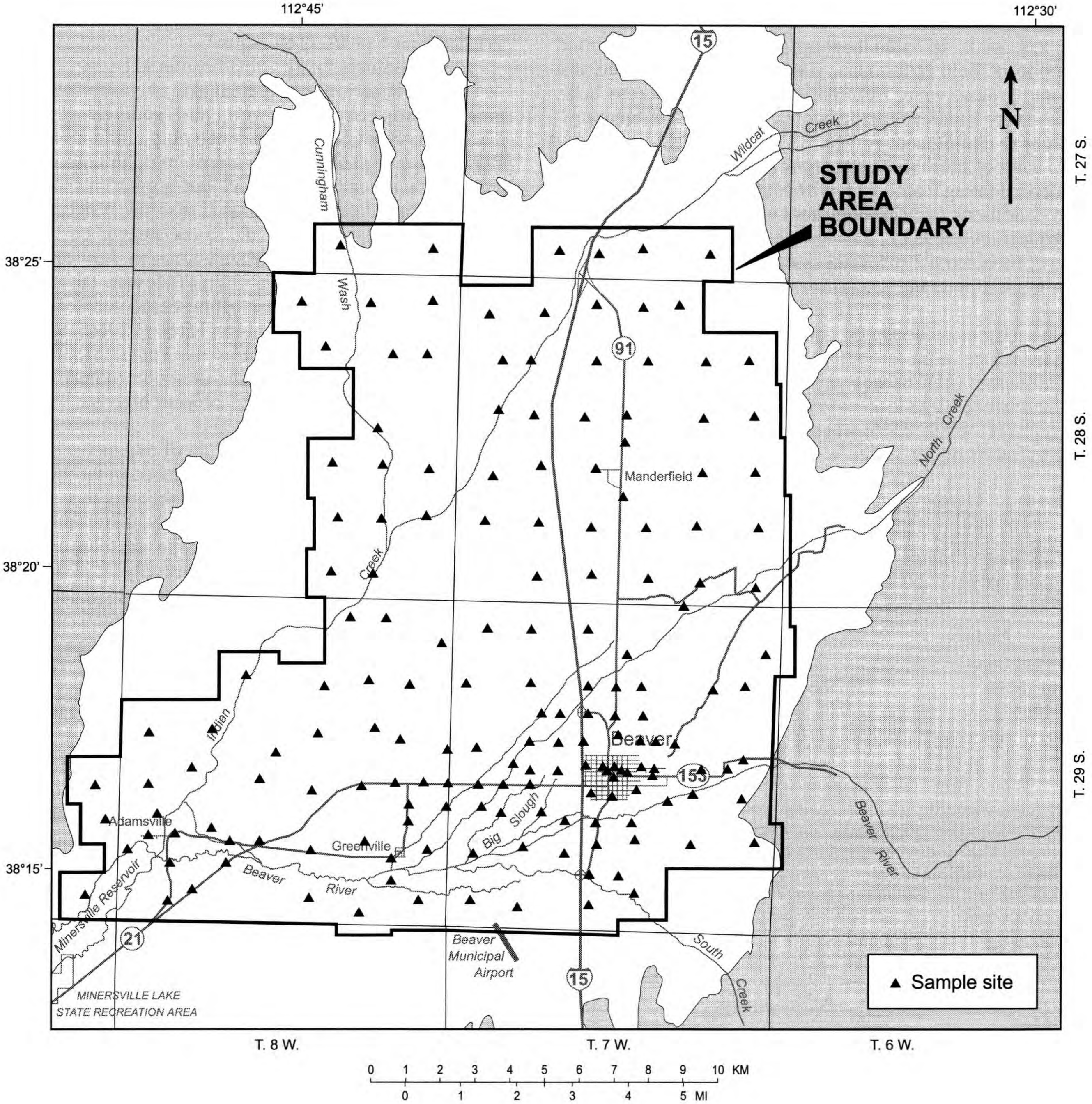


Figure 7*. Sample site locations for the ground survey, and study-area boundary.*

ing, and some undeveloped areas. The study-area boundary, independent of mapped geologic units, reflects the sample site locations and an assumed 0.5 mile (0.8 m) radius of influence. The study area encompasses about 126 square miles (414 km^2). Sample-site locations and soil-texture information are in the appendix. In some local areas, poor access prohibited collection of field radiometric data, urban areas lacked soil data, and ground-water information was sparse. Areas lacking data were small, so factors were averaged from surrounding areas to complete coverage.

To each of these geologic factors listed above I assigned a numerical rating from 1 to 3, with higher ratings corresponding to conditions contributing more to elevated indoor-radon concentrations (table 1). Ratings were summed and assigned to one of three hazard-potential categories (table 2). The three radon-hazard-potential categories are:

1. low (L): areas where no geologic factors contribute to indoor-radon hazards;
2. moderate (M): areas where some geologic factors contribute to indoor-radon hazards; and
3. high (H): areas where all geologic factors contribute to indoor-radon hazards.

Table 1. *Hazard-potential ratings of geologic factors that affect levels of indoor radon. Soil-permeability classes are based on hydraulic conductivity (K).*

	Point Value		
Factor	**1**	**2**	**3**
Uranium (ppm)	<2	2-3	>3
Permeability (K, in/hr)	Low 0.06 - 0.6	Moderate 0.6 - 6.0	High 6.0 - 20.0
Ground-water depth (ft)	<10	10 - 30	>30

Table 2. *Radon-hazard-potential categories. See table 1 for point value of factors in each category. Probable average indoor-radon concentrations for all homes in each category is also shown, but concentrations in individual homes may not fall within the expected range.*

Low	3 -4	<2
Moderate	5 7	2 - 4
High	8 -9	>4

Summed ratings describe in qualitative terms the relative potential for an indoor-radon hazard. Insufficient evidence exists to decide the relative contribution of each geologic factor to the radon hazard (Black and Solomon, 1996). Therefore, all geologic factors are weighted equally.

The radon-hazard-potential map considers only the effects of geologic factors. Significant non-geologic factors influencing indoor-radon concentrations such as weather, home construction, and occupant lifestyle are not considered. Mapped hazard potentials should roughly correlate with indoor-radon concentrations, but geologic interpretations of radon-hazard potentials do not accurately predict indoor-radon levels in specific homes (Fleischer and others, 1982). Areas with low hazard potential have expected indoor-radon concentrations less than 2 pCi/L (74 Bq/m^3) (table 2). Areas with high hazard potential have expected concentrations greater than 4 pCi/L (148 Bq/m^3).

Other geologic factors not considered because of the scale of the investigation are fluctuations of ground-water levels, active faults, expansive soil, and geothermal processes. These may also contribute to locally high indoor-radon levels. Fluctuation of ground-water levels could potentially contribute to upward radon transport, but applied research on this mechanism is only beginning (LeGrand, 1987; Gregg and Holmes, 1990). Water levels in the Beaver basin generally have a seasonal peak in March through July and annually fluctuate as much as 36 feet (11 m) (Mower, 1978). Elevated indoor-radon levels because of increased permeability along active faults are also possible (Tanner, 1980; Sprinkel and Solomon, 1990). At the base of the Tushar Mountains along the active Beaver fault zone and along the extensively faulted Last Change Bench, localized areas of high radon concentration may occur.

Repeated shrinking or swelling of expansive soil because of changes in moisture content can damage building foundations, and enhance radon entry into the structure. Expansive soil may also develop cracks when dry, providing additional pathways for soil-gas transport (Peake and Schumann, 1991). Clay-rich sediments, like some of the silty clays in the Beaver basin area, are commonly associated with expansive soils and may contribute to local high radon concentrations.

Anomalous radon concentrations are associated with many active geothermal areas (Nielsen, 1978; Blackett and others, 1990). Geothermal fluids contain larger amounts of dissolved minerals, including radioactive species, and geothermal systems offer an effective transportation mechanism. In the Beaver basin, no known geothermal resource exists although the potential appears moderate (Mundorff, 1970). The Cove Fort-Sulphurdale and Roosevelt Known Geothermal Resource Areas (KGRA) are to the north and west, respectively. The Radium Warm Springs discharges along the Beaver River a few miles west of the Beaver basin, east of Minersville (Mundorff, 1970).

Uranium Concentration

Quantities of indoor radon depend primarily upon the concentration of uranium in the soil. Radiometric reconnaissance of the Beaver basin in the 1970s found abnormally high surface radioactivity, compared to adjacent basins (Miller and others, 1980; Miller and McHugh, 1981; McHugh and Miller, 1982). In the present study, Quaternary basin fill eU concentrations measured at 176 sample sites ranged from 3.1 to 13.5 ppm (figure 8), had a mean of 7.5 ppm, a standard deviation of 2.1 ppm, a slight positive skewness of 0.32 to the right, and a coefficient of variation of 27 (table 3). Median concentration is 7.35 ppm, very close to the mean. The distribution of uranium concentrations is approximately normal (figure 9),

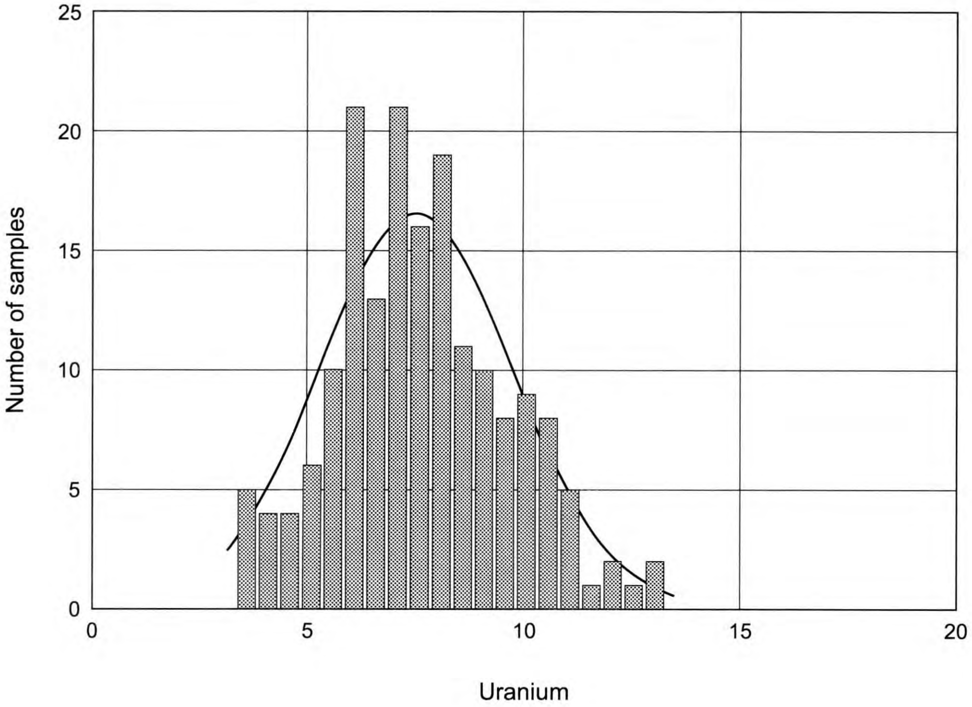


Figure 8. *Histogram of uranium concentrations in the Beaver basin area.*

Table 3. *Statistical summary of radiometric data for the Beaver basin area.*

	Total Counts (ppm)	K (%)	eU (ppm)	eTh (ppm)	eU/eTh	^{222}Rn (pCi/L)
Number of samples	176	176	176	176	176	104
Mean	26.63	3.15	7.59	27.84	0.28	514.67
Standard Deviation	6.38	0.56	2.11	8.03	0.05	564.68
Skewness	-0.12	-0.41	0.32	-0.029	0.49	2.67
Minimum	12.9	1.4	3.1	9.7	0.17	50.53
Median	27.4	3.2	7.35	28.1	0.28	316.68
Maximum	43.1	4.3	13.5	48.9	0.45	3555.99

K = *potassium*
eU = *equivalent uranium*
eT = *equivalent thorium*
eU/eTh = *the equivalent uranium-equivalent thorium ratio*
^{222}**Rn** = *Radon-222*

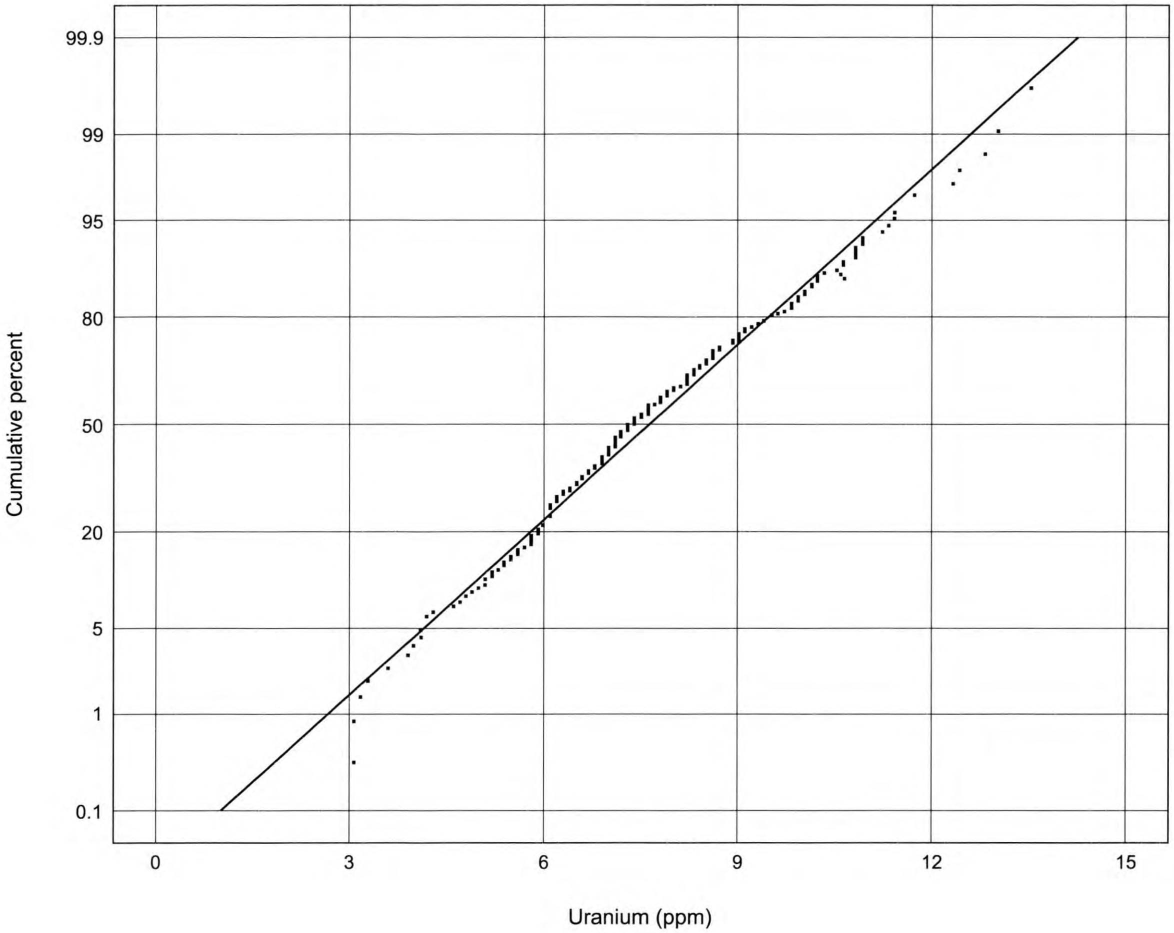


Figure 9. *Distribution curve of uranium concentrations in the Beaver basin area.*

justifying analyzing the data with parametric statistical techniques.

Meussig (1988) showed a correlation between areas with mean eU concentrations greater than 2.4 ppm and indoor-radon levels exceeding 4 pCi/L (148 Bq/m^3). Soils with naturally high eU concentrations, greater than 2 ppm, are most likely to correlate with high indoor-radon levels. Indoor-radon levels less than 4 pCi/L (148 Bq/m^3) are typically associated with eU concentrations less than 2 ppm, whereas elevated indoor-radon levels are consistently associated with eU concentrations of 3 ppm or greater (Meussig, 1988; Duval and others, 1989; Peake and Schumann, 1991).

Highest uranium concentrations coincide with modern and ancestral terrace, fan, piedmont-slope, and floodplain alluvium deposited by streams from the Tushar Mountains (figure 10). These reflect a high content of relatively radioactive rhyolite from the Mount Belknap Volcanics. The Mount Belknap Volcanics have a mean concentration of about 13 ppm uranium (Steven and others, 1981) and they alone probably supplied several billion pounds of uranium to the nearby Beaver basin (Steven and others, 1981). Locally high uranium concentrations in the alluvial fans from the Tushar Mountains may result from preferential leaching of uranium from the volcanics. The concentration and mobility of uranium leached from the rock and sediment surrounding or within the Beaver basin is influenced by several factors:

1. uranium content of the source material;
2. proximity of water to the uranium source;
3. degree of isolation of water containing leached uranium from fresher water; and
4. other factors such as climatic effects, the pH and oxidation state of the water, and the presence of sorptive material such as organic matter and clays (Durrance, 1986).

Lowest uranium concentrations are in the southern benches above the modern floodplain of the Beaver River. These areas consist of sediment derived from the volcanics of the Black Mountains (south of the study area).

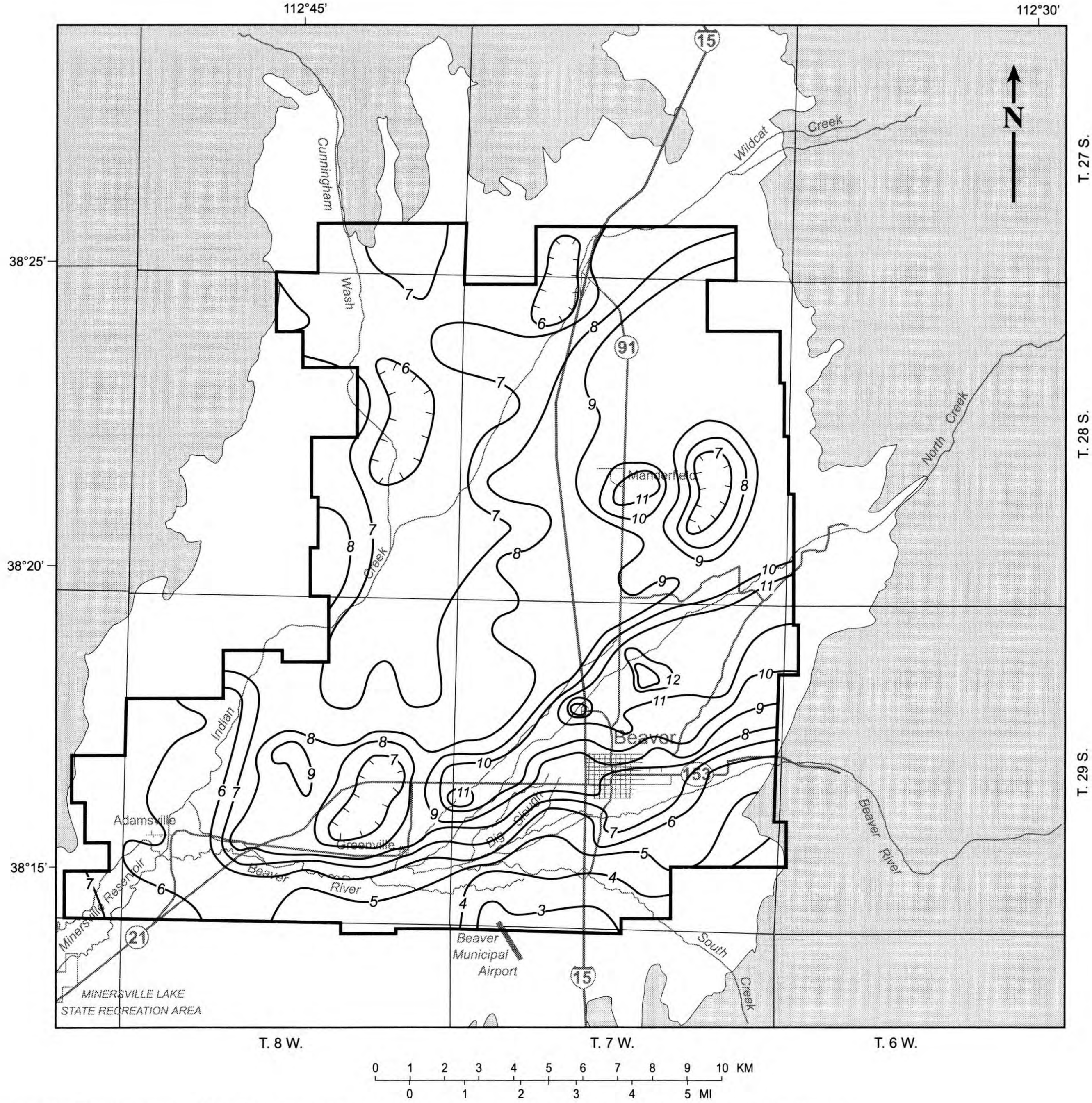


Figure 10. *Contour map of uranium concentrations in the Beaver basin area. Contour interval is 1 ppm.*

Soil

When assessing an area for radon-hazard potential, the soil must be considered because radon gas must migrate through it. Permeability is the capacity of soil to transmit a gas or fluid. Impermeable soils block the flow of soil gas, whereas highly permeable soils provide excellent pathways for soil-gas migration (McLemore and others, 1991) and allow rapid transport of radon gas under very small pressure differentials. Thus, radon can accumulate from a larger area in highly permeable soils. Conversely, relatively impermeable soils do not allow the migration of significant amounts of soil gas. Radon's short half-life limits transport by diffusion of radon in impermeable soils.

The U.S. Soil Conservation Service (SCS), now the Natural Resources Conservation Service, mapped soils in the Beaver basin area. The SCS divided soils into permeability classes based on soil structure and porosity, and the ability to transmit water or air (Stott and Olsen, 1976). They express soil permeability in terms of hydraulic conductivity, in inches per hour, with which water moves through the soil. Permeability classes range from less than 0.06 inches/hour (4.2 x 10^{-5} cm/sec) to greater than 6.0 inches/hour (4.2 x 10^{-3} cm/sec). Based on the lowest permeability class in the upper

60 inches (24 cm) of soil, the SCS permeability classes were assigned to one of three categories:

1. low (L), less than 0.6 inches/hour (4.2 x 10^{-4} cm/sec);
2. moderate (M), from 0.6 to 6.0 inches/hour (4.2 x 10^{-4} to 4.2 x 10^{-3} cm/sec); and
3. high (H), greater than 6.0 inches/hour (4.2 x 10^{-3} cm/sec).

Soil permeability in the area varies from low to high. Permeability is highest in coarse-grained sandy and gravely alluvial-fan deposits, stream alluvium, and pediment deposits along the range front of the Tushar Mountains (figure 11) and in the floodplain of Indian Creek (figure 12). Moderate permeability soils are the most common in the study area in fan, terrace, and fanglomerate-facies alluvium. Soils with low permeability are fine-grained silt and clay deposits on floodplains and some terraces in low-lying areas (figure 11).

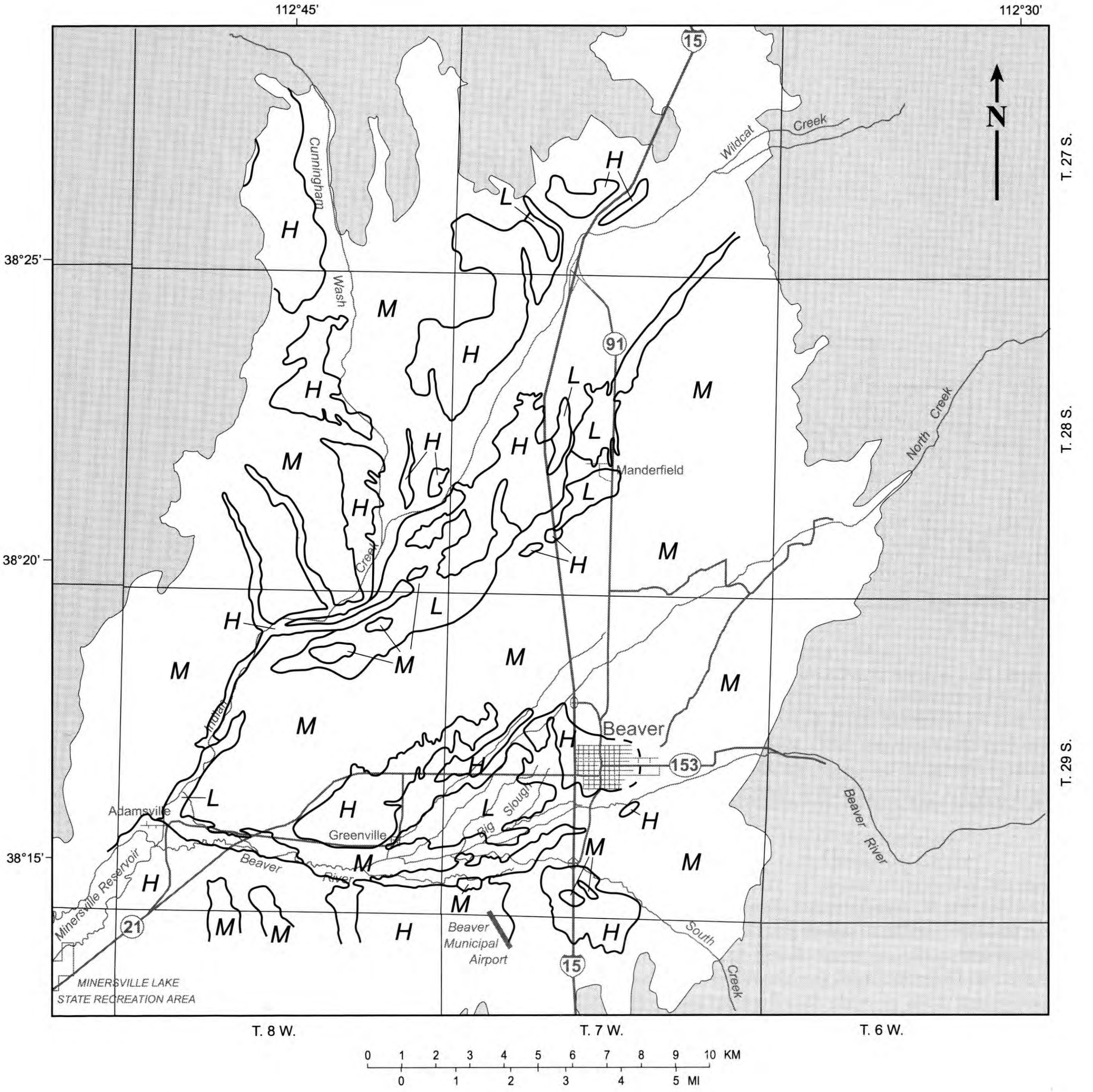


***Figure 11**. Soil permeability in the Beaver basin area. Soil survey maps and permeabilities from Stott and Olsen (1976) were used to determine soil permeability: L - low, hydraulic conductivity <0.6 inches/hour (4.2 x 10^{-4} cm/sec); M - moderate, hydraulic conductivity 0.6 to 6.0 inches/hour (4.2 x 10^{-4} to 1.4 x 10^{-3} cm/sec; and H -high, hydraulic conductivity >6.0 inches/hour (1.4 x 10^{-3} cm/sec). Soil permeability values extrapolated in the area lacking data (shown by dashed line).*

Figure 12. *Cut on Last Chance Bench near Manderfield showing upper part of soil profile consisting of stratified fine sandy loam beds with cobbly and gravelly zones.*

Ground Water

Ground water can inhibit soil-gas transport and reduce the amount of radon available to enter a home. Although radon easily dissolves in water, soil pore water reduces diffusion and obstructs convective flow of soil gases. Pore water effectively inhibits radon migration whereas a low moisture content will not hinder convection or diffusion of radon in the soil (Tanner, 1980). Shallow ground water, less than 10 feet (3 m) deep (within the construction zone of basements), can reduce radon levels even in uranium-rich soils. Conversely, a low moisture content in soils improves radon migration into buildings, thus contributing to indoor radon. Ground water deeper than 30 feet (9 m) has little effect on indoor-radon levels (Black and Solomon, 1996).

In the Beaver basin shallow unconfined ground water is in coarse unconsolidated and semi-consolidated basin-fill deposits. Small areas of confined ground water are found in the Greenville area, southwest of Beaver, and in the North Creek drainage. Two perched water tables are also found in the basin (Mower, 1978). Depth to water ranges from the land surface along the Beaver River and North Creek to greater than 60 feet (18 m) in the northern parts of the basin (figure 13). Unconfined ground water is commonly less than 10 feet (3 m) deep in the Beaver River floodplain, low-lying areas around Manderfield, and the south-central part of the study area in drainages from the Tushar Mountains where phreatophytes and springs are common. Areas of shallow ground water are usually used for agriculture purposes (figure 14). Unconfined ground water less than 30 feet (9 m) deep is primarily in river floodplains.

Although shallow ground water impedes the movement of radon from soils into buildings, ground water from wells may be a source of indoor radon. Ground-water-radon concentration was the focus of studies by Miller and others (1980) and McHugh and Miller (1982). These studies used radon in ground water to indicate uranium sources in the Beaver basin and found anomalously high concentrations. McHugh and Miller (1982) conducted a radon survey of springs and water wells in the Beaver basin during 1981 and noted that groundwater geochemistry, bedrock geology and mineralogy, and uranium concentration control the levels of radon in well water. Water samples for their survey were collected from domestic wells and springs, with some uncertainty in the stratigraphic interval producing the water. Sampling of existing wells limited the samples to the depth from which water is drawn. The concentration of radon in the water ranged from a low of 10 pCi/L to a high of 8,300 pCi/L (figure 15). The radon data suggest a lognormal distribution. The highest radon value of 8,300 pCi/L was on the eastern flank of the Mineral Mountains, perhaps due to vein-type uranium occurrences in the area. High radon values in well water near Manderfield and the town of Beaver exceed the proposed EPA safety levels of 300 pCi/L of dissolved radon in water. No studies have been performed to evaluate their contribution to indoor radon in the area.

Hazard Potential

The radon-hazard potential is generally high throughout much of the basin (figure 16). Moderately permeable, unsaturated, uraniferous deposits derived from volcanic rocks characteristically underlie these areas. Locally, uranium concentrations in the basin are sufficiently high to give a high hazard potential even in areas where ground water is shallow or soil permeabilities are low. Areas of moderate hazard potential are found just south of Beaver, westward along the Beaver River to Adamsville, and along the floodplain of Indian Creek. Low permeability soil and/or shallow ground water and uraniferous Quaternary floodplain alluvium and pediment deposits underlie these areas. No areas of low hazard potential are found in the Beaver basin.

Soil Gas

I measured soil-gas-radon concentrations for correlation with uranium concentrations and radon-hazard potential. Radon's short half-life restricts its migration, so its occurrence is unlikely at great distances from sources. Soil-gas-radon concentrations at 104 sample sites in the area range from 50 to 3,556 pCi/L (1850-13.2 x 10^4 Bq/m^3), with a mean concentration of 514 pCi/L (1.9 x 10^4 Bq/m^3) and a standard deviation of 564 pCi/L (figure 17; table 3). The probability distribution of soil-gas-radon data is approximately lognormal (figure 18), with a positive skewness of 2.6 and a coeffi-

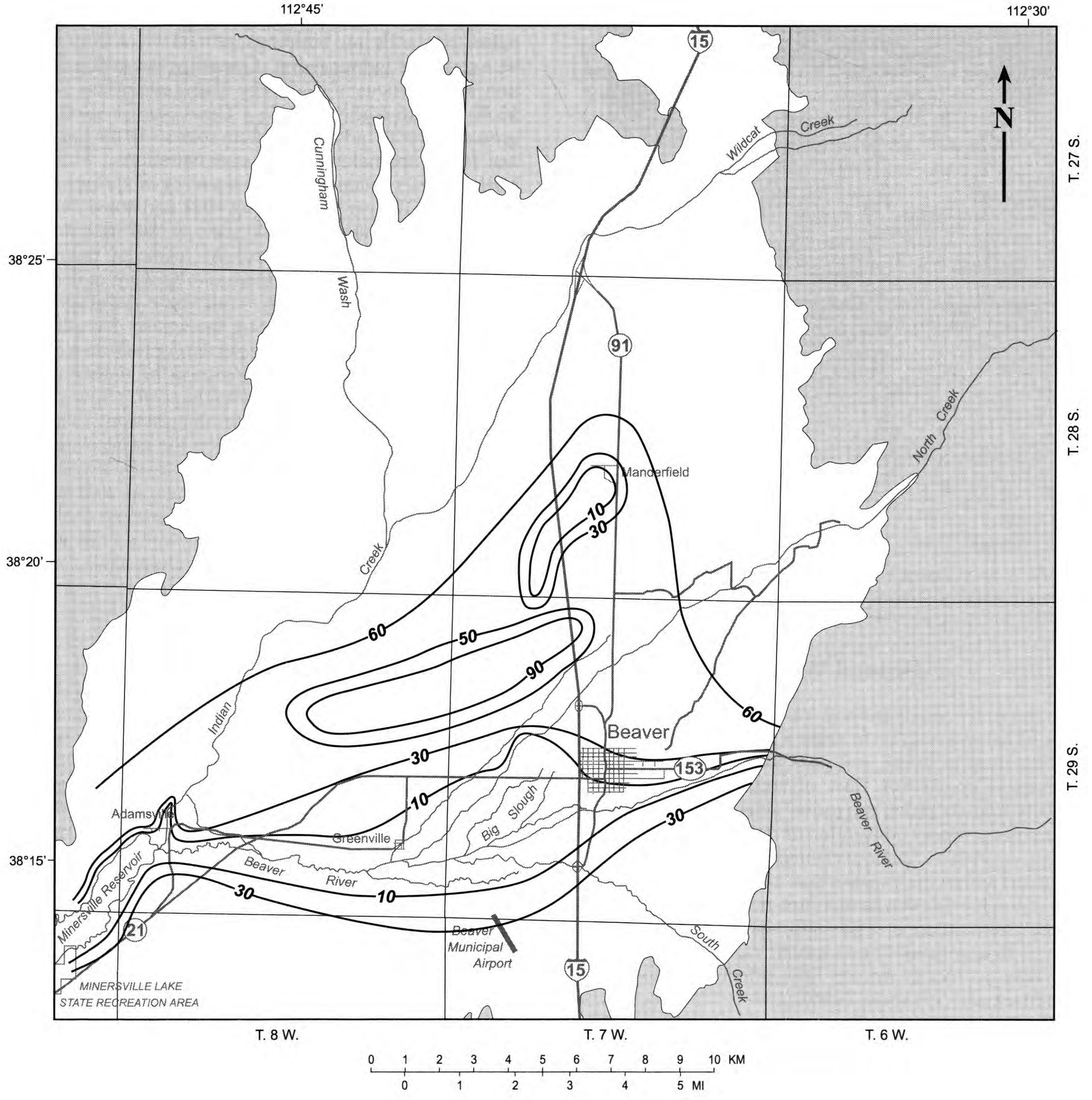


Figure 13. *Depth to shallow ground water in the Beaver basin area (modified from Sandberg, 1966; Mower, 1978; and unpublished data). Contours at depths of 10, 30, 60 and 90 feet (3, 9, 18, and 27 m).*

Figure 14. *Agricultural land in shallow ground-water area, looking northwest toward Manderfield, Beaver basin area.*

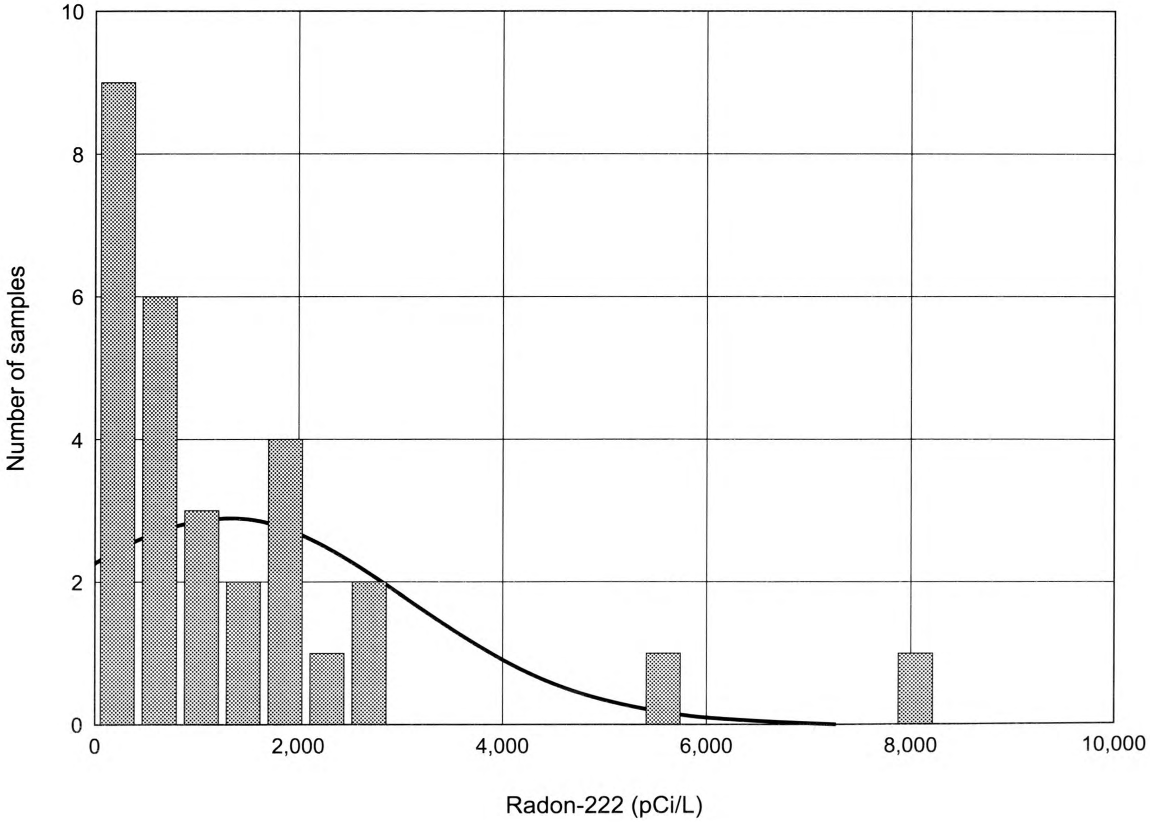


Figure 15. *Histogram of radon-gas concentrations in water in the Beaver basin area.*

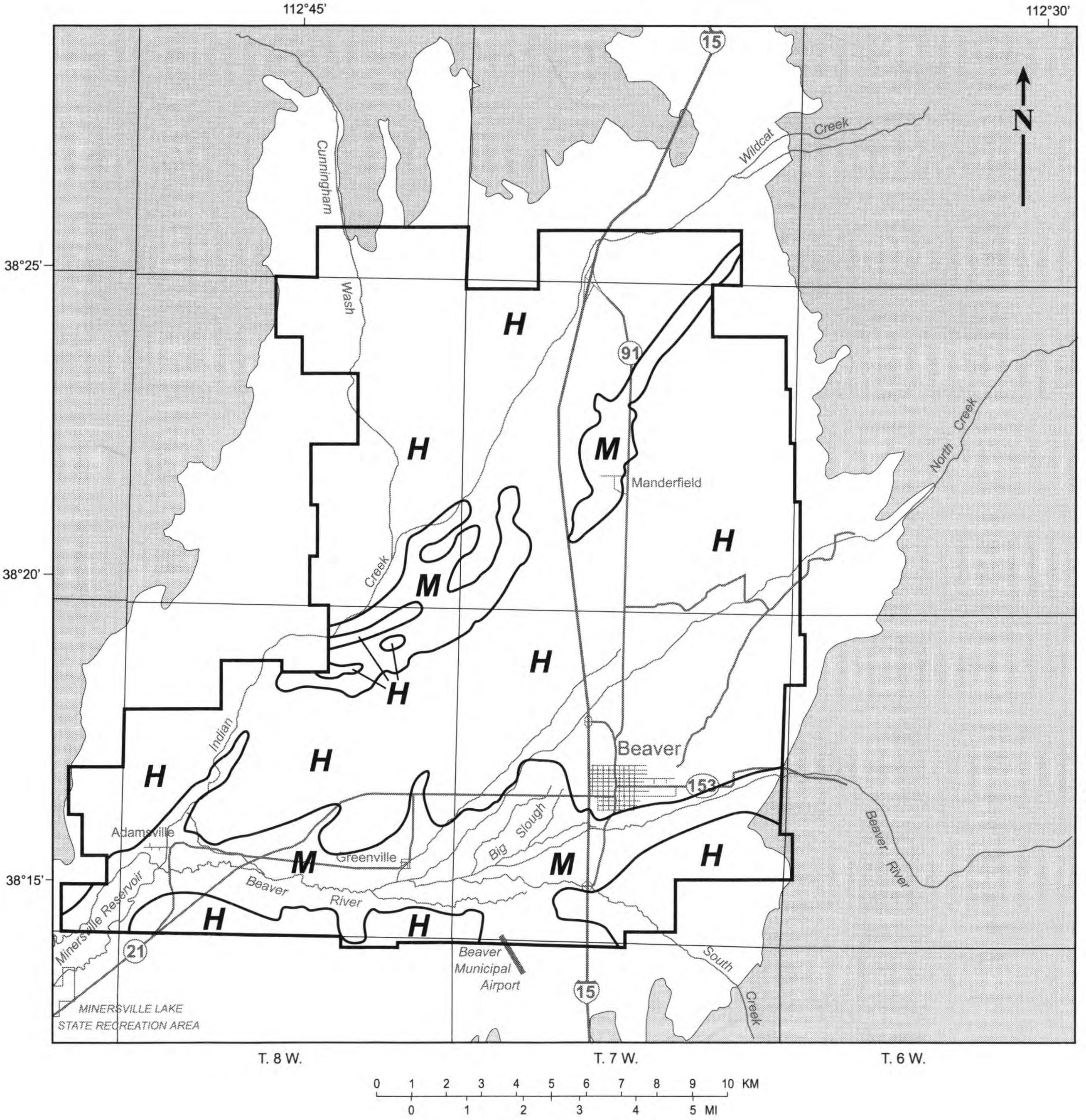


Figure 16. *Radon-hazard-potential map for the Beaver basin area. Hazard potential categories are H - high - areas with geologic factors generally conducive to elevated indoor-radon levels; and M - moderate - areas with one or two factors conducive to elevated indoor-radon levels, but limited by one or two unfavorable geologic conditions.*

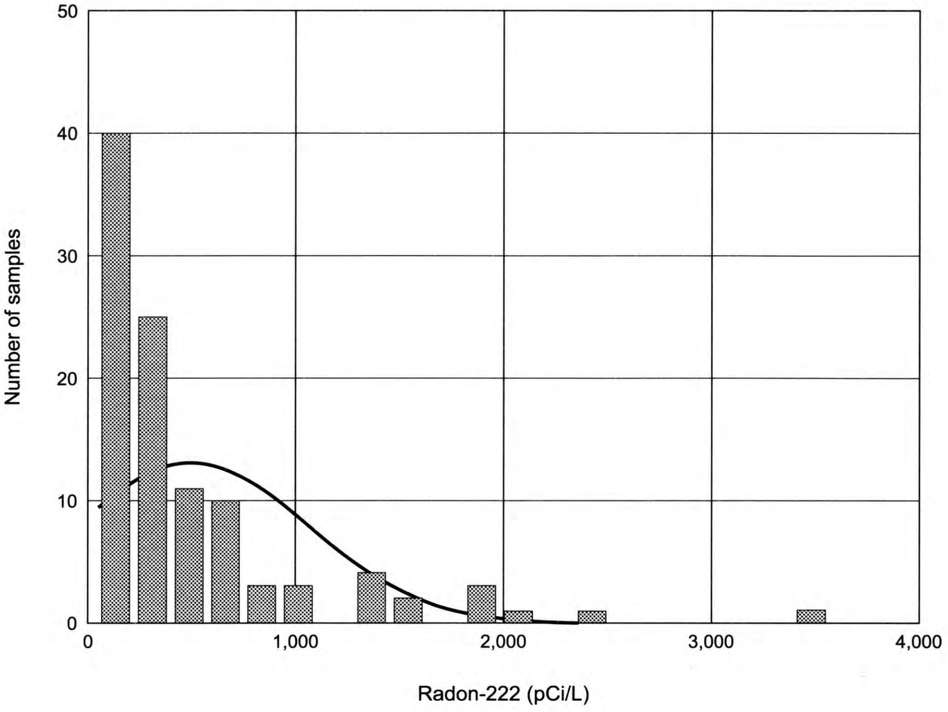


Figure 17. *Histogram of soil-gas-radon concentrations in the Beaver basin area.*

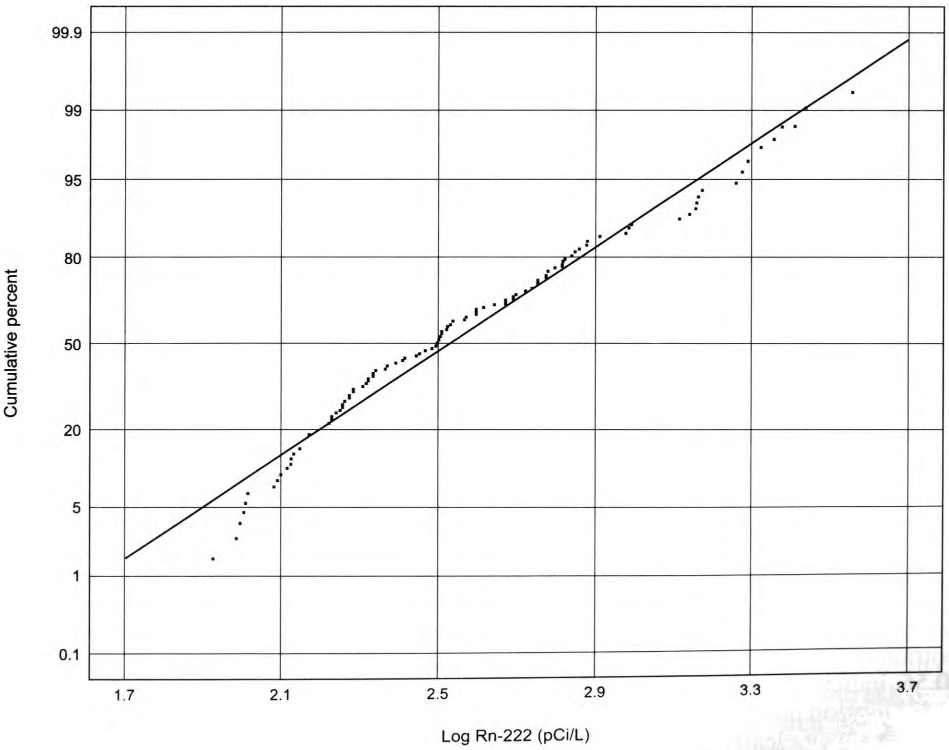


Figure 18. *Distribution curve of soil-gas-radon concentrations in the Beaver basin area.*

cient of variation of 109. The median concentration is 316 pCi/L (11.7 x 10^3 Bq/m^3). The mean and median soil-gas-radon concentrations are generally higher than other measured levels in the state.

Historically, comparisons of average eU and soil-gas-radon concentrations in other studies show a good correlation despite radon being highly mobile in soil (Gundersen and others, 1988). The ideal correlation at the same sample site between soil-gas-radon and uranium concentration should be linear because radon is a naturally occurring product in the uranium decay series. In reality, however, the relationship between uranium and soil-gas radon varies due to measurements at different horizons in the ground, removal of radionucleides from a system, atmospheric contamination of soil-gas samples by air leaking between the probe and adjacent soil, and the effect of grain size on radon emanation. The influence of changing weather during sampling further complicates the correlation of these factors. Because radon-hazard potential is partly based on uranium content, these factors also affect the comparison between soil-gas-radon concentrations and radon-hazard potential. Soil-gas-radon concentrations are therefore difficult to accurately characterize, and correlations with uranium concentration or hazard potential are typically imperfect.

A scatter plot of eU and soil-gas-radon concentration from samples measured at the same site gives a rough idea of the relationship between these variables in the Beaver basin (figure 19). The data-point scatter indicates a poor relationship. The plot shows only a broad correlation between the two variables, with higher values of uranium corresponding to higher soil-gas radon. Uranium concentrations of data pairs vary from 3 to 13 ppm with values spread evenly throughout the range. Most soil-gas-radon concentrations cluster in a range between 200 and 800 pCi/L (7,400-22,200 Bq/m^3) with more values in the lower part of the range. Ideally, radon concentrations should increase within a narrow band with each corresponding increase in uranium concentration.

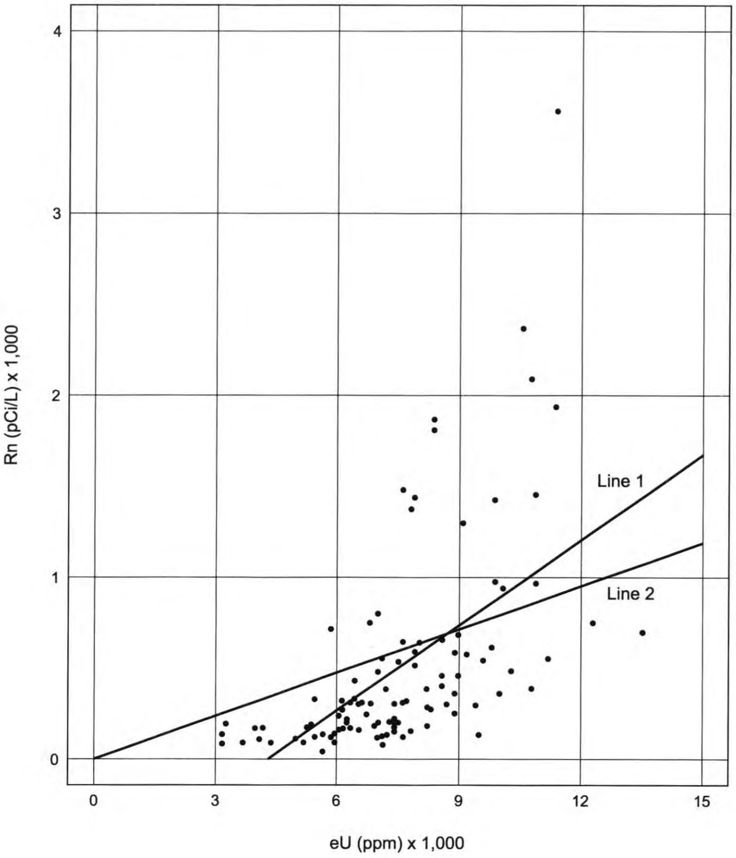


Figure 19. Scatter plot and linear regression of equivalent uranium (eU) and soil-gas-radon (Rn) data pairs in the Beaver basin area. Regression line 1 shows that when the line is not forced to 0, concentrations are related by the formula Rn = 154 eU - 647.4, with a correlation coefficient = 0.561. Regression line 2 shows that when the line is forced to 0, reflecting the absence of the decay-product Rn when none of the parent U is present, concentrations are related by the formula Rn = 75 eU, with a correlation coefficient = 0.718.

Nevertheless, to help predict soil-gas radon if uranium concentration is known, I quantified the relationship between soil-gas radon and uranium. The simplest type of relationship is linear, where I assume that the dependence of one variable (soil-gas radon) on another (uranium) is described by a straight line. Linear regression of soil-gas radon and uranium data pairs is shown in figure 19 (line 1) and is related by the formula:

$$Rn = 154eU - 647.4$$

where Rn is the soil-gas-radon concentration in pCi/L, and eU is the uranium concentration in ppm. The correlation coefficient of this line is 0.56, indicating a somewhat poor linear relationship. Also, the regression line continues into negative values for soil-gas radon. This is clearly unrealistic because radon values are never negative, and it is appropriate to set negative predictions to zero. Although average soil-gas-radon concentrations determined by this formula at intermediate uranium levels compare favorably with those derived from other studies in Utah, the lack of correlation with increases in soil-gas-radon concentrations at high uranium levels results in a poorer correlation than in most other areas (Solomon and others, 1991, 1993; Solomon, 1995, 1996). If the linear regression is forced to zero, indicating an absence of radon when no uranium is present, the data pairs are related by the formula:

$$Rn = 75eU$$

Although theoretically more realistic, this correlation is also poor (correlation coefficient of 0.718). This regression analysis underestimates the values of soil-gas radon at lower levels of uranium and overestimates the values of soil-gas radon at extreme levels of uranium where the scatter is large.

As part of the evaluation of the Beaver basin soil-gas data, I applied a semiquantitative interpretative method of analysis

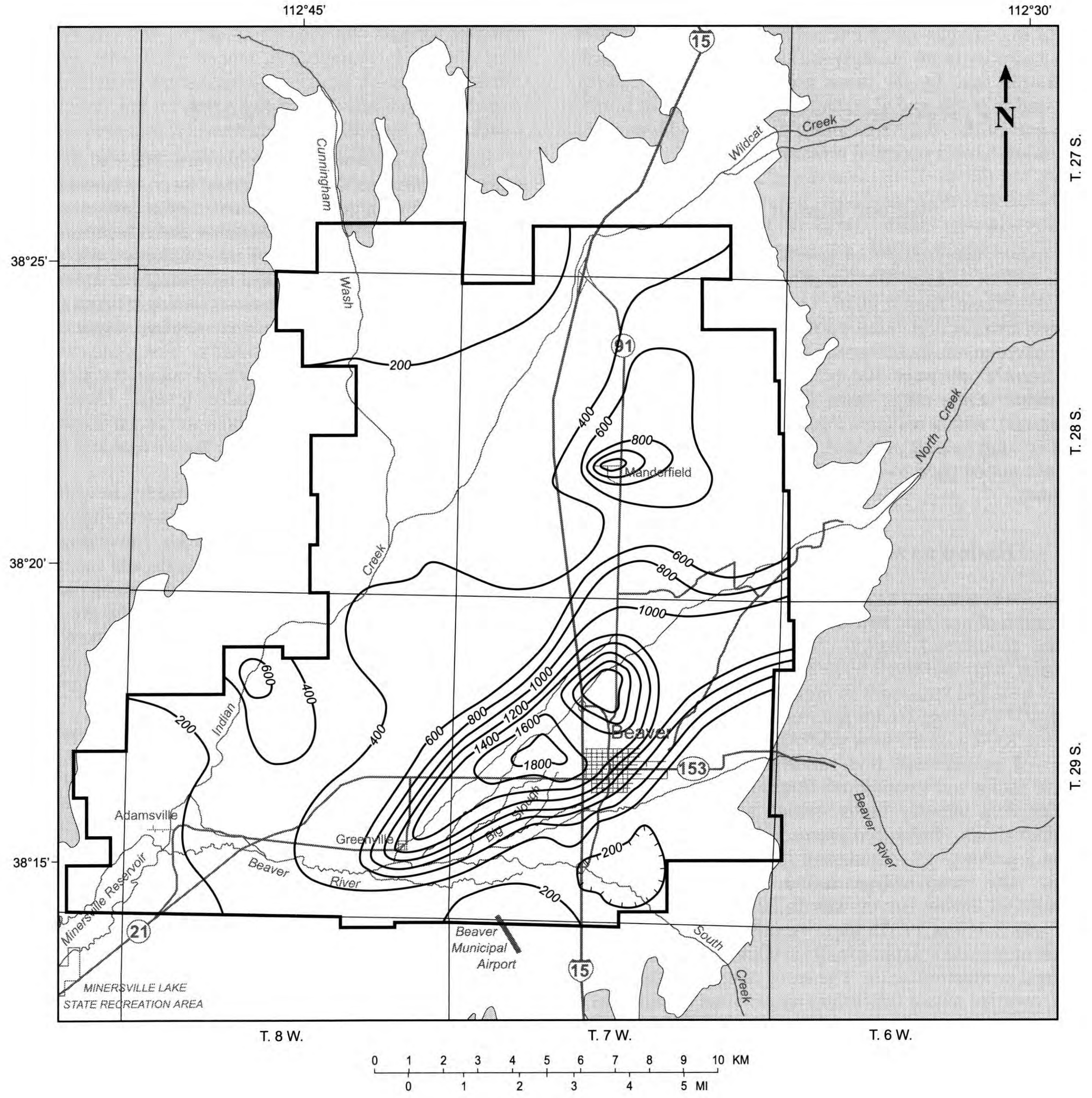


***Figure 20.** Exclusion isoline map of soil-gas-radon concentrations in the Beaver basin area. Contour interval is 200 pCi/L (7.4 x 10^{-3} Bq/m^3).*

developed by Durrance (1978). This method uses exclusion isolines to lessen the effects of factors that reduce the soil-gas-radon concentration of a sample. The method assumes that whereas many factors can reduce soil-gas levels, only the influx of radon will produce high levels; thus higher concentrations are geologically more meaningful. Instead of constructing contour lines of equal value, exclusion isolines enclose higher values and ignore erratic low values.

Soil-gas-radon exclusion isoline patterns correspond moderately well to the eU concentration contours despite the lack of correlation between data pairs. They both indicate a significant contribution from the North Creek drainage. The highest soil-gas-radon levels and eU concentrations are in the eastern part of the study area, near the towns of Beaver and Manderfield (figure 20). The correlation between soil-gas radon and the hazard potential is poor, except that they both indicate a high radon content for most of the basin. The pattern of the soil-gas-radon exclusion isolines suggests that soil-gas radon is more strongly influenced by the uranium concentration than by the other geologic factors. Lowest soil-gas-radon levels and eU concentrations are in the northwestern part of the study area along the Mineral Mountains, but the radon-hazard potential remains high.

Indoor Radon

The mean concentration of seven indoor-radon samples from the city of Beaver is 119.9 pCi/L (4,436 Bq/m^3), with all samples greater than 4 pCi/L (148 Bq/m^3). All samples came from areas of high hazard potential (figure 16). Two of these measurements, including the highest value of 343 pCi/L (1,269 Bq/m^3), are over 300 pCi/L (11,100 Bq/m^3). The indoor-radon levels range from 20.75 to 343 pCi/L (767-1,269 Bq/m^3), with a median of 50 pCi/L (1,850 Bq/m^3), all in areas of high hazard potential. Because data are limited, they could not be used to determine a meaningful statistical distribution.

Radon as an Exploration Tool

Radon has been used as a tracer of geologic processes for identification of geologic structures, and exploration for uranium and geothermal energy. Studies focusing on radon distribution in ground water have been applied to the investigation of geologic structures in areas near the Beaver basin. Nielson (1978) reported radon measurements at the Roosevelt Hot Spring KGRA on the west side of the Mineral Mountains, and showed anomalously high radon concentrations associated with faults and geothermal fluids in the area. Radon anomalies help identify faults, which act as conduits for geothermal fluids. Enhanced permeability in the fault zone provides a pathway for circulating fluids carrying radon in solution. The mean soil-gas-radon concentration for the Roosevelt Hot Spring survey was 11,027 pCi (408 Bq); the median was 8,513 pCi (315 Bq). Anomalies were found in areas that intersected mapped faults and areas with successful geothermal production wells. The study concluded that radon surveys, coupled with a structural analysis, can be useful as a site-specific tool in siting exploration holes in KGRAs. In the 1980s, radon was examined throughout the Beaver basin for uranium exploration.

Cautions When Using This Report

Radon-hazard categories on the radon-hazard-potential map of the Beaver basin are relative and only comparable to areas that have been mapped using similar classification criteria. Because of the complex relationship between geologic and non-geologic factors controlling indoor-radon levels, this report should not be used to predict specific indoor-radon levels. Small localized areas of higher or lower radon potential may be found within the hazard areas depicted on the maps. Radon-hazard categories are relative, and all map boundaries between hazard categories are approximate and gradational.

SUMMARY

Radon is a natural radioactive gas that can accumulate indoors in sufficient concentrations to pose a health hazard. The indoor-radon hazard depends on both geologic and non-geologic factors. We can estimate the effects of geologic factors whereas the effects of non-geologic factors such as construction type, weather, and individual lifestyles, are difficult to quantify and characterize. Geologic factors affecting radon levels include uranium concentration, depth to shallow ground water, and soil permeability. The radioactive decay of uranium produces radon, and high uranium concentrations can lead to elevated indoor-radon levels. Once radon is present in soil gas, shallow ground water and soil permeability affect radon's ability to migrate to the surface and into structures.

Radon-hazard-potential maps are useful to organize and prioritize testing in existing buildings and to indicate where radon-resistant construction should be considered in new buildings. Indoor-radon levels are easily and inexpensively measured, and various methods to reduce indoor-radon levels are available. Radon-hazard-potential maps are based on geologic factors, and do not consider the effect of non-geologic factors. Measuring indoor-radon levels in existing buildings is the only way to determine the combined effect of geologic and non-geologic factors.

Rocks in the Tushar and Mineral Mountains surrounding the Beaver basin are chiefly Tertiary volcanic rocks with high uranium content. Sediments in the Beaver basin record a history of nearly continuous middle Miocene to early Pleistocene closed-basin deposition and middle Pleistocene to Holocene open-basin deposition. Subsequent downcutting has left a mainly erosional sequence of late Quaternary terrace and piedmont-slope alluvium. Soils in the Beaver basin have high uranium content. Ground water is shallow along modern floodplains and relativity deep elsewhere. Coarse-grained pediment and alluvial-fan deposits across the basin have high to moderate permeability. Low permeabilities are associated with modern floodplain alluvium.

A numerical rating system was used to quantify the relative radon hazard. To each geological factor I assigned a numerical rating and then summed ratings to assess the relative radon hazard. The ratings were used to create a radon-hazard-potential map, which shows that most of the basin has a high radon-hazard potential. In areas of high radon-hazard potential, all geologic factors contribute to elevated radon levels. In areas of moderate and low potential, low uranium concentration, shallow ground water, and/or low permeability soils contribute to lower the radon levels. Geologic factors not considered, such as geothermal activity, fluctuations of the ground-water table, expansive soils, and active faults may produce locally high indoor-radon levels.

High uranium concentrations throughout the Beaver basin lead to a moderate or high radon-hazard potential everywhere.

Uranium concentrations dominate the radon-hazard potential, although locally low-permeability soils and shallow groundwater depth reduce the hazard to moderate. Radon-hazard potential is high on slopes along the Tushar Mountains, on the basin margins, and on bench, piedmont, and alluvial slopes. The hazard potential is moderate in the interior of the basin along the Beaver River and near Manderfield.

The radon-hazard-potential map generally indicates average indoor radon levels based on geologic factors. Local anomalous indoor radon levels may exist either because of the local influence of factors not measured or the influence of measured factors beyond the map-scale resolution. Soil-gas-radon measurements provide useful information, but are unreliable to assess indoor-radon-hazard potential because of inaccuracies introduced by sampling techniques and variations caused by weather.

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APPENDIX

Ground Survey Data

***Table A1.** Location and soil types of sample sites in the Beaver basin.*

Sample Number	UTM Coordinates		Cadastral Coordinates			7.5-minute Quadrangle Name	Soil Texture
	Northing	Easting	Township	Range	1/4 Section		
B-001	4238570	358520	29S	7W	SW14	Black Ridge	very gravelly loam
B-002	4238080	360550	29S	7W	SW13	Black Ridge	very gravelly loam
B-003	4237060	359070	29S	7W	NW23	Black Ridge	very gravelly loam
B-004	4236910	360680	29S	7W	SW24	Black Ridge	very gravelly loam
B-005	4235610	360905	29S	7W	NE25	Black Ridge	boulder and very gravely loam
B-006	4235550	359000	29S	7W	NW26	Black Ridge	very gravely loam
B-007	4238650	357500	29S	7W	NE15	Beaver	gravelly loam
B-008	4237190	357380	29S	7W	NW22	Beaver	gravelly loam
B-009	4235700	357320	29S	7W	NW27	Beaver	gravelly loam
B-010	4234090	357300	29S	7W	NW34	Greenville Bench	gravelly loam
B-011	4233750	355980	29S	7W	SE23	Greenville Bench	gravelly loam
B-012	4235560	356120	29S	7W	NE28	Beaver	gravelly loam
B-013	4237090	356030	29S	7W	NE21	Beaver	gravelly loam
B-014	4238650	355800	29S	7W	NW16	Beaver	gravelly loam
B-015	4238650	354190	29S	7W	SW17	Beaver	gravelly loam
B-016	4237370	354210	29S	7W	NW20	Beaver	gravelly loam
B-017	4235480	354010	29S	7W	NW29	Beaver	gravelly loam
B-018	4233680	353840	29S	7W	SW32	Greenville Bench	loam
B-019	4233890	352480	29S	7W	SW31	Greenville Bench	gravelly loam
B-020	4235280	352560	29S	7W	SW30	Beaver	loam
B-021	4237370	352680	29S	7W	NE19	Beaver	loam
B-022	4238450	352650	29S	7W	SE18	Beaver	loam
B-023	4238730	350350	29S	8W	SW13	Beaver	gravelly loam
B-024	4237400	351050	29S	8W	NE24	Beaver	loam, some small gravel
B-025	4235400	351200	29S	8W	SE25	Beaver	loam
B-026	4233900	350890	29S	8W	SW36	Greenville Bench	silty to sandy loam
B-027	4233540	349150	29S	8W	SW35	Greenville Bench	sandy loam
B-028	4235680	349310	29S	8W	NW26	Greenville Bench	sandy-gravelly loam
B-029	4237340	349210	29S	8W	NW23	Beaver	silty-gravelly loam
B-030	4239070	349600	29S	8W	NE14	Beaver	gravelly loam
B-031	4238900	347900	29S	8W	NE15	Beaver	gravelly loam
B-032	4237200	347720	29S	8W	NE22	Beaver	laom
B-033	4238840	356820	29S	7W	NW15	Beaver	clay loam
B-034	4238835	356834	29S	7W	NW15	Beaver	clay loam
B-035	4237570	356670	29S	7W	NE21	Beaver	clay to sandy loam
B-036	4237570	356670	29S	7W	NW22	Beaver	silty-sandy loam
B-037	4237730	357080	29S	7W	NW27	Beaver	loam
B-038	4235400	347680	29S	8W	SW27	Beaver	gravelly loam
B-039	4233970	347640	29S	8W	SE34	Greenville Bench	loam
B-040	4238350	346640	29S	8W	SE16	Adamsville	silty-gravelly loam
B-041	4239030	344760	29S	8W	NE17	Adamsville	silty loam
B-042	4237880	344150	29S	8W	NW20	Adamsville	silty loam
B-043	4238950	342900	29S	8W	NE18	Adamsville	silty loam
B-044	4237400	342890	29S	8W	NE19	Adamsville	silty loam
B-045	4237370	341290	29S	9W	SE24	Adamsville	silty loam
B-046	4236330	341620	29S	9W	NE25	Adamsville	gravelly loam
B-047	4235820	342850	29S	8W	NE30	Adamsville	silty loam
B-048	4233880	343490	29S	8W	SE31	Minersville Reservoir	silty loam
B-049	4234200	344200	29S	8W	NW32	Minersville Reservoir	silty loam

Table A1. *(continued)*

Sample Number	UTM Coordinates		Cadastral Coordinates			Quadrangle Name	Soil Texture
	Northing	Easting	Township	Range	1/4 Section		
B-050	4235690	346170	29S	8W	NE28	Adamsville	silty loam
B-151	4237540	346170	29S	8W	NE21	Adamsville	silty loam
B-052	4236070	344740	29S	8W	NE29	Adamsville	silty loam
B-053	4234080	340980	29S	9W	NE36	Minersville Reservoir	silty loam
B-054	4240160	359640	29S	7W	SE11	Black Ridge	gravelly loam
B-055	4240290	360600	29S	7W	NW12	Black Ridge	gravelly loam
B-056	4241260	361210	29S	7W	SE1	Black Ridge	silty-gravelly loam
B-057	4242700	358780	28S	7W	SE35	Black Ridge	gravelly loam
B-058	4240295	357510	29S	7W	NW10	Beaver	gravelly loam
B-059	4241250	357060	29S	7W	SW3	Beaver	gravelly loam
B-060	4240320	355910	29S	7W	NW9	Beaver	gravelly loam
B-061	4240410	354230	29S	7W	NW8	Beaver	gravelly loam
B-062	4242000	354240	29S	7W	NW5	Beaver	loam
B-063	4243590	354380	28S	7W	NW32	Beaver	loam
B-064	4245200	354450	28S	7W	NE-SE line, 29	Beaver	silty-gravelly loam
B-065	4246890	354510	28S	7W	NE20	Beaver	silty-gravelly loam
B-066	4246770	356120	28S	7W	SE21	Beaver	silty loam
B-067	4245060	355990	28S	7W	SW28	Beaver	silty-gravelly loam
B-068	4243650	356000	29S	7W	NE33	Beaver	gravelly loam
B-069	4242000	355910	29S	7W	NW4	Beaver	loam
B-070	4243550	357700	28S	7W	NE34	Beaver	gravelly loam
B-071	4245040	357640	28S	7W	SE27	Beaver	gravelly loam
B-072	4246695	360900	28S	7W	NW24	Black Ridge	gravelly loam
B-073	4245080	359140	28S	7W	SW26	Black Ridge	gravelly loam
B-074	4246700	359300	28S	7W	SE23	Black Ridge	gravelly loam
B-075	4245050	360990	28S	7W	SE25	Black Ridge	gravelly loam
B-076	4243250	360910	28S	7W	SE36	Black Ridge	silty-gravelly loam
B-077	4243400	359240	28S	7W	SE35	Black Ridge	sandy-gravelly loam
B-078	4253180	356200	27S	7W	S33	Gillies Hill	sandy, lightly gravelly loam
B-079	4253360	357520	27S	7W	NW34	Gillies Hill	sitly-gravelly loam
B-080	4253200	359530	27S	7W	E35	Pole Mountain	loam
B-081	4251680	358640	28S	7W	NW2	Pole Mountain	silty-gravelly loam
B-082	4251600	357520	27S	7W	NW3	Gillies Hill	gravelly loam
B-083	4251705	356140	27S	7W	NE4	Gillies Hill	loam
B-084	4250020	356130	28S	7W	NE9	Gillies Hill	silty-gravelly loam
B-085	4250010	357680	28S	7W	NE10	Gillies Hill	gravelly loam
B-086	4259960	359400	28S	7W	NE11	Pole Mountain	gravelly loam
B-087	4250020	360705	28S	7W	NW12	Pole Mountain	gravelly loam
B-088	4248370	360860	28S	7W	SW13	Black Ridge	loam
B-089	4248300	359350	28S	7W	SW14	Black Ridge	loam
B-090	4248570	353240	28S	7W	NE18	Beaver	silty loam, little gravel
B-091	4248410	354300	28S	7W	SW17	Beaver	silty loam
B-092	4240310	356740	29S	7W	NE9	Beaver	gravelly loam
B-093	4239500	355920	29S	7W	S9	Beaver	gravelly loam
B-094	4239420	356720	29S	7W	NE16	Beaver	gravelly loam
B-095	4239430	357550	29S	7W	NE15	Beaver	loam
B-096	4238640	357980	29S	7W	E15	Black Ridge	loam
B-097	4237880	357510	29S	7W	NE15	Beaver	gravelly loam
B-098	4237810	357940	29S	7W	E15	Black Ridge	Loam

Table A1. *(continued)*

Sample Number	UTM Coordinates		Cadastral Coordinates			Quadrangle Name	Soil Texture
	Northing	Easting	Township	Range	1/4 Section		
B-099	4237800	359300	29S	7W	NE23	Black Ridge	loam
B-100	4237800	360080	29S	7W	SW13	Black Ridge	loam
B-101	4237880	356700	29S	7W	SW15	Beaver	gravelly loam
B-102	4237940	355860	29S	7W	NE16	Beaver	loam
B-103	4238620	355070	29S	7W	NE17	Beaver	gravelly loam
B-104	4237750	355070	29S	7W	NW21	Beaver	loam
B-105	4253295	355050	27S	7W	NE32	Gillies Hill	loam
B-106	4251460	354600	28S	7W	SE5	Gillies Hill	loam, silty
B-107	4250050	354195	28S	7W	NW8	Gillies Hill	loam
B-108	4248340	355800	28S	7W	SW16	Beaver	gravelly loam
B-109	4248400	356950	28S	7W	SW15	Beaver	gravelly loam
B-110	4246790	356120	28S	7W	SW22	Beaver	gravelly loam, seems to be very gravelly at depth
B-111	4245260	352870	28S	7W	NE30	Beaver	gravelly loam
B-112	4246580	353097	28S	7W	SE19	Beaver	loam, some gravelly
B-113	4234650	355970	29S	7W	SE28	Beaver	loam
B-114	4234600	356860	29S	7W	SW27	Greenville Bench	gravelly loam
B-115	4236200	356180	29S	7W	NE28	Beaver	loam
B-116	4236190	357230	29S	7W	NW27	Beaver	very gravelly loam
B-117	4236870	358300	29S	7W	SW23	Black Ridge	loam
B-118	4237000	356650	29S	7W	SE21	Beaver	gravelly loam
B-119	4236520	354540	29S	7W	SE20	Beaver	loam
B-120	4236270	355260	29S	7W	SW21	Beaver	loam
B-121	4235291	355260	29S	7W	SW28	Beaver	loam
B-122	4237750	356480	29S	7W	NE21	Beaver	gravelly loam
B-123	4237890	356370	29S	7W	SE16	Beaver	loam
B-124	4237750	356930	29S	7W	NW22	Beaver	loam w/cobbles @ about 15"
B-125	4237598	357850	29S	7W	NE22	Beaver	loam
B-126	4245970	356870	28S	7W	NW27	Beaver	loam
B-127	4247600	356910	28S	7W	NW22	Beaver	loam, some gravels, hard
B-128	4242050	352930	29S	7W	NE6	Beaver	gravelly loam
B-129	4240410	352320	29S	7W	W7	Beaver	gravelly loam
B-130	4241610	351595	29S	7W	SE1	Beaver	gravelly loam
B-131	4240370	350650	29S	8W	SW12	Beaver	gravelly loam
B-132	4240498	349420	29S	8W	NW11	Beaver	gravelly loam (hard)
B-133	4240310	348100	29S	8W	SE10	Beaver	gravelly loam
B-134	4240609	345770	29S	8W	NW9	Adamsville	loam
B-135	4236270	350560	29S	8W	NW25	Beaver	loam
B-136	4235210	350095	29S	8W	NE35	Beaver	loam
B-137	4234498	350095	29S	8W	NE35	Greenville Bench	loam
B-138	4246800	351195	28S	8W	SW24	Beaver	loam, gravels underneath
B-139	4248030	349660	28S	8W	SE14	Beaver	loam
B-140	4245310	349760	28S	8W	E26	Beaver	loam
B-141	4245410	351120	28S	8W	E25	Beaver	loam
B-142	4243698	349520	28S	8W	E35	Beaver	loam
B-143	4242340	349950	29S	8W	NE2	Beaver	sandy loam
B-144	4243760	348280	28S	8W	NE34	Beaver	gravelly loam
B-145	4242370	348870	29S	8W	N3	Beaver	sandy loam
B-146	4235440	342270	29S	8W	SW30	Adamsville	loam with gravels
B-147	4236510	343170	29S	8W	NE30	Adamsville	loam

Table A1. *(continued)*

Sample Number	UTM Coordinates		Cadastral Coordinates			Quadrangle Name	Soil Texture
	Northing	Easting	Township	Range	1/4 Section		
B-148	4235080	343480	29S	8W	SE30	Adamsville	loam
B-149	4235900	343670	29S	8W	NW29	Adamsville	loam
B-150	4235690	345290	29S	8W	NW28	Adamsville	loam
B-151	4235010	345200	29S	8W	SE29	Adamsville	loam
B-152	4246930	349810	28S	8W	E23	Beaver	loam sandy
B-153	4245350	348480	28S	8W	E27	Beaver	sandy loam
B-154	4246950	348300	28S	8W	SE22	Beaver	sandy loam
B-155	4251780	347360	28S	8W	SE3	Gillies Hill	sandy loam
B-156	4253480	348550	28S	8W	E34	Gillies Hill	loam
B-157	4253360	351310	28S	8W	E36	Gillies Hill	loam
B-158	4251750	349450	28S	8W	SW2	Gillies Hill	loam
B-159	4250470	348100	28S	8W	NE10	Gillies Hill	sandy loam
B-160	4250200	350095	28S	8W	NE11	Gillies Hill	loam
B-161	4250200	351130	28S	8W	W12	Gillies Hill	sandy loam
B-162	4251810	351280	28S	8W	NW1	Gillies Hill	sandy loam
B-163	4251410	352950	28S	7W	SE6	Gillies Hill	sandy loam
B-164	4250040	353350	28S	7W	SE7	Gillies Hill	sandy loam
B-165	4239480	355090	29S	7W	NE17	Beaver	loam-gravel hardpan @ about 12"
B-166	4239498	354560	29S	7W	NE17	Beaver	loam gravel
B-167	4237790	354198	29S	7W	NW20	Beaver	loam
B-168	4237980	353720	29S	7W	SW17	Beaver	loam
B-169	4237370	353420	29S	7W	NW20	Beaver	loam
B-170	4236500	353350	29S	7W	SE19	Beaver	loam
B-171	4238405	351780	29S	8W	SE13	Beaver	gravelly loam
B-172	4237400	351780	29S	8W	NE24	Beaver	loam
B-173	4236700	351740	29S	8W	SE24	Beaver	loam
B-174	4236770	350560	29S	8W	SW24	Beaver	gravelly loam
B-175	4237397	350200	29S	8W	NW24	Beaver	loam
B-176	4236690	352785	29S	7W	SE19	Beaver	loam

***Table A2.** Radiometric data from the Beaver basin.*

Sample Number	Total Gamma (ppm)	K %	eU (ppm)	eTh (ppm)	eU/eTh	eU/K	^{222}Rn (pCi/L)
B-001	32.3	3.5	11.4	30.2	0.38	3.26	-
B-002	26.7	3.2	6.0	29.5	0.20	1.88	248.22
B-003	23.3	3.3	6.2	22.9	0.27	1.88	-
B-004	23.4	3.1	5.0	24.7	0.20	1.61	-
B-005	18.4	2.9	4.2	17.7	0.24	1.45	-
B-006	21.6	2.7	7.3	20.4	0.36	2.70	-
B-007	32.0	3.4	9.7	32.3	0.30	2.85	-
B-008	29.2	3.2	7.6	31.7	0.24	2.38	654.06
B-009	19.5	2.5	5.2	20.3	0.26	2.08	193.73
B-010	16.0	2.3	4.1	15.2	0.27	1.78	182.03
B-011	13.7	2.2	3.3	12.5	0.26	1.50	-
B-012	23.3	2.8	6.1	25.8	0.24	2.18	-
B-013	30.3	3.3	8.4	34.3	0.24	2.55	1865.18
B-014	31.1	3.8	8.3	33.1	0.25	2.18	
B-015	35.6	4.0	10.6	35.9	0.30	2.65	2367.50
B-016	30.0	3.3	8.5	30.1	0.28	2.58	-
B-017	20.1	2.7	5.2	18.0	0.29	1.93	181.90
B-018	13.9	2.3	3.1	11.9	0.26	1.35	97.40
B-019	12.9	2.1	3.2	9.7	0.33	1.52	208.26
B-020	23.6	2.8	6.7	23.7	0.28	2.39	-
B-021	34.2	3.6	10.8	34.0	0.32	3.00	2089.59
B-022	23.3	2.6	5.4	22.9	0.24	2.08	133.59
B-023	26.1	3.4	7.5	28.2	0.27	2.21	547.78
B-024	28.2	3.2	8.2	26.9	0.30	2.56	189.30
B-025	18.5	1.9	6.1	19.9	0.31	3.21	-
B-026	16.3	2.4	5.1	12.2	0.42	2.13	102.73
B-027	16.0	2.4	4.9	14.9	0.33	2.04	121.65
B-028	27.6	3.3	7.4	26.3	0.28	2.24	193.15
B-029	27.6	3.4	6.9	29.3	0.24	2.03	189.58
B-030	29.0	3.5	7.8	30.8	0.25	2.23	-
B-031	26.5	2.9	6.9	28.0	0.25	2.38	-
B-032	30.0	3.4	9.0	27.8	0.32	2.65	-
B-033	29.9	2.6	9.9	32.2	0.31	3.81	1426.95
B-034	31.6	3.4	10.9	30.2	0.36	3.21	968.30
B-035	22.9	2.8	6.1	23.1	0.26	2.18	333.93
B-036	33.6	4.0	9.5	34.5	0.28	2.38	142.43
B-037	24.9	2.6	6.8	27.0	0.25	2.62	757.81
B-038	27.5	3.6	8.6	23.8	0.36	2.39	471.07
B-039	15.9	2.4	4.7	12.7	0.37	1.961.96	-
B-040	30.6	3.3	9.6	32.4	0.30	2.91	555.43
B-041	19.3	2.7	6.1	16.5	0.37	2.26	283.64
B-042	18.0	2.5	5.8	15.2	0.38	2.32	131.47
B-043	16.6	2.4	4.2	16.1	0.26	1.75	-
B-044	18.0	2.5	5.9	16.0	0.37	2.36	99.52
B-045	21.9	2.9	6.7	18.8	0.36	2.31	-
B-046	21.6	3.2	6.6	20.5	0.32	2.06	-
B-047	23.5	3.4	6.3	22.0	0.29	1.85	183.50
B-048	13.2	1.8	3.1	11.7	0.27	1.72	147.65
B-049	25.0	2.9	6.3	25.3	0.25	2.17	323.29

Table A2. *(continued)*

Sample Number	Total Gamma (ppm)	K %	eU (ppm)	eTh (ppm)	eU/eTh	eU/K	^{222}Rn (pCi/L)
B-050	30.8	3.5	8.9	30.5	0.29	2.54	259.84
B-051	33.4	4.1	8.0	35.2	0.23	1.95	-
B-052	25.2	3.2	5.4	28.8	0.19	1.69	342.93
B-053	25.3	3.8	7.1	19.9	0.36	1.87	85.14
B-054	37.2	4.1	11.7	36.8	0.32	2.85	-
B-055	37.5	4.0	10.0	38.0	0.26	2.50	-
B-056	21.4	2.6	7.0	19.4	0.36	2.69	-
B-057	34.3	3.7	10.3	37.0	0.28	2.78	495.92
B-058	38.6	4.2	13.0	35.8	0.36	3.10	-
B-059	43.1	4.3	12.8	42.2	0.30	2.98	-
B-060	39.1	3.9	11.4	44.9	0.25	2.92	3555.99
B-061	27.0	3.0	6.8	28.8	0.24	2.27	317.51
B-062	28.4	3.3	8.2	28.4	0.29	2.48	294.32
B-063	28.4	3.1	8.7	29.3	0.30	2.81	312.83
B-064	29.0	3.3	6.5	35.8	0.18	1.97	313.55
B-065	29.1	3.3	7.7	32.4	0.24	2.33	332.19
B-066	35.4	3.5	9.1	45.6	0.20	2.60	1300.26
B-067	32.2	3.5	8.9	33.2	0.27	2.54	370.81
B-068	27.5	2.9	8.6	28.5	0.30	2.97	-
B-069	26.8	3.3	6.2	30.3	0.20	1.88	233.80
B-070	34.5	3.9	10.1	36.3	0.28	2.59	946.00
B-071	34.2	3.5	9.0	40.4	0.22	2.57	471.45
B-072	26.0	2.7	8.6	27.0	0.32	3.19	411.68
B-073	21.8	2.7	6.9	20.2	0.34	2.56	-
B-074	21.1	2.3	6.6	21.3	0.31	2.87	-
B-075	18.6	2.2	5.6	18.6	0.30	2.55	148.89
B-076	31.0	3.4	11.3	28.9	0.39	3.32	-
B-077	32.5	3.6	8.9	37.0	0.24	2.47	594.51
B-078	29.7	3.1	7.4	33.8	0.22	2.39	235.24
B-079	16.1	2.0	3.6	18.1	0.20	1.80	101.58
B-080	30.6	3.3	8.2	35.1	0.23	2.48	396.35
B-081	30.8	3.4	9.0	34.3	0.26	2.65	693.29
B-082	31.3	3.2	10.0	31.6	0.32	3.13	369.55
B-083	25.6	2.9	7.0	27.4	0.26	2.41	491.00
B-084	29.8	3.1	9.4	31.6	0.30	3.03	306.10
B-085	36.1	3.6	9.2	44.4	0.21	2.56	585.53
B-086	14.5	1.6	4.6	15.2	0.30	2.88	-
B-087	27.6	3.2	7.1	29.2	0.24	2.22	566.86
B-088	27.1	3.1	8.3	23.8	0.35	2.68	280.10
B-089	30.5	3.9	9.1	28.7	0.32	2.33	-
B-090	29.2	3.9	6.5	31.6	0.21	1.67	170.22
B-091	26.2	2.8	8.1	27.3	0.30	2.89	-
B-092	34.9	3.5	8.3	39.3	0.21	2.37	-
B-093	30.6	3.2	7.6	36.0	0.21	2.38	-
B-094	37.5	4.1	10.5	35.7	0.29	2.56	-
B-095	32.3	3.5	7.9	38.9	0.20	2.26	1439.08
B-096	29.5	3.4	8.6	31.5	0.27	2.53	666.18
B-097	30.1	3.2	8.5	35.8	0.24	2.66	-
B-098	25.7	2.8	7.3	26.6	0.27	2.61	217.19

Table A2. *(continued)*

Sample Number	Total Gamma (ppm)	K %	eU (ppm)	eTh (ppm)	eU/eTh	eU/K	^{222}Rn (pCi/L)
B-099	25.7	3.4	6.5	27.1	0.24	1.91	-
B-100	16.8	2.3	3.9	16.8	0.23	1.70	179.60
B-101	33.6	3.6	10.1	32.0	0.32	2.81	-
B-102	31.5	3.9	7.6	33.4	0.23	1.95	1482.99
B-103	35.2	3.7	10.6	35.0	0.30	2.86	-
B-104	28.9	3.1	8.4	27.8	0.30	2.71	1814.25
B-105	24.8	2.9	6.1	28.8	0.21	2.10	174.62
B-106	25.8	3.2	5.3	29.2	0.18	1.66	203.68
B-107	27.2	3.4	7.6	25.6	0.30	2.24	320.09
B-108	29.3	3.3	8.7	30.5	0.29	2.64	-
B-109	37.5	3.6	9.9	45.3	0.22	2.75	980.19
B-110	33.9	3.7	9.4	33.7	0.28	2.54	-
B-111	26.1	3.3	6.6	25.2	0.26	2.00	322.36
B-112	26.8	3.1	7.9	26.0	0.30	2.55	599.41
B-113	14.8	2.2	4.0	12.2	0.33	1.82	124.24
B-114	22.6	2.8	6.0	25.9	0.23	2.14	169.69
B-115	20.6	2.4	6.1	19.0	0.32	2.54	-
B-116	22.1	2.7	7.3	20.9	0.35	2.70	-
B-117	22.6	2.3	7.3	21.1	0.35	3.17	220.96
B-118	36.9	3.8	10.8	41.8	0.26	2.84	-
B-119	20.2	2.2	5.8	19.7	0.29	2.64	721.29
B-120	21.7	2.7	5.8	21.5	0.27	2.15	-
B-121	15.9	1.9	5.5	13.9	0.40	2.89	-
B-122	36.2	3.7	11.2	36.6	0.31	3.03	561.99
B-123	25.2	2.9	7.9	24.9	0.32	2.72	526.21
B-124	27.3	2.9	7.0	32.1	0.22	2.41	812.57
B-125	20.0	2.5	5.8	19.3	0.30	2.32	-
B-126	41.4	3.7	12.3	48.9	0.25	3.32	753.78
B-127	38.2	3.9	9.8	42.7	0.23	2.51	623.98
B-128	28.9	2.8	8.2	32.2	0.25	2.93	-
B-129	28.3	3.0	7.4	31.7	0.23	2.47	160.02
B-130	17.1	2.3	4.1	17.5	0.23	1.78	-
B-131	29.1	3.4	6.2	36.5	0.17	1.82	-
B-132	26.4	3.1	7.8	26.0	0.30	2.52	163.08
B-133	30.4	3.4	7.2	33.7	0.21	2.12	-
B-134	28.6	3.1	8.0	32.5	0.25	2.58	651.38
B-135	26.9	2.8	6.9	28.7	0.24	2.46	-
B-136	28.8	3.4	7.8	28.2	0.28	2.29	1379.19
B-137	13.2	1.4	4.3	11.1	0.39	3.07	104.50
B-138	24.3	3.1	6.0	24.8	0.24	1.94	-
B-139	24.4	2.7	7.1	25.6	0.28	2.63	-
B-140	22.4	3.5	6.2	19.2	0.32	1.77	217.60
B-141	27.5	3.2	6.4	31.3	0.20	2.00	339.17
B-142	23.6	2.9	6.4	23.8	0.27	2.21	440.61
B-143	25.0	2.7	10.2	22.5	0.45	3.78	-
B-144	33.6	3.8	9.3	37.9	0.25	2.45	-
B-145	28.7	3.4	7.2	33.0	0.22	2.12	394.71
B-146	22..6	3.3	5.9	20.5	0.29	1.79	146.42
B-147	21.1	3.0	5.6	20.6	0.27	1.87	50.53

Table A2.* *(continued)

Sample Number	Total Gamma (ppm)	K %	eU (ppm)	eTh (ppm)	eU/eTh	eU/K	^{222}Rn (pCi/L)
B-148	21.3	2.4	5.9	21.5	0.27	2.46	-
B-149	22.0	2.7	5.5	19.9	0.28	2.04	-
B-150	28.1	3.4	8.2	25.7	0.32	2.41	-
B-151	15.3	2.1	5.1	12.3	0.41	2.43	-
B-152	21.6	2.9	5.7	22.4	0.25	1.97	-
B-153	24.1	3.0	7.5	22.8	0.33	2.50	210.64
B-154	26.3	3.6	7.1	27.6	0.26	1.97	-
B-155	24.9	3.1	7.0	24.0	0.29	2.26	126.90
B-156	30.7	3.5	7.8	32.2	0.24	2.23	167.94
B-157	28.4	4.3	7.2	25.5	0.28	1.67	141.91
B-158	23.8	3.4	4.8	24.9	0.19	1.41	-
B-159	28.0	3.5	7.6	27.5	0.28	2.17	134.21
B-160	23.5	2.7	6.0	27.3	0.22	2.22	-
B-161	27.5	3.8	7.1	25.7	0.28	1.87	136.31
B-162	27.1	3.3	6.9	26.2	0.26	2.09	-
B-163	32.9	3.8	7.0	37.0	0.19	1.84	210.58
B-164	30.8	3.8	7.1	33.0	0.22	1.87	-
B-165	38.8	3.8	13.5	40.4	0.33	3.55	703.66
B-166	37.6	4.0	10.2	42.0	0.24	2.55	-
B-167	29.5	3.3	8.5	32.0	0.27	2.58	-
B-168	36.8	3.7	10.8	39.4	0.27	2.92	396.29
B-169	34.1	3.4	11.4	36.3	0.31	3.35	1934.97
B-170	30.4	3/0	9.8	31.6	0.31	3/27	-
B-171	25.6	3.1	7.4	23.7	0.31	2/39	315.85
B-172	35.0	3.9	10.9	37.2	0.29	2.79	1453.05
B-173	36.9	3.8	12.4	36.4	0.34	3.26	-
B-174	23.2	2.5	8.2	23.2	0.35	3.28	-
B-175	25.8	3.2	6.7	26.7	0.25	2.09	257.90
B-176	32.1	3.2	9.8	35.9	0.27	3.06	-

K = *potassium-40*
eU = *equivalent uranium-238*
eTh = *equivalent thorium-232*
eU/eTh = *ratio of eU and eTh*
^{222}**Rn** = *radon-222 (soil-gas radon)*