Solomon

RADON-HAZARD POTENTIAL - SOUTHERN ST. GEORGE BASIN, WASHINGTON COUNTY, AND OGDEN VALLEY, WEBER COUNTY, UTAH

UGS Special Study 87

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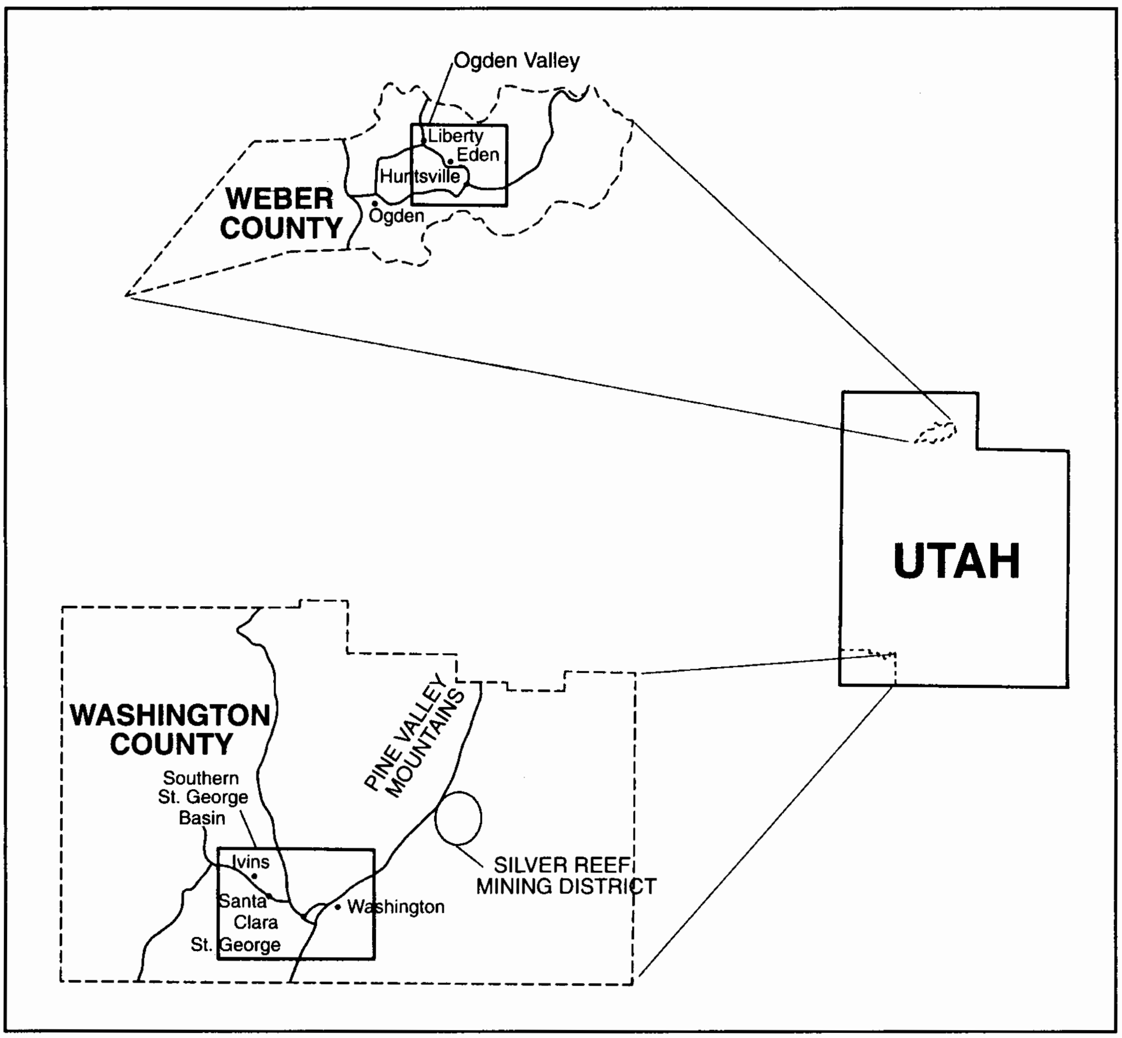
by
B. J. Solomon



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by
Barry J. Solomon

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

formula Rn = 52.8 U + 7.5, where Rn is the concentration of soil-gas radon in pCi/L and U is the concentration of uranium in ppm. The sample size is 82. At the 99 percent confidence level, the correlation coefficient of 0.415 exceeds the threshold value of 0.283. Similar data pairs in Ogden Valley do not correlate as well, however. This may be caused by either inhomogeneities in the soil between material at the ground surface tested for uranium and material at shallow depth tested for soil-gas radon, or atmospheric contamination of soil-gas samples.

INTRODUCTION

In 1988, in response to growing national concern over the threat of radon gas, Congress enacted Title III, Indoor Radon Abatement Act (IRAA), as an amendment to the Toxic Substances Control Act. The IRAA has the goal of reducing public health risks from radon gas by rendering air within buildings in the United States free of radon. Section 306 of the IRAA, the State Indoor Radon Grant (SIRG) Program, authorizes the U.S. Environmental Protection Agency (EPA) to provide grants to states to support the development and implementation of state radon assessment and mitigation programs. A principal SIRG activity of the Utah Geological Survey (UGS) is to identify areas throughout the state that have geologic factors conducive to elevated indoor-radon levels, and assess the radon-hazard potential of these areas. Indoor-radon levels measured during a 1988 statewide survey conducted by the Utah Division of Radiation Control (UDRC) indicate that high levels of indoor radon occur locally in the southern St. George basin and Ogden Valley (Sprinkel and Solomon, 1990). The U.S. Environmental Protection Agency (1992) recommends reduction of indoor radon when levels are high, exceeding 4 picocuries per liter (pCi/L) (148 Becquerels per cubic meter [Bq/m^3]). The number of samples in the southern St. George basin and Ogden Valley indoor-radon surveys, however, was insufficient to accurately delineate all areas where elevated levels of radon may occur. An evaluation of geologic factors conducive to elevated indoor-radon levels was therefore undertaken during the second year of the multi-year SIRG program to more accurately delineate the hazard in these areas. The mapped hazard distribution can then be used to concentrate testing in buildings more likely to have elevated levels, and guide the use of radon-resistant new construction.

The southern St. George basin is centered on the confluence of the Virgin and Santa Clara Rivers, in Washington County, southwestern Utah (figure 1). The area includes the cities of St. George (including the Bloomington and Middleton areas), Santa Clara, and Washington, and the town of Ivins (figure 2). The population of the area has grown dramatically in the past two decades, from 9,285 in 1970 to 36,875 in 1990, and population growth is expected to continue with an estimated population of 46,660 by the year 2000 (U.S. Department of Agriculture and Utah Department of Natural Resources, 1990).

Ogden Valley is drained by three forks of the Ogden River, in Weber County, northeastern Utah (figure 1). River flow is regulated by the earth-fill dam that impounds Pineview Reservoir in the southwestern part of the valley, which includes the city of Huntsville and the unincorporated communities of Eden and Liberty (figure 3). Population of the valley has grown significantly, although not as rapidly as that of the southern St. George basin. The population of Ogden Valley increased from 1,960 in 1970 (Weber County Planning Commission, 1985) to

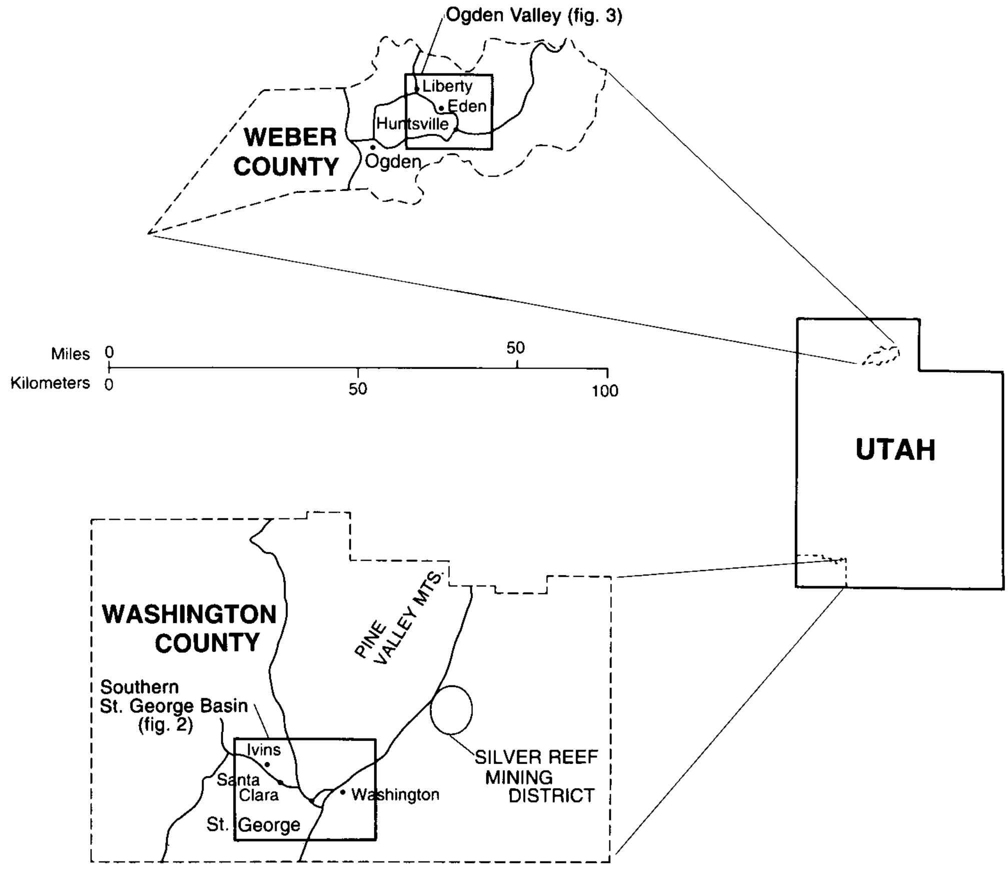


Figure 1. *Location of the southern St. George basin and Ogden Valley. See figures 2 and 3 for geographic details.*

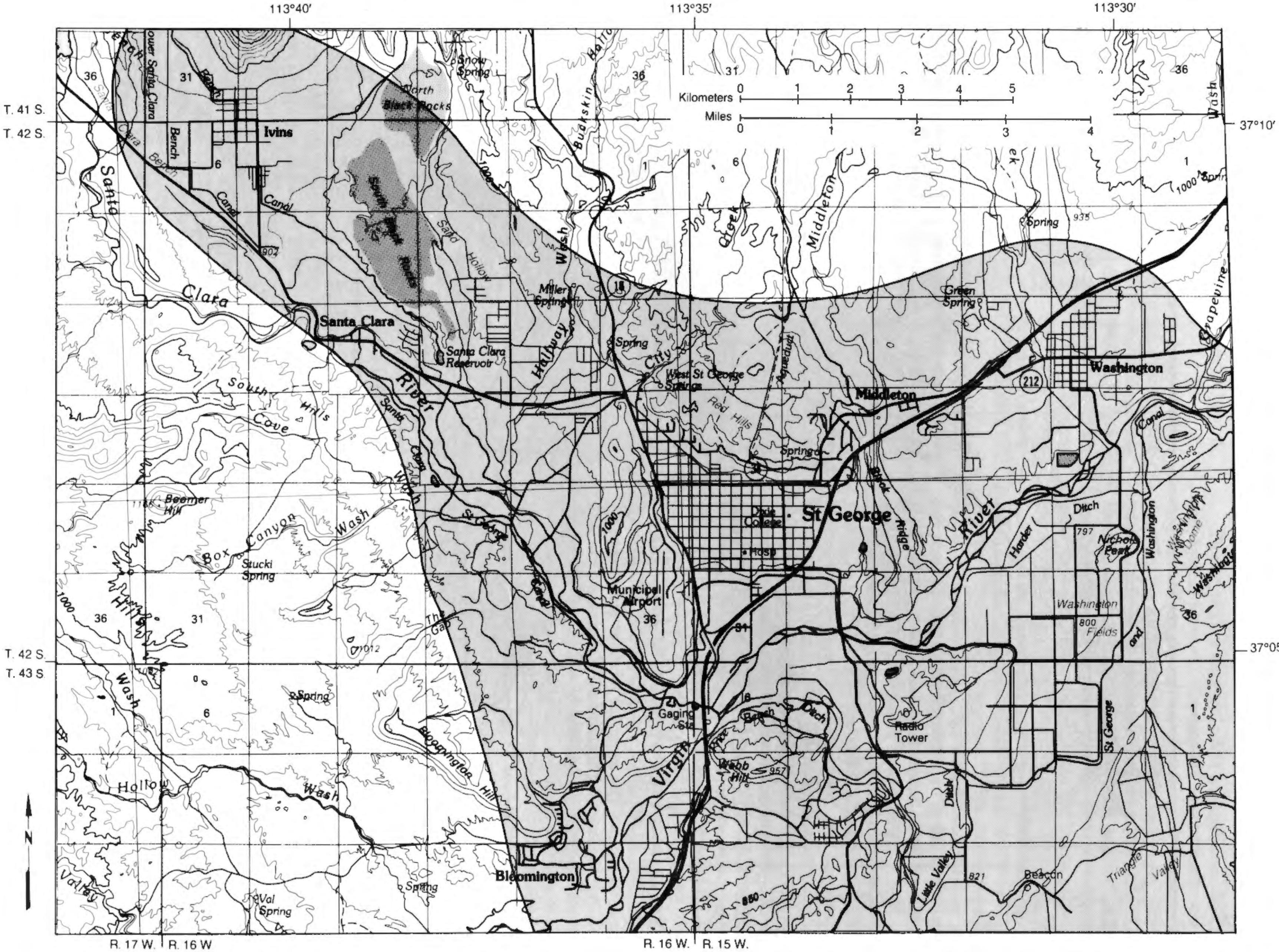


Figure 2. Map of locations in the southern St. George basin discussed in text. The study area is shaded. Base from U.S. Geological Survey St. George 30 x 60 minute topographic quadrangle map (1980). Contour interval 50 meters (160 ft).

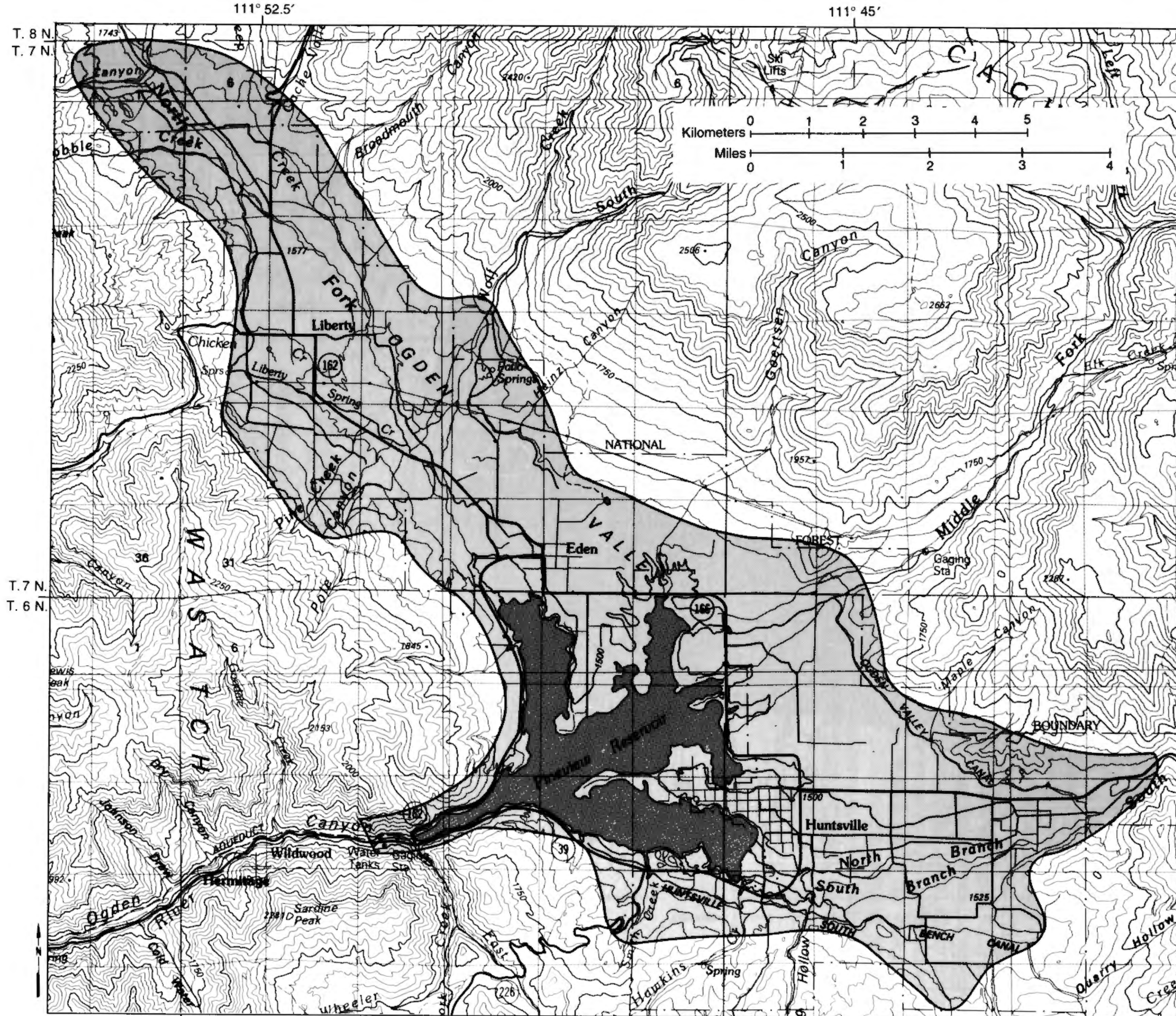


Figure 3. Map of locations in Ogden Valley discussed in text. The study area is shaded. Base from U.S. Geological Survey Ogden 30 x 60 minute topographic quadrangle map (1986). Contour interval 50 meters (160 ft).

3,954 in 1990 (Sherri Sillitoe, Weber County Planning Commission, verbal communication, 1992), and population is projected to be 5,500 by the year 2000 (Wasatch Front Regional Council, in Weber County Planning Commission, 1985).

The primary geologic prerequisite for elevated indoor-radon levels is uranium in the soil around building foundations. The airborne radiometric survey completed under the National Uranium Resource Evaluation (NURE) program provides an excellent data base for the regional delineation of areas of high surface uranium concentrations, and can be used as an indicator of areas that have the potential for indoor-radon hazards (Duval, 1991). NURE data, however, were collected on a coarse scale, generally with 5-kilometer (3-mi) line spacing and 10-kilometer (6-mi) spacing on tie lines.

Although the NURE data indicate that surface uranium concentrations in the southern St. George basin are less than 2 parts per million (ppm) (Geodata International, 1979), insufficient to contribute to a significant radon hazard, a more detailed surface evaluation might indicate that localized areas of higher concentrations exist. The presence of Triassic and Jurassic bedrock in the southern St. George basin, which serves as host rock to uranium deposits elsewhere in southern Utah, suggests that elevated uranium levels may be present but in small areas that were undetected in the NURE survey because their size was beyond the survey resolution. The NURE data show surface uranium concentrations as high as 4.5 ppm on the margin of Ogden Valley (EG&G Geometrics, 1979; Madson and Reinhart, 1982). These airborne anomalies generally coincide with outcrops of Tertiary silicic tuff, a lithology commonly associated with elevated uranium levels, although specific correlations between geologic units and NURE radiometric data are not reliable at the scale of the airborne survey. Ground-based surveys of surface uranium concentrations using a gamma-ray spectrometer with closely spaced measurement stations were therefore undertaken in both study areas to improve upon the resolution obtained by the airborne surveys.

Other geologic factors contribute to radon hazards. Pore water in foundation soils effectively traps radon and, if pores are saturated, inhibits radon migration (Tanner, 1980). Conversely, low soil-moisture content above the ground-water table facilitates diffusion of radon to the air and to buildings (Lindmark and Rosen, 1985). The rate of radon migration is also a function of soil permeability. Permeable soils with open pathways enable radon migration (Schery and Siegel, 1986). For this study, the depth to ground water and soil permeability were estimated from existing data and, when combined with surficial uranium concentrations, were used to derive maps showing relative indoor-radon-hazard potential in the southern St. George basin and Ogden Valley. Radon in soil gas, measured by radon emanometry, was then compared to the map of relative hazard potential, and serves as an independent check of the map. Radon in soil gas was not used to assess the hazard potential because soil-gas radon is not a primary factor, but is derived from the primary factors of uranium concentrations, ground-water levels, and soil permeability. Additional indoor-radon levels were also measured for comparison with mapped hazard potential. Preliminary results of this study for the southern St. George basin were reported in Solomon (1992).

SAMPLING METHODS

Three types of radiometric data were collected during ground geophysical surveys. Gamma-ray spectrometry was used to measure soil concentrations of radioactive elements including uranium, the parent material of radon in soil gas. Radon emanometry was used to measure levels of soil-gas radon available for migration into buildings. Alpha-track detectors (ATDs) were used to measure indoor-radon levels. One radon isotope, ^{222}Rn, is the most significant contributor to the indoor-radon problem, and forms as a product in the ^{238}U decay series. References to radon and uranium in this paper refer to these isotopes. Another radon isotope, ^{220}Rn, is a significant contributor in areas of high thorium concentration (Stranden, 1984), and forms as a product in the ^{232}Th decay series. Accurate measurement of ^{220}Rn was not possible with the equipment used in this study, but relative levels of this isotope may be estimated using concentrations of ^{232}Th measured by gamma-ray spectrometry.

Concentrations of gamma-emitting elements in soil were determined using an Exploranium GR-256 portable gamma-ray spectrometer, with a GPS-21 detector. The detector assembly contains a 3 x 3 inch (7.5 x 7.5 cm) sodium-iodide crystal with an integral bi-alkali photomultiplier tube. Values for total gamma, potassium-40 (K), equivalent uranium-238 (eU), and equivalent thorium-232 (eTh) were collected. Peak energy levels used for measurement were 1.46 million electron volts (MeV) for K (K has only one emission line), 1.76 MeV for eU (corresponding to Bismuth-214), and 2.62 MeV for eTh (corresponding to Thalium-208). The spectrometer was calibrated at the factory using calibration pads. A survey was conducted using a station spacing of about 0.5 miles (0.8 km); exact spacing was affected by access. Measurement on roadbeds was avoided to reduce the possibility of masking by foreign materials. The detector was held at a height of about 2 feet (0.6 m) to correct for the influence of local topography and uranium anomalies. Spectrometer readings were collected at 194 sites in the southern St. George basin (figure 4) and 130 sites in Ogden Valley (figure 5).

Radon concentrations in soil were determined using an RDA-200 portable alpha-sensitive scintillometer manufactured by EDA Instruments. Scintillator cells are coated with a phosphor sensitive to alpha particles in the 5.5 MeV range emitted by the decay of isotopic radon in its gas phase. The individual scintillator cells were calibrated using the Geotech, Inc. alpha-track chamber in Grand Junction, Colorado, to determine the efficiency of the phosphor material coating the cells. The scintillometer was calibrated at the factory, and the unit's sensitivity was checked against a standard test cell with a known count rate to account for gradual changes in the sensitivity of the photomultiplier tube.

The soil-gas sampling system consisted of a 0.4-inch (1-cm) diameter, hollow steel probe that was placed into a hole made by pounding a rod of slightly smaller diameter into the soil. The probe was inserted to a depth of 26 inches (65 cm), and samples were collected from perforations in the lower 6 inches (15 cm) of the probe. This depth enabled samples to be collected below the root zone for grasses, within the lower B or upper C soil horizons, and close to sampling depths which provided consistent and reproducible data to other researchers (Reimer and

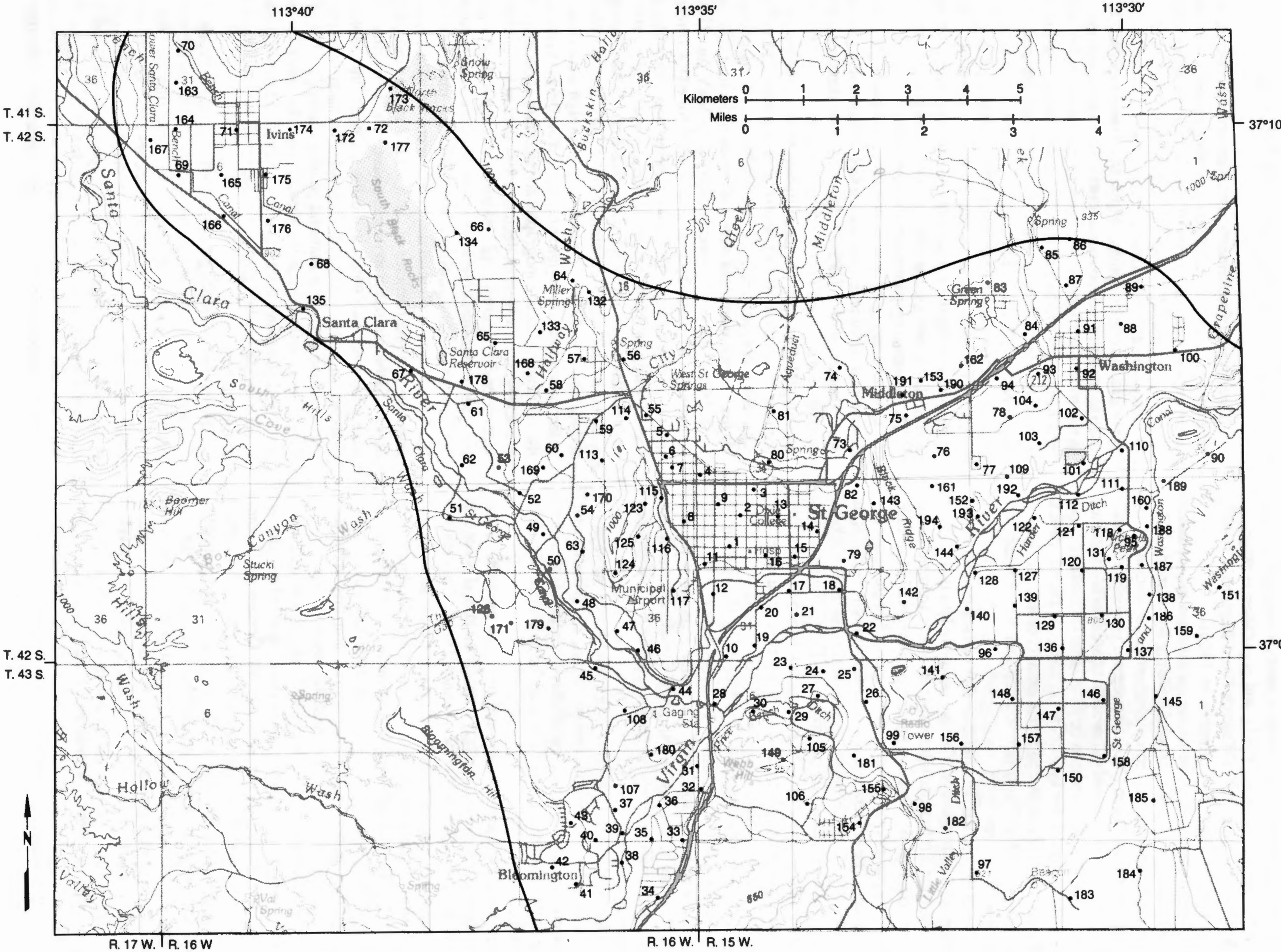


Figure 4. Sample locations for gamma-ray spectrometry and radon emanometry, southern St. George basin.

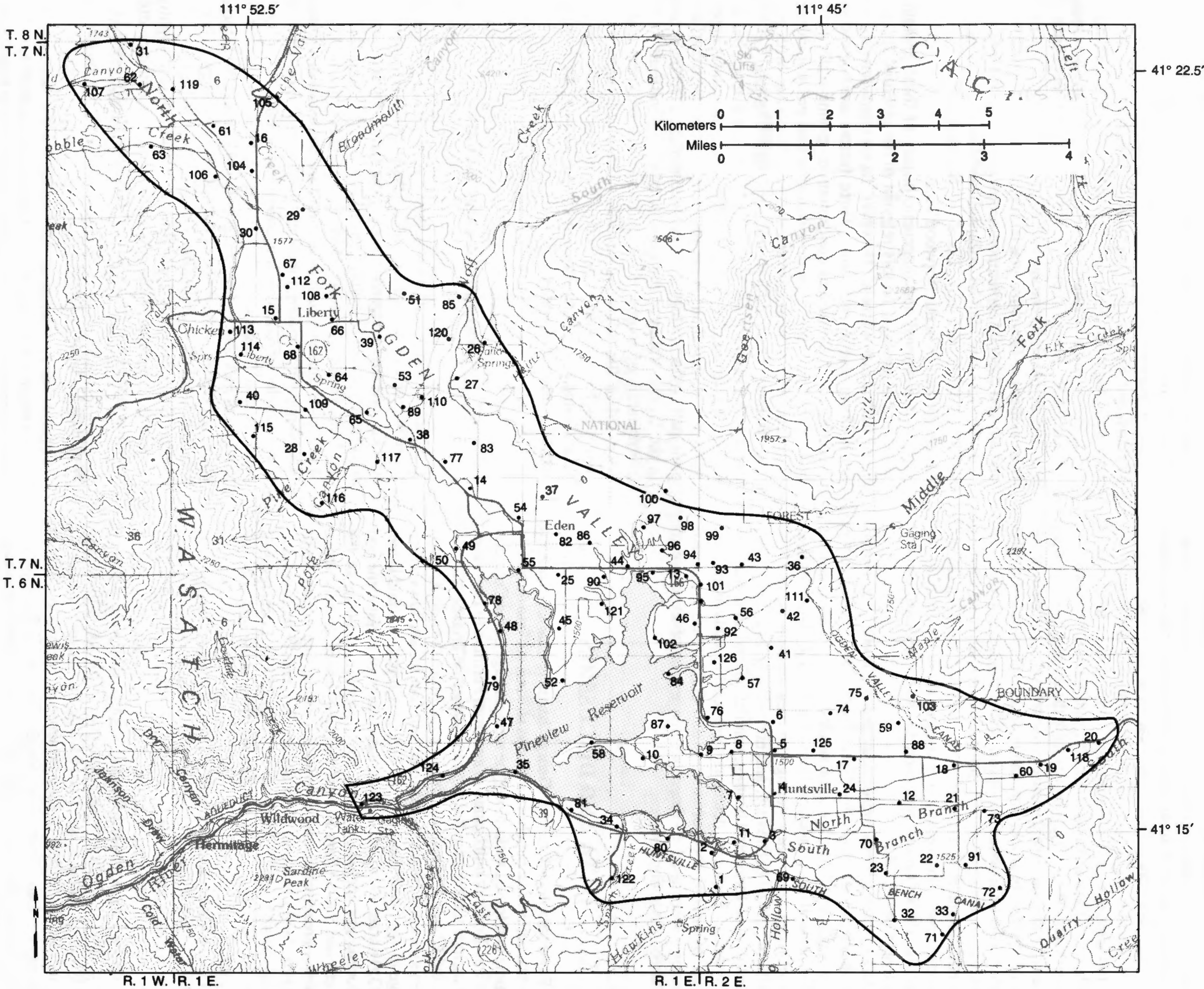


Figure 5. Sample locations for gamma-ray spectrometry and radon emanometry, Ogden Valley.

Bowles, 1979; Hesselbom, 1985; Reimer and Gundersen, 1989). A hand-held evacuation pump was used for 60 seconds to purge the probe of ambient air and pump soil gas into the scintillator cells. Samples were collected from vacant lots and undeveloped, non-irrigated land. Soil-gas samples were collected from 82 of the 194 sites at which spectrometer readings were taken in the southern St. George basin (figure 4), and 80 of the 130 sites in Ogden Valley (figure 5). Samples from the remainder of the sites were not collected either because probe refusal occurred in dense soil or shallow bedrock; dry, sandy soils collapsed before the probe could be inserted; or spectrometer readings were taken merely to fill data gaps and, therefore, soil-gas sample collection was not attempted. A delay time of 2 to 3 hours between sample collection and measurement was used to allow for decay of the short-lived ^{220}Rn isotope and radon daughters, and ensure measurement of only ^{222}Rn.

Indoor-radon levels were measured for a one-year period with ATDs manufactured by Alpha Spectra, Inc., placed in the lowest occupied living space of single-family, owner occupied homes, as well as in classrooms of two schools in Ogden Valley. School-room occupancy during the measurement period was typical of normal occupancy, and normal operating procedures were followed for central heating, ventilation, and air conditioning systems. Duplicate detectors were used to analyze the precision of school measurements, and field blanks (control detectors) were used to determine the extent of exposure to extraneous radiation sources.

DATA AND DISCUSSION

Physiography of the St. George basin is characterized by cuestas, buttes, and benches formed as streams cut into the gently dipping and folded rocks along the western edge of the Colorado Plateau. Bedrock units range in age from Permian to Holocene, and include the Permian Kaibab Limestone; the Triassic Moenkopi and Chinle Formations; the Jurassic Moenave and Kayenta Formations and Navajo Sandstone; and four basalt flows which range in age from Pliocene to Holocene (Christenson and Deen, 1983; Hintze, 1988). Unconsolidated units of Pleistocene and Holocene age include channel and floodplain deposits of the Virgin and Santa Clara Rivers, elevated terrace gravels above modern stream channels, alluvial-fan sands, and eolian sands derived chiefly from the Moenave and Kayenta Formations and Navajo Sandstone (Christenson and Deen, 1983). Local residual deposits of clay and silt are derived from shale and siltstone bedrock.

Ogden Valley is a back valley which developed during uplift of the Wasatch Range (Gilbert, 1928). As the range was uplifted on the western edge of the Middle Rocky Mountains, basin-and-range block faulting encroached. The valley was downdropped and crossed by westward-flowing streams that were superimposed upon it as they eroded canyons. Bedrock units on the valley margin range in age from Middle Proterozoic to Eocene, and include the Middle or Late Proterozoic Formation of Perry Canyon; the Late Proterozoic Maple Canyon, Kelly Canyon, Caddy Canyon, Inkom, Mutual, and Browns Hole Formations; the Cambrian Geertsen Canyon Quartzite; the Cambrian Ute, Blacksmith, and Maxfield Limestones; the Cambrian Bloomington Formation; the Cambrian Nounan Dolomite; the Mississippian Gardison and Deseret Limestones; the Mississippian Humbug Formation; the Upper Cretaceous (?) to Eocene Wasatch and Evanston (?) Formations, undivided; and the Eocene and Oligocene Norwood Tuff (Coody, 1957; Crittenden, 1972; Sorensen and Crittenden, 1979; Crittenden and Sorensen, 1985a, 1985b; Lowe, in preparation). Unconsolidated units of Pleistocene and Holocene age include lacustrine deposits of Lake Bonneville; pre-lacustrine glacial and alluvial deposits; deltaic and alluvial deposits contemporaneous with lacustrine deposits; and post-lacustrine alluvial, colluvial, landslide, and talus deposits (Lowe, in preparation). Local residual deposits of clay and silt are derived from the Norwood Tuff.

The depositional and diagenetic history of these geologic units control geologic factors relevant to the potential for elevated indoor-radon levels. However, factor characteristics are not uniform within each unit. Three factors are mapped on overlays: surficial-uranium concentration, ground-water level, and soil permeability. The distribution of soil-gas and indoor-radon concentration are also mapped for comparison with geologic factors. Other radiometric data, including total gamma count and concentrations of K and eTh, are not mapped but are statistically summarized in table 1. Total gamma count is higher in Ogden Valley than in the southern St. George basin, and principally reflects a higher concentration of the eTh component in the Ogden Valley. The eU/eTh ratio is significant to the interpretation of source rocks for U-enriched sediment and is discussed in the following section. The K concentration is similar in the two study areas, and no particular significance can be attributed to it. Data for each sample location are listed in appendix tables A-1 and A-2.

Uranium Concentrations

Uranium concentrations less than 2 ppm are typically associated with indoor-radon levels of less than 4 pCi/L (148 Bq/m^3), whereas uranium concentrations greater than 3 ppm are more consistently associated with higher indoor-radon levels (Meussig, 1988; Duval and others, 1989; Peake and Schumann, 1991). When trace elements such as uranium are randomly distributed in a homogenous material their distribution is lognormal, with many samples of relatively low concentration but a few of high concentration (Rogers, 1964). However, local enrichment of uranium in rock and soil occurs in both the southern St. George basin and Ogden Valley, and is controlled by geology. Therefore, the distribution of uranium concentrations in the two areas (figures 6 and 7) is only approximately lognormal, and slightly skewed from normal. Skewness of uranium-concentration distribution in the two areas is 1.0 and 0.6, respectively (table 1).

Southern St. George Basin

The mean concentration of uranium in the southern St. George basin is 2.3 ppm, with a standard deviation of 1.0. The most extensive area of uranium concentrations less than 2 ppm, including the lowest measured concentration of 0.2 ppm north-

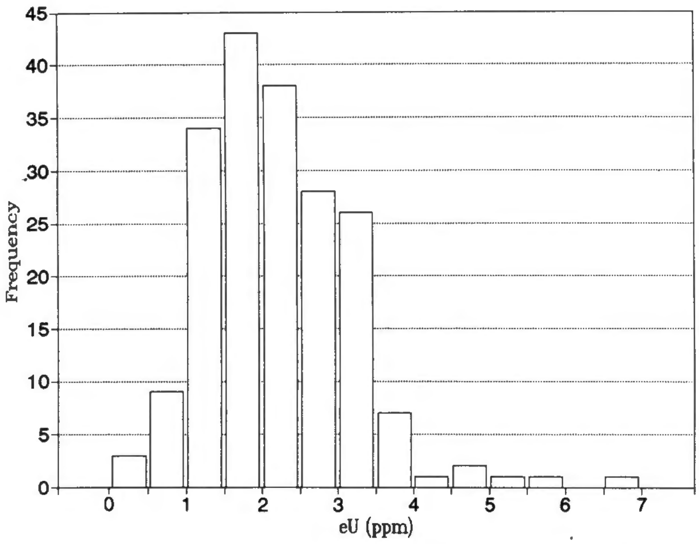


Figure 6. *Histogram of uranium concentrations from gamma-ray spectrometry in the southern St. George basin.*

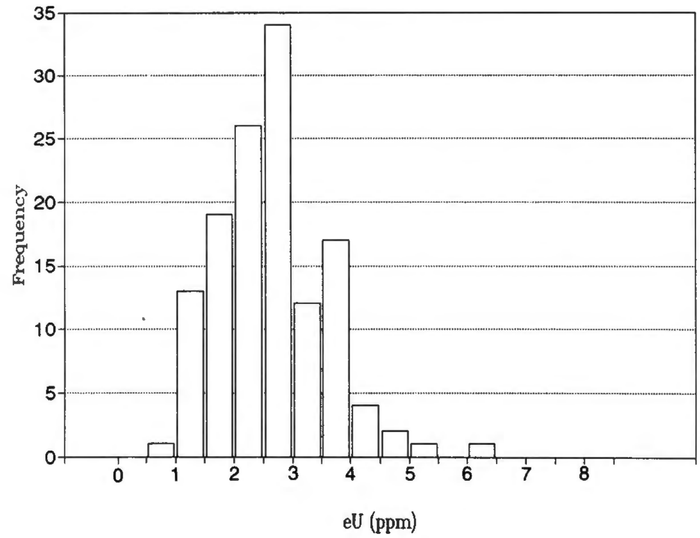


Figure 7. *Histogram of uranium concentrations from gamma-ray spectrometry in Ogden Valley.*

Table 1.
Statistical summary of radiometric data. SG - southern St. George basin, OV - Ogden Valley

	Total count (ppm)		K (%)		eU (ppm)		eTh (ppm)		eU/eTh		Soil-gas Rn (pCi/L)		Indoor Rn (pCi/L)	
Study area	**SG**	**OV**	**SG**	**OV**	**SG**	**OV**	**SG**	**OV**	**SG**	**OV**	**SG**	**OV**	**SG**	**OV**
Sample Size	194	130	194	130	194	130	194	130	194	130	82	80	10	36
Mean	9.1	11.6	1.4	1.5	2.3	2.7	5.9	10.5	0.45	0.27	134	388	1.9	5.2
Variance	7.5	13.0	0.3	0.2	0.9	0.8	6.4	13.5	0.12	0.01	12,262	151,918	3.3	25.7
Standard Deviation	2.7	3.6	0.5	0.5	1.0	0.9	2.5	3.7	0.34	0.09	111	390	1.8	5.1
Skewness	0.2	0.4	0.6	0.4	1.0	0.6	0.7	0.6	7.08	0.77	4	2	8.7	259.6
Minimum	2.4	5.9	0.1	0.6	0.2	0.8	1.1	4.6	0.09	0.11	22	0	0.0	1.2
Median	8.9	11.7	1.4	1.5	2.1	2.6	5.4	10.9	0.40	0.26	108	325	1.2	2.9
Maximum	17.5	23.8	3.7	3.0	6.7	6.1	13.5	25.7	4.19	0.57	878	2,269	6.2	23.8

west of Washington, occurs in the northern portion of the study area (figure 8). This broad band of low uranium concentrations is underlain by eolian fine sand derived from Triassic and Jurassic sandstone. The sandstone is exposed just to the north, and the few radiometric readings in it are similar in magnitude to readings in eolian material. Uranium concentrations are also commonly low in Pleistocene basalt west of St. George (West Black Ridge) and Holocene basalt northeast of Santa Clara (South Black Rocks). Low to moderate concentrations in basalt are consistent with concentration of uranium in late-stage differentiation of igneous melts (Nielson and others, 1991).

Moderate uranium concentrations are common in Pleistocene basalt east of St. George (Middleton Black Ridge), Pliocene basalt west of St. George (West Black Ridge), and unconsolidated Quaternary alluvium near Bloomington. Uranium concentrations in these areas are generally between 2 and 3 ppm, but range from 1.2 to 3.3 ppm. The alluvium near Bloomington consists of gravelly and silty sand derived from shale and sandstone of the Moenkopi and Chinle Formations, which bound it to the northwest.

The highest uranium concentrations occur in hills west of the Santa Clara River and southeast of Santa Clara, alluvium of the Virgin River floodplain, the Washington Fields area southeast of St. George, and scattered Triassic bedrock outcrops throughout the area. Uranium concentrations in these areas are generally between 3 and 4 ppm, with a maximum of 6.7 ppm near Washington Dome. Elevated uranium levels in the hills west of the Santa Clara River are in shale, mudstone, and associated residual soil of the Petrified Forest Member of the Chinle Formation. Fine-grained bentonitic rocks of the Petrified Forest Member overlie coarse-grained, channel sandstone and conglomerate of the Shinarump Member of the Chinle Formation, and underlie shale, siltstone, and sandstone of the Moenave Formation. Some uranium in the Petrified Forest Member has reportedly been mobilized by oxidizing solutions and moved to reducing sites in these adjacent units. The Shinarump Member is a host for sandstone-uranium deposits in the Colorado Plateau of southeastern Utah (Thamm and others, 1981). The Moenave Formation is the host for silver-rich sandstone-uranium deposits in the Silver Reef mining district 15 miles (24 km) northeast of St. George (Proctor and Brimhall, 1986) (figure 1).

Elevated uranium levels in the Virgin River floodplain and areas underlain by the Petrified Forest Member are associated with low eU/eTh ratios, generally from 0.2 to 0.4 (figure 9). Low ratios reflect source-rock chemistry. A significant component of the floodplain alluvium was derived from Miocene monzonite to quartz monzonite porphyry in the Pine Valley Mountains 20 miles (32 km) north of St. George (Cook, 1957; Grant, 1991). Bentonite in the Petrified Forest Member is the result of devitrification and alteration of tuffaceous material, and volcanic detritus in this unit has been described in petrographic studies (Stewart and others, 1972). These igneous lithologies are typically enriched in thorium with respect to uranium. In contrast, eU/eTh ratios are higher, generally between 0.5 and 1.0 but sometimes greater, in Washington Fields and the vicinity of scattered Triassic bedrock outcrops elsewhere. This suggests uranium enrichment from non-igneous processes.

Individual populations of data points, based on geologic units and sediment-source areas, are reflected on the probability diagram for uranium concentrations (McCammon, 1980) (figure 10). The inflection points in the slope of the data separate distinct data sets. Two inflection points are easily recognized. The first ("1" on figure 10), at somewhat less than 2 ppm, separates eolian sediments, and Pleistocene and Holocene basalt flows, from Quaternary alluvium and Pleistocene basalt with higher uranium concentrations. The second inflection point ("2" on figure 10), at somewhat less than 4 ppm, separates the latter units from isolated samples with the highest uranium concentrations measured near scattered Triassic bedrock outcrops. These highest uranium concentrations are found in the same samples with the highest eU/eTh ratios, and support the idea of uranium enrichment by non-igneous processes.

Ogden Valley

The mean concentration of uranium in Ogden Valley, 2.7 ppm with a standard deviation of 0.9, is somewhat higher than in the southern St. George basin. The most extensive area in Ogden Valley of uranium concentrations less than 2 ppm, including the lowest measured concentration of 0.8 ppm east of Huntsville, occurs in the southeastern portion of the study area (figure 11) near the mouths of the South and Middle Forks of the Ogden River. Here, low uranium concentrations are associated with sandy to cobbly silt of fluvial origin derived from Precambrian conglomerate and quartzite and Tertiary conglomerate and sandstone. The bedrock lies to the east and northeast, and airborne-radiometric data (EG&G Geometrics, 1979; Madson and Reinhart, 1982) indicate that bedrock uranium levels are similar in magnitude to those of the fluvial material. Isolated low uranium concentrations were also measured elsewhere in Ogden Valley, but these are associated with natural random variations and not with specific lithologies.

Moderate uranium concentrations occur in unconsolidated Quaternary alluvium in the central and southern part of the valley, undivided alluvium and colluvium east of Liberty, and nearshore Lake Bonneville deposits east of Huntsville. Uranium concentrations in these areas are generally between 2 and 3 ppm. The alluvial and lacustrine deposits are texturally similar to unconsolidated material in areas of low uranium concentrations, but the colluvium consists of gravelly sand derived from Precambrian and Cambrian quartzite outcrops upslope. The colluvial deposits are commonly near, or form a thin veneer on, the Tertiary Norwood Tuff.

The highest uranium concentrations are in unconsolidated Quaternary alluvial-fan, fluvial, and lacustrine deposits of northwestern Ogden Valley; and fluvial and lacustrine deposits in central and southern Ogden Valley. Uranium concentrations in these areas are generally between 3 and 5 ppm, with a maximum of 6.1 ppm south of Huntsville. Elevated uranium levels in these unconsolidated materials are present near outcrops of the Norwood Tuff and, in northwestern Ogden Valley, Precambrian Formation of Perry Canyon. High concentrations in the silicic Norwood Tuff are consistent with concentration of uranium in late-stage differentiation of igneous melts (Nielson and others, 1991). High concentrations in the Formation of Perry Canyon are likely associated with three lithologies: low-grade metamorphic rocks, carbonaceous mudstone, and diamictite derived from older granitic rocks. Clay-rich metasedimentary rocks are typically uraniferous, and carbonaceous mudstones concentrate uranium during deposition in a euxinic sedimentary environment (Otton, 1988). Lithologically similar diamictites have been associated with elevated levels of uranium near radon-hazard areas along the Wasatch Front (Solomon and others, 1994).

Elevated uranium levels and higher eU/eTh ratios generally coincide in Ogden Valley, but ratios are lower than in the southern St. George basin. Mean ratio values are 0.45 in the southern St. George basin, but only 0.27 in Ogden Valley (table 1) where individual values rarely exceed 0.40 (figure 12). The low ratio values in Ogden Valley are consistent with uranium enrichment from igneous processes. The relative lack of ratio variability in Ogden Valley, variance with respect to the mean ratio value is 0.12 in the southern St. George basin but only 0.01

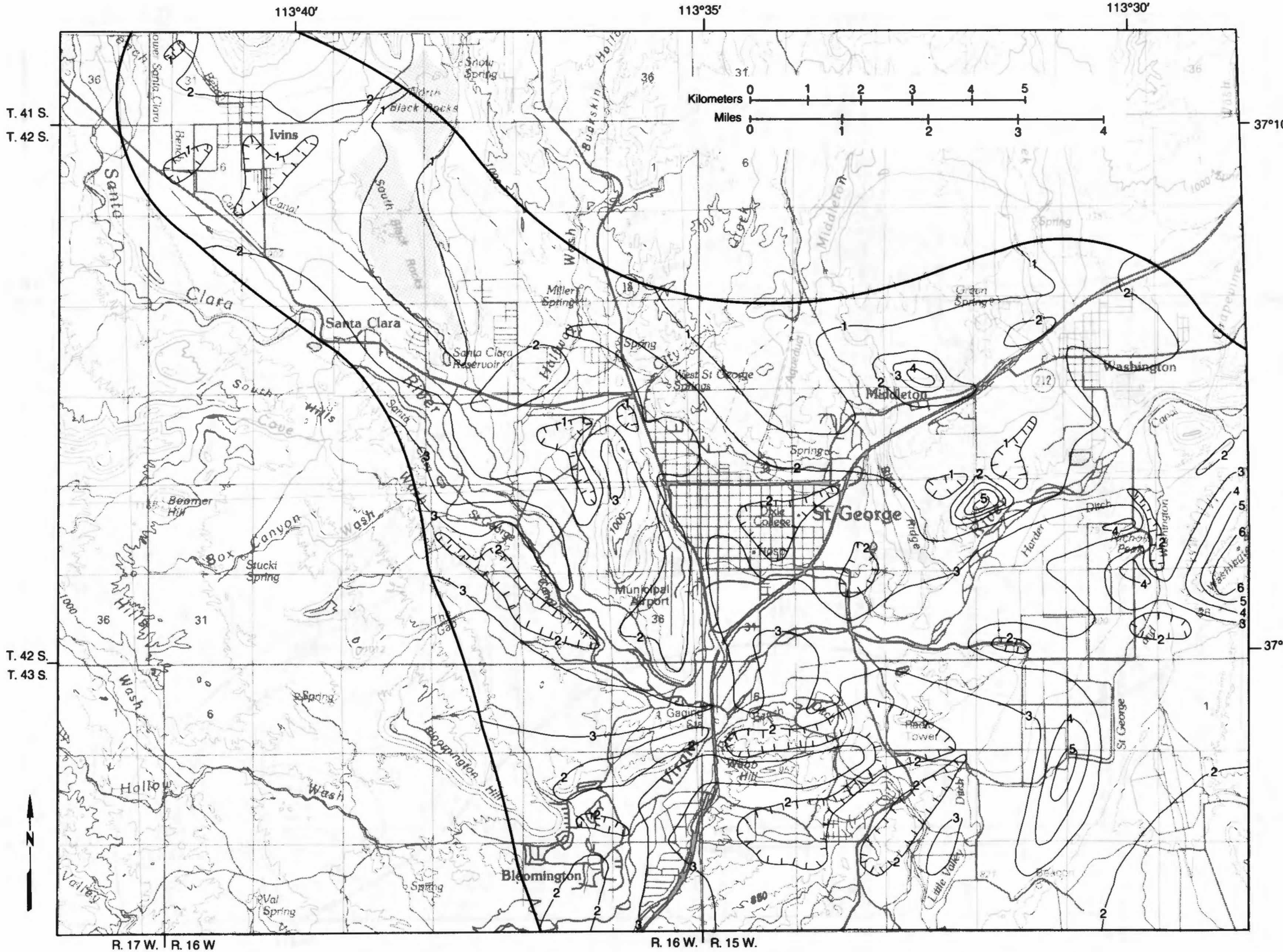


Figure 8. Uranium concentrations from gamma-ray spectrometry in the southern St. George basin. Contour interval 1 ppm. Sample locations are shown on figure 4; sample values are listed in table A-1.

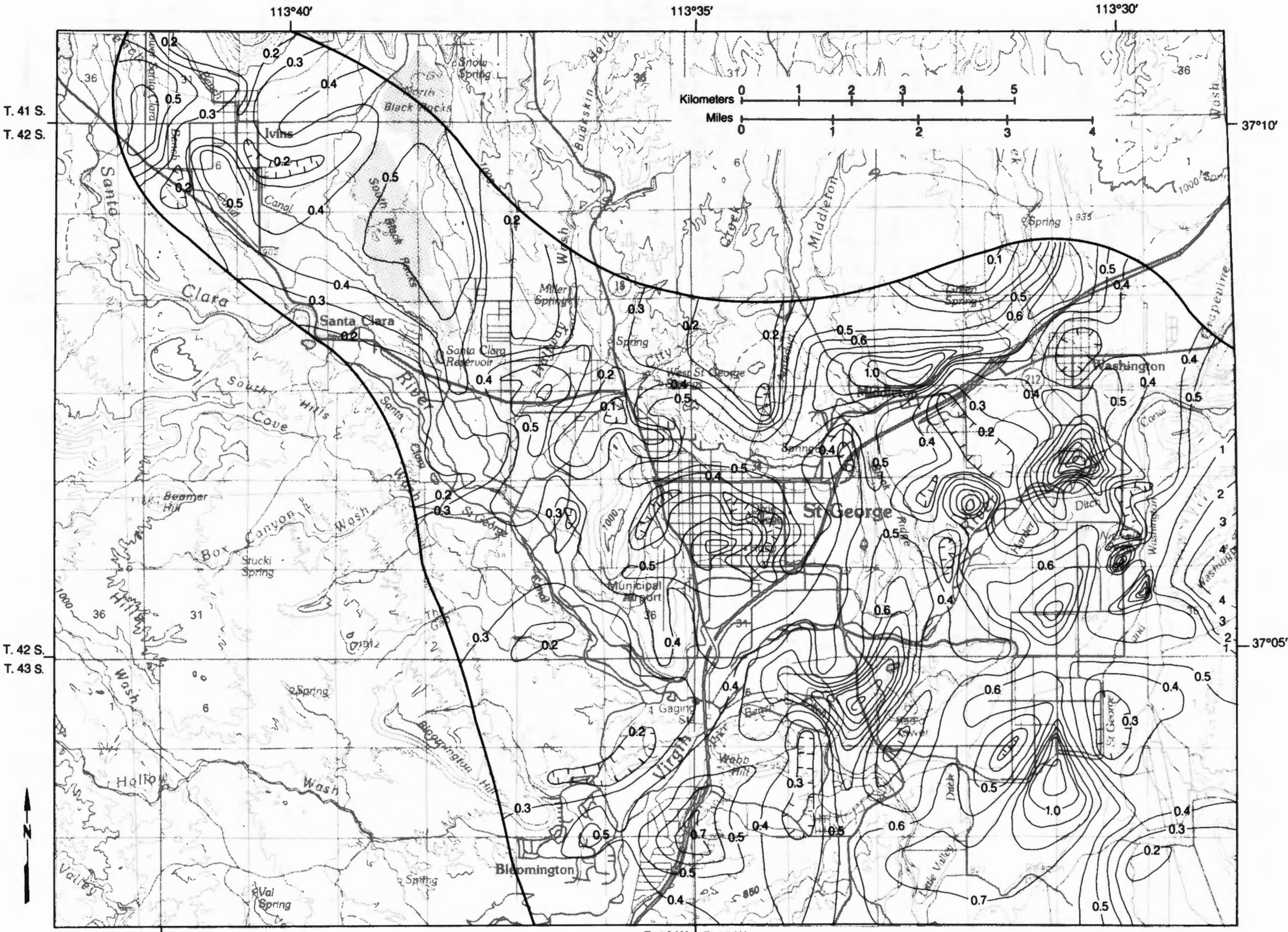


Figure 9. *eU/eTh ratios from gamma-ray spectrometry in the southern St. George basin. Contours at intervals of 0.1, except in the vicinity of Washington Dome where contours are at intervals of 1.0. Sample locations are shown on figure 4; sample values are listed on table A-1.*

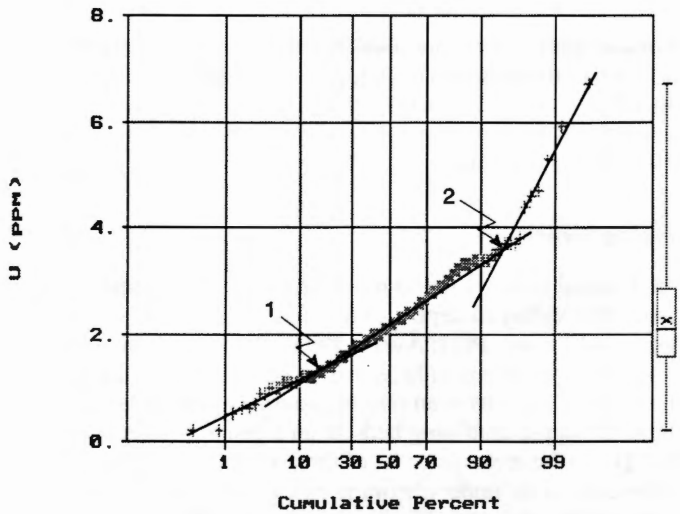
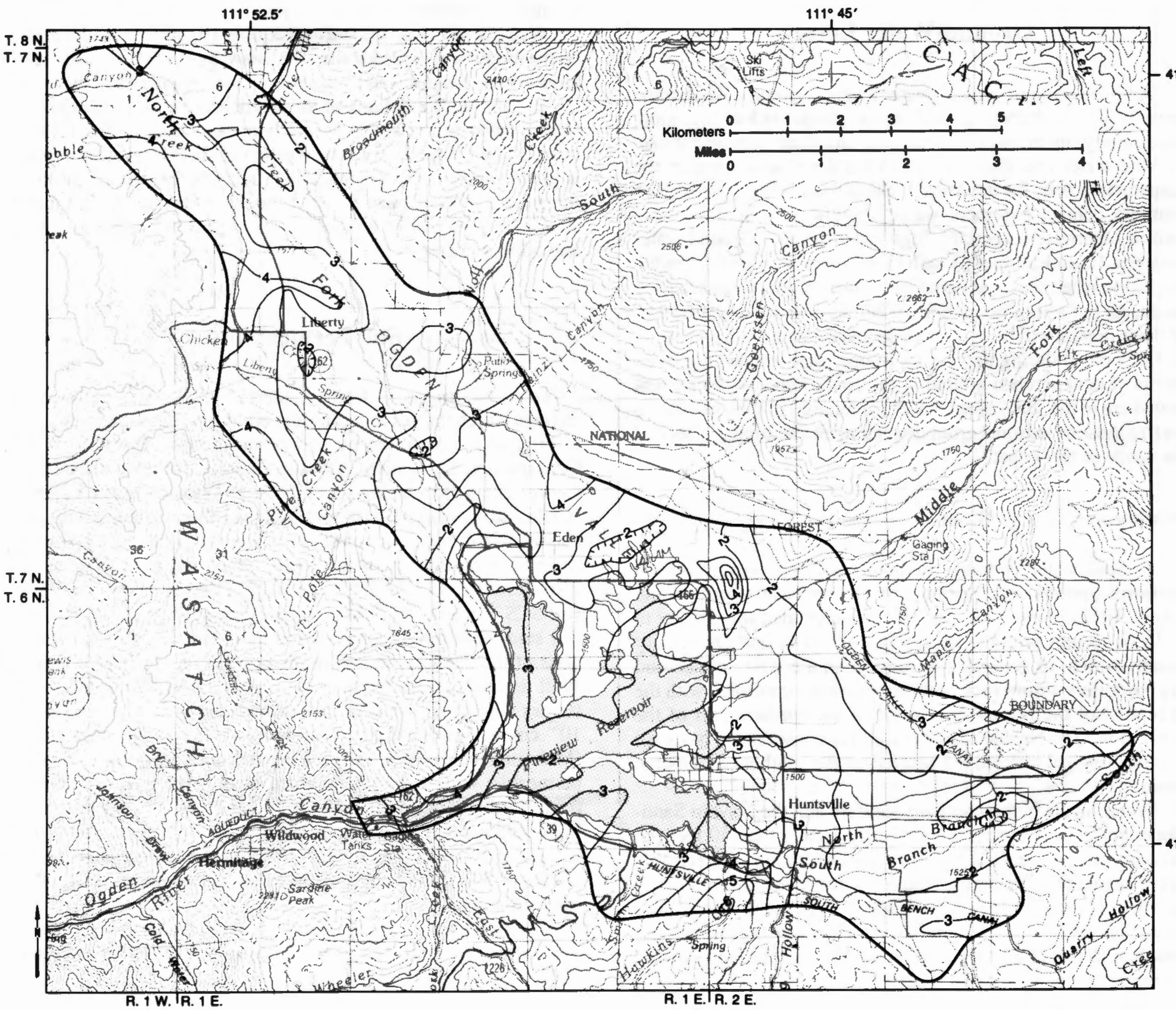


Figure 10. *Normal probablility diagram of uranium concentrations in the southern St. George basin. Inflection points "1" and "2" are discussed in the text. The boxplot to the right of the diagram depicts the limits (the ends of the line which extends outward from the rectangle), quartiles (the ends of the rectangle), median (the solid line within the rectangle), and arithmetic mean (the "X" within the rectangle) of the data set.*

Figure 11. *Uranium concentrations from gamma-ray spectrometry in Ogden Valley. Contour interval 1 ppm. Sample loactions are shown on figure 5; sample values are listed in table A-2.*



in Ogden Valley, reflects the predominant contribution of a single lithology, the Norwood Tuff.

Stratigraphy and alteration are reflected by the probability diagram for uranium concentrations in Ogden Valley (figure 13). Data distribution is similar to that of the southern St. George basin (figure 10), with two inflection points separating three distinct data sets. Fluvial sediments in the southeastern portion of Ogden Valley have the lowest uranium concentrations, and are separated by inflection point "1" from samples with higher uranium values that are predominantly derived from the Norwood Tuff. Samples with uranium values greater than inflection point "2" have the highest eU/eTh ratios, which suggests that these isolated samples in Ogden Valley have undergone similar alterations to analogous samples in the southern St. George basin. In both areas uranium enrichment by non-igneous processes has likely occurred.

Ground-Water Levels

An evaluation of ground-water levels is useful to determine areas in which shallow ground water inhibits radon migration, particularly in areas with elevated uranium concentrations. Ground water less than 10 feet (3 m) deep occurs within the construction zone for basements. Should soil with high levels of uranium contact basement walls, shallow ground water may reduce otherwise potentially high radon levels. Ground water between 10 and 50 feet (3 and 15 m) deep also inhibits radon migration when seasonal variations cause ground-water levels to decrease, but a significant portion of radon generated from soil at these depths will have already decayed (the half-life of radon is 3.825 days) during upward migration prior to reaching basements. Local perched ground-water conditions may be present anywhere in the study areas, but consideration of their effects, as well as those of seasonal ground-water level variations, is beyond the scope of this paper.

Southern St. George Basin

Ground water is found in both rock and unconsolidated basin-fill aquifers in the southern St. George basin (Cordova and others, 1972). Nearly all rock units have yielded some water to wells or springs with the exception of Tertiary and Quaternary basalts which, in general, cap ridges and are well drained and dry. Aquifers within rock units are generally confined, with the exception of the Navajo Sandstone in the northern part of the study area. The Navajo Sandstone and unconsolidated basin fill are the principal unconfined aquifers in the southern St. George basin.

Water levels in the confined aquifers and the Navajo Sandstone unconfined aquifer are generally greater than 50 feet (15 m) deep, and do not affect shallow radon migration. Water levels in unconsolidated, unconfined aquifers, however, are commonly less than 50 feet (15 m) deep (figure 14). In the stream valleys of the Santa Clara and Virgin Rivers, water levels generally are less than 10 feet (3 m) deep, and locally are near the land surface. Ground-water levels are also this shallow in the southern and western portions of St. George, and in a small area south of Ivins. In other areas of the southern St. George basin underlain by unconfined aquifers, water levels occur between depths of 10 and 50 feet (3 and 15 m).

Ogden Valley

Ground water is found in unconsolidated basin-fill aquifers in Ogden Valley to depths of 600 feet (180 m) and more (Leggette and Taylor, 1937; Avery, 1994). In the western portion of the valley, pre-Bonneville lacustrine offshore silts, which underlie surficial deposits in an area of about 10 square miles (25 km^2), form the upper confining beds of an artesian aquifer (Doyuran, 1972). In the recharge areas of the artesian aquifer, beyond the outer edge of the upper confining bed, ground water occurs under water-table conditions (Lowe and Miner, 1990). Ground water also occurs under water-table conditions in the Bonneville and younger sediments above the silt confining beds.

Water levels in the unconfined aquifer (figure 15) are deepest on the margins of Ogden Valley underlain by Quaternary alluvial fans, where ground water occurs at depths greater than 50 feet (15 m). In the floodplains of the North and South Forks of the Ogden River, water levels generally are less than 10 feet (3 m) deep, although the most extensive area of shallow ground water is present in southern Ogden Valley near the confluence of the three forks of the Ogden River at Pineview Reservoir. In other areas of Ogden Valley water levels occur between depths of 10 and 50 feet (3 and 15 m).

Soil Permeability

Once radon gas is formed, there must be soil pathways through which the gas migrates into buildings. The ability of gas to migrate is controlled by soil permeability. The U.S. Soil Conservation Service (SCS) mapped soils in the southern St. George basin (Mortensen and others, 1977) and Ogden Valley (Carley and others, 1980), and assigned them to permeability classes based on soil textural classification. Soils in the study areas have hydraulic conductivities which range from 0.06 to 20.0 inches/hour (4.2×10^{-5} to 1.4×10^{-2} cm/sec), and fall within five SCS permeability classes. These classes were combined for this study into three groups, based upon the SCS permeability class of the thickest interval in the upper 5 feet (1.5 m) of soil. Well-drained, permeable soils, typically with hydraulic conductivities ranging from 6.0 to 20.0 inches/hour (4.2×10^{-3} to 1.4×10^{-2} cm/sec), provide excellent pathways for radon migration (McLemore and others, 1991). Clay-rich soils are normally least permeable, with hydraulic conductivities ranging from 0.06 to 0.6 inches/hour (4.2×10^{-5} to 4.2×10^{-4} cm/sec), but may become more permeable if desiccation cracks form. Soils with moderate hydraulic conductivities, ranging from 0.6 to 6.0 inches/hour (4.2×10^{-4} to 4.2×10^{-3} cm/sec), have an intermediate ability to transmit radon.

The SCS classification is based upon the permeability of soil to the flow of water. The permeability of soil to the flow of gas

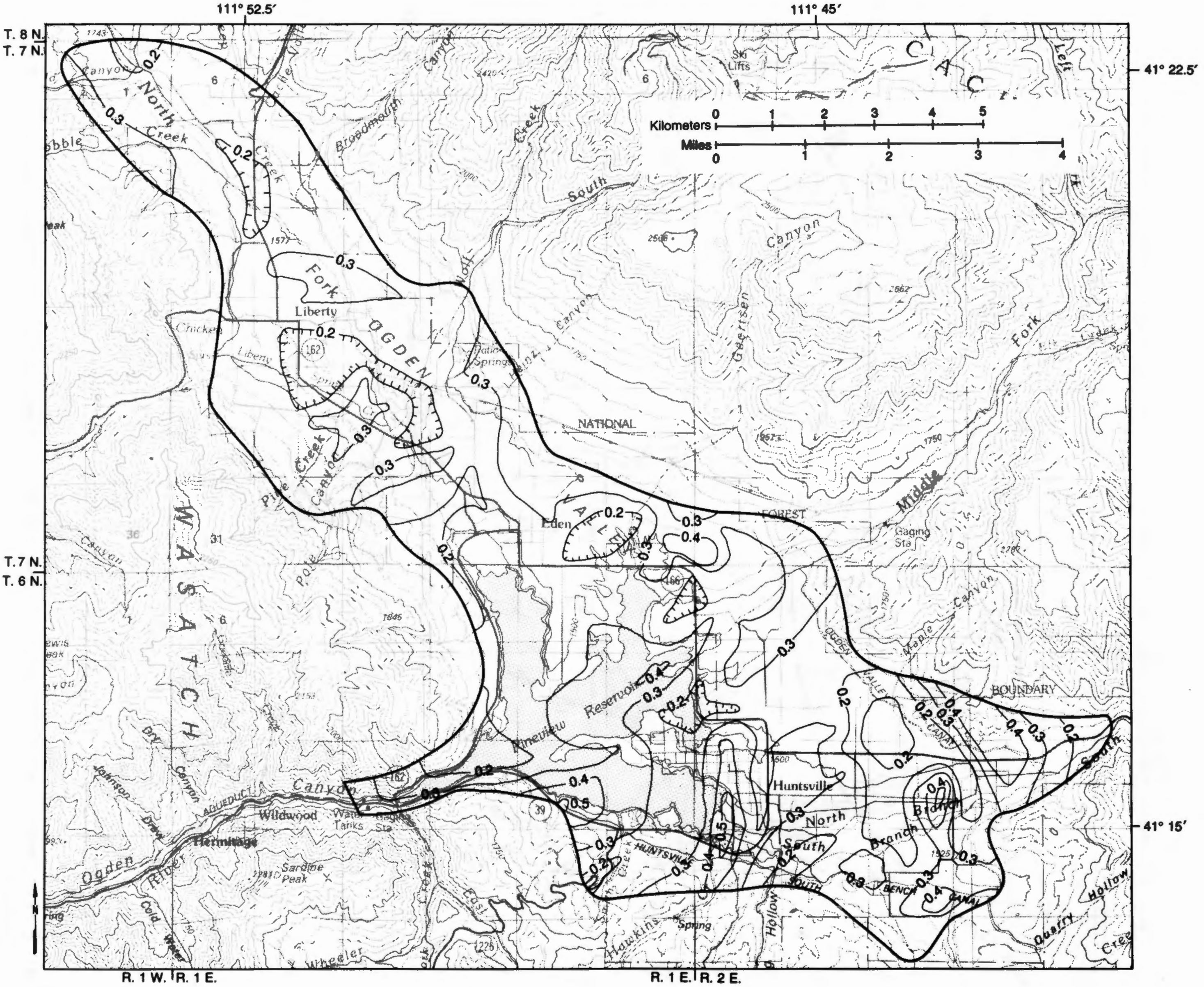


Figure 12. *eU/eTh ratios from gamma-ray spectrometry in Ogden Valley. Contour interval 0.1. Sample locations are shown on figure 5; sample values are listed in table A-2.*

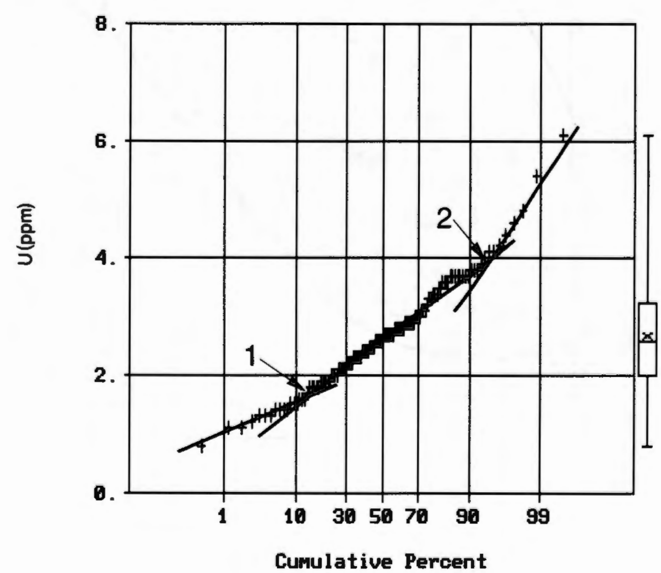


Figure 13. *Normal probability diagram of uranium concentrations in Ogden Valley. Inflection points "1" and "2" are discussed in the text. The boxplot to the right of the diagram depicts statistical values defined for figure 10.*

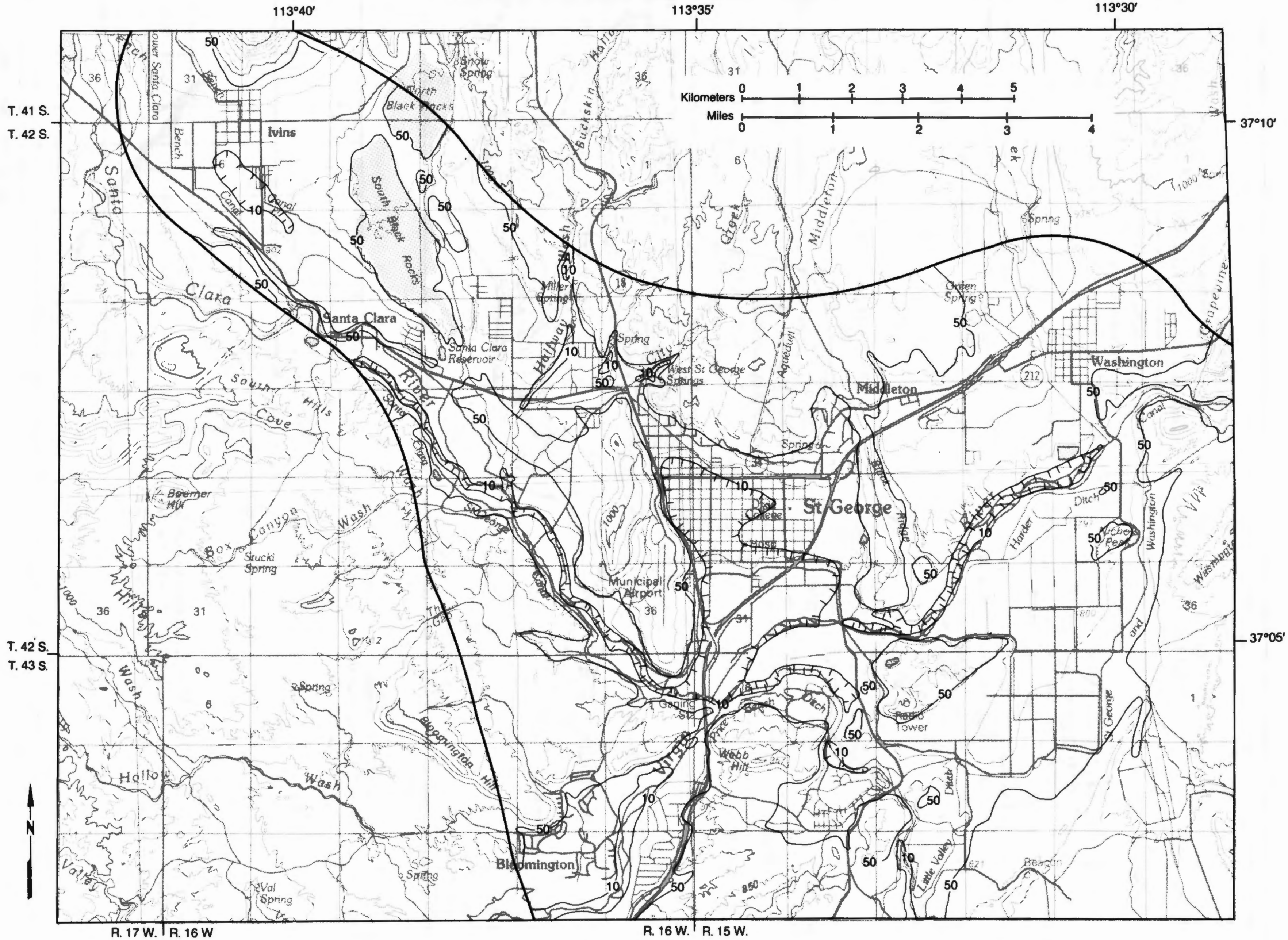


Figure 14. Depth to ground water in wells in the southern St. George basin, from well data in Cordova and others (1972). Contours at depths of 10 and 50 feet (3 and 15 m).

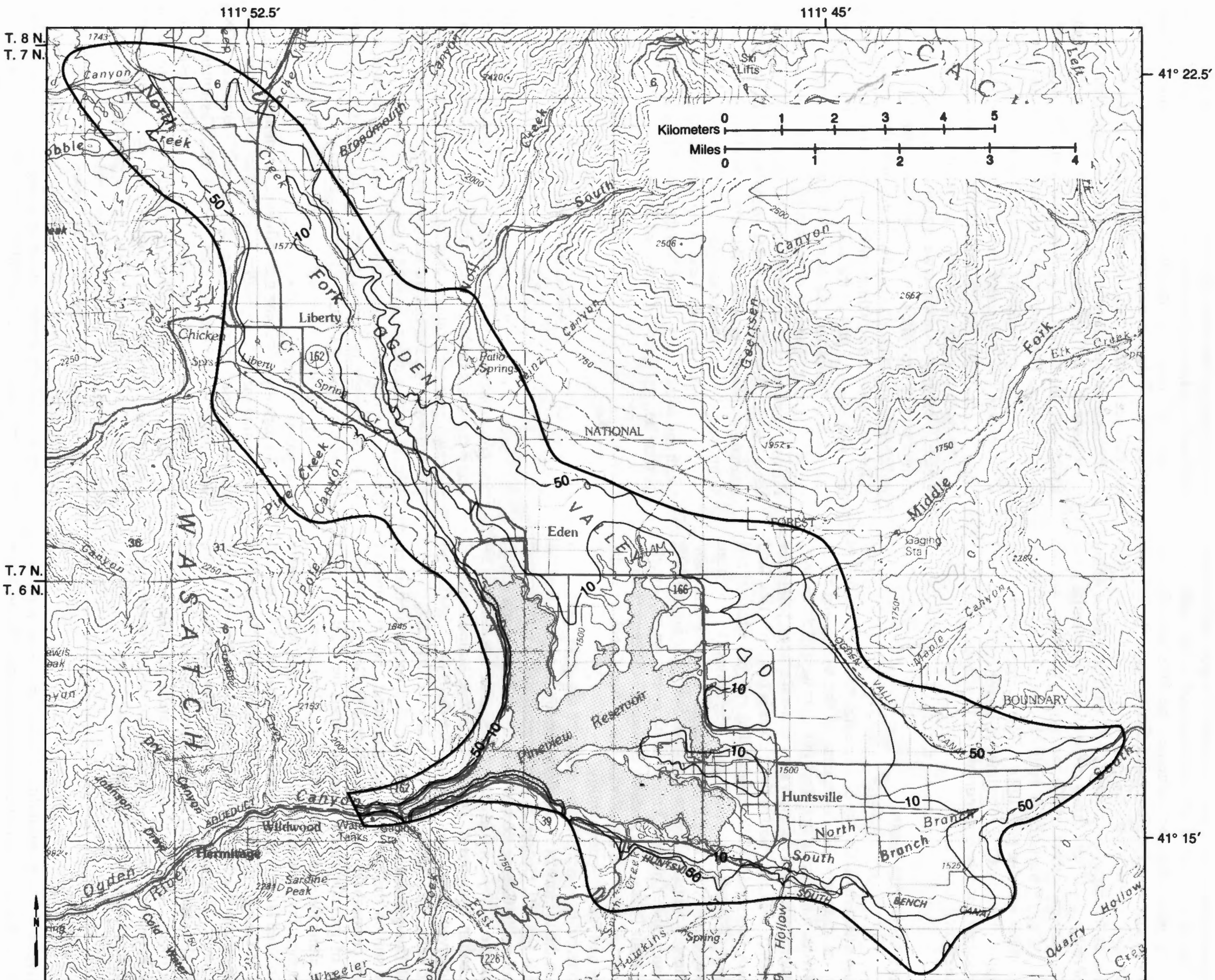


Figure 15. Depth to ground water in wells in Ogden Valley, from well data in Leggette and Taylor (1937), Doyuran (1972), and Avery (1994). Contours at depths of 10 and 50 feet (3 and 15 m).

is almost identical, with one significant exception -- sandy clay is more permeable to soil gas than to water (Rogers and Nielson, 1990). Sandy clay was therefore designated in this study as a moderately permeable soil, whereas the SCS classification would otherwise have justified designation of sandy clay as a low permeability soil.

Areas underlain by permeable rock, with or without a thin cover of residual soil, also affect radon migration potential. One study (Schery and others, 1982) has shown, however, that the presence of large fractures in bedrock does not significantly increase radon flux due to diffusion. The authors speculate that the volume of studied fractures may not have been significant enough to influence the bulk porosity and diffusion coefficients of exposed rock.

Southern St. George Basin

In the southern St. George basin permeability is classified as high in the channels and floodplains of the Virgin and Santa Clara Rivers, the South Black Rocks vicinity west of St. George, and scattered areas of Triangle Valley in the southeast part of the study area (figure 16). Soil in these areas is primarily fine sand and loamy fine sand, locally indurated by caliche. Channel and floodplain alluvium consists, in part, of detritus derived from intrusive bodies of the Pine Valley Mountains; fine-grained soil components have likely been winnowed. Soil in the South Black Rocks area and Triangle Valley is of eolian origin, locally derived from Triassic and Jurassic sandstone. Quaternary basalt which forms South Black Rocks has a significant vesicular porosity and fracture permeability.

Permeability is classified as moderate along the Santa Clara Bench in the vicinity of Ivins, along the southern margin of the Red Hills from St. George to Washington, and in northern and southeastern St. George, central and eastern Washington Fields, and Triangle Valley. Soil in each of these areas has a significant sandy, eolian component, but also has fine-grained material likely derived from clay- and silt-rich beds in Triassic and Jurassic units. This sandy and silty loam is chiefly alluvium in areas of fine-grained source rock, and also occurs as thinner, residual soil on shallow shale and mudstone. Smaller areas of moderate permeability occur southwest of St. George. Soil here consists of gravelly sandy loam deposited on older, elevated terraces along the south side of the Santa Clara River.

The most impermeable soil occurs north and west of Santa Clara, in Sand Hollow and its southern extension northwest and west of St. George, in a broad band extending from Washington to southwestern Washington Fields, and in small areas throughout the basin. This soil includes clayey, silty, and sandy loam, and silty clay, and is locally derived from clay-rich Triassic and Jurassic rocks. Although parts of these areas, particularly Sand Hollow, have a thin eolian, sandy soil at the surface, deeper soils, more representative of the soil column, are clay rich.

Ogden Valley

In Ogden Valley permeability is classified as high in and near parts of the floodplains of the three forks of the Ogden River (figure 17). Soils in these areas are primarily cobbly loam, gravelly loam, fine sandy loam, and loam. This soil was derived from Holocene floodplain alluvium deposited near modern channels and, in adjacent low-lying areas, Pleistocene alluvium deposited by streams graded to the Provo shoreline of Lake Bonneville. The alluvium consists of detritus from sedimentary and metasedimentary rocks in upstream drainage basins.

Permeability is classified as moderate in the channels and other parts of the floodplains of the three forks of the Ogden River, and on alluvial fans in northwestern and southeastern Ogden Valley. These areas are overlain by stony loam, gravelly loam, and loam derived from Holocene material. This material is somewhat less well sorted than alluvium beneath soils with higher permeability, but contains detritus of similar origin.

The most impermeable soil is scattered throughout Ogden Valley, but is predominant between Huntsville and Liberty in the central part of the valley, and on the valley margins. This soil includes loam, clayey and silty loam, and silty clay, and is commonly mantled by a thin veneer of stony loam. Impermeable soils in the central part of the valley are derived from material deposited offshore in Lake Bonneville which underlies a thin cover of stream alluvium deposited by streams graded to the Provo shoreline. Impermeable soils on the valley margins are largely residual deposits derived from the Norwood Tuff, locally overlain by coarser grained colluvium with clasts derived from sedimentary and metasedimentary rocks. Impermeable soils also form a discontinuous band along the mountain front at the south end of the valley, where nearshore Lake Bonneville deposits were derived from the Norwood Tuff.

Soil-Gas Radon

The correlation between soil-gas-radon and surface-uranium concentrations measured at the same sites should be linear because radon is a decay product of uranium. This relationship is roughly linear for samples collected in the southern St. George basin (figure 18), but not for samples in Ogden Valley (figure 19). There is, however, a broad correlation between geology and the distribution of soil-gas-radon concentrations in both areas. The poor correlation between radon and uranium concentrations at specific sites in Ogden Valley is due to many factors, but primarily results from the influence of soil permeability on the soil-gas-sampling apparatus.

To partially overcome this influence, a semiquantitative interpretation method, originally developed for radon activity distributions based upon surface-water surveys (Durrance, 1978), was applied to the soil-gas data. This method assumes many factors can act to reduce the radon concentration of a sample, but only the influx of radon will produce high concentrations. In an area of uniformly high radon input, a survey with irregularly distributed sample points will show an apparently random pattern of high and low values. The high values are true indicators of radon input, while the low values result from factors which produce artificially low concentrations. Such factors may include atmospheric contamination of soil-gas samples or insufficient sampling of soil gas in soils of low permeability. It may be inferred, therefore, that only the high values have significance.

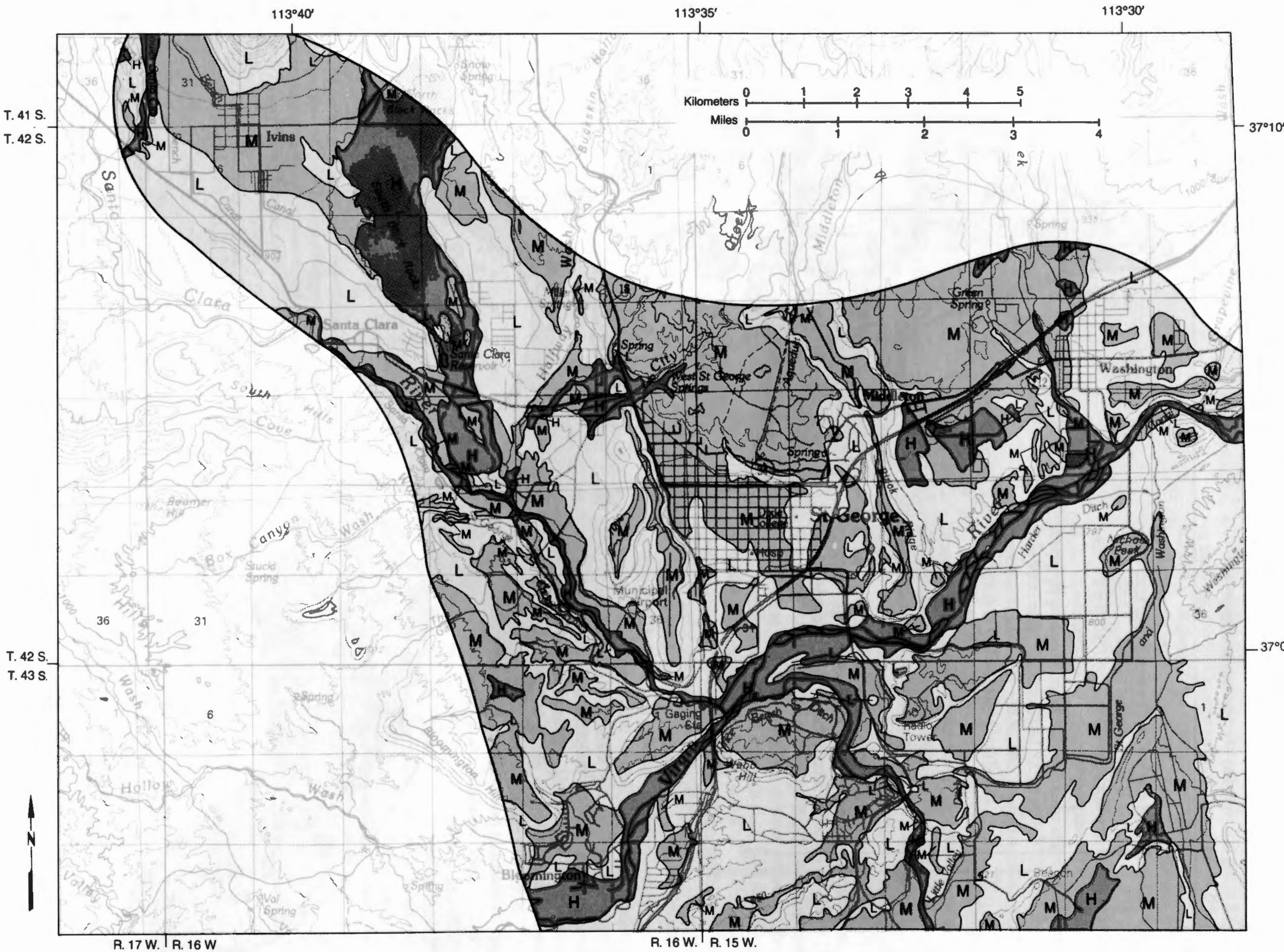


Figure 16. Soil permeability in the southern St. George basin, from data in Mortensen and others (1977). L (light shading) -low; K (hydraulic conductivity) = 0.06 to 0.6 inches/hour (4.2×10^{-5} to 4.2×10^{-4} cm/sec); M (medium shading) - moderate; K = 0.6 to 6.0 inches/hour (4.2×10^{-4} to 4.2×10^{-3} cm/sec); and H (dark shading) - high, K = 6.0 to 20.0 inches/hour (4.2×10^{-3} to 1.4×10^{-2} cm/sec).

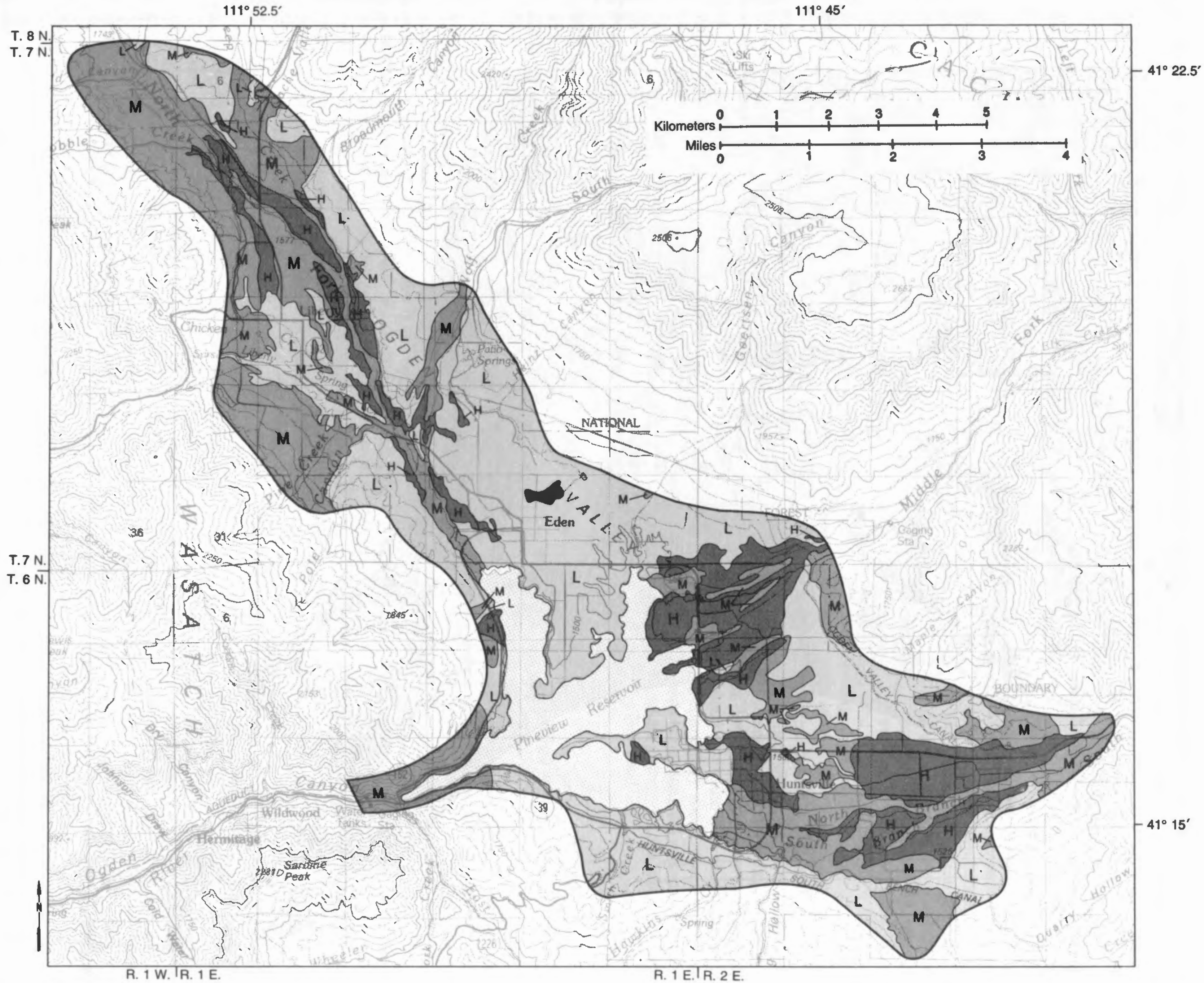


Figure 17. Soil permeability in Ogden Valley, from data in Carley and others (1980). Symbols for soil permeability classifications are defined for figure 16.

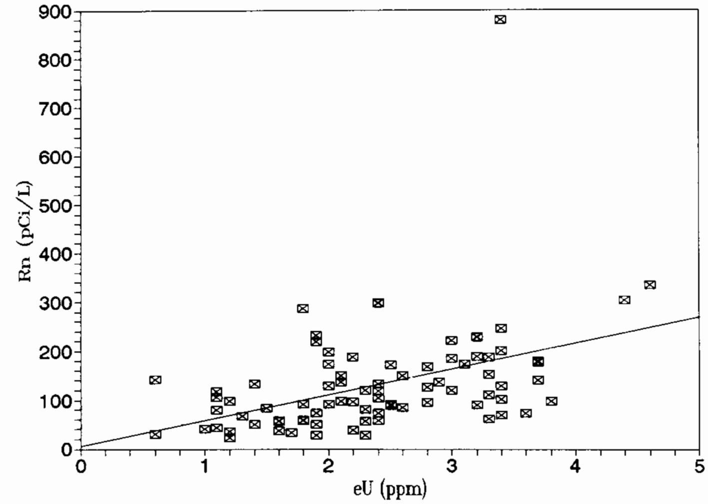


Figure 18. *Scatter plot and linear regression of uranium (U) and soil-gas radon (Rn) in the southern St. George basin. Concentrations are related by the formula Rn = 52.8 U + 7.5, with a correlation coefficient = 0.415.*

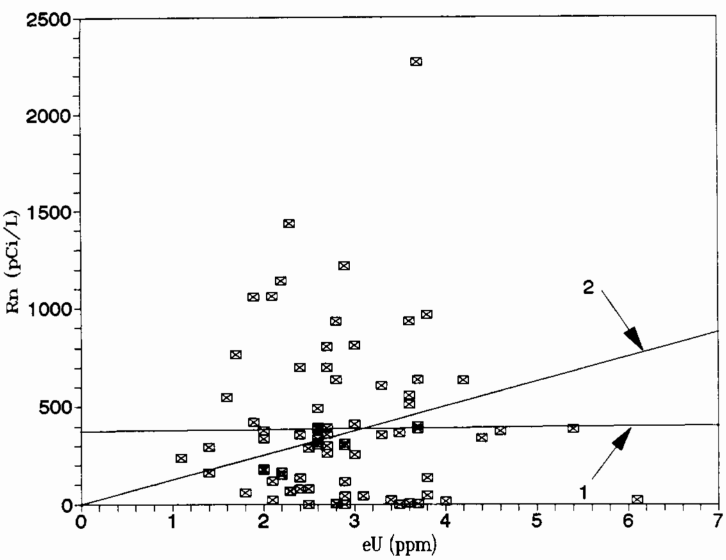


Figure 19. *Scatter plot and linear regression of uranium (U) and soil-gas radon (Rn) in Ogden Valley. Regression line 1 shows that, when the line is not forced to 0, concentrations are related by the formula Rn = 3.6 U + 377.6, with a correlation coefficient = 0.008. Regression line 2 shows that, when 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 = 125.2 U, with a correlation coefficient = 0.278.*

Instead of constructing contour lines of equal value, exclusion isolines are constructed which enclose all data points that have values equal to or greater than the value of the isoline, as well as some data points that have values less than the value of the isoline. Areas of consistently high concentrations are geologically meaningful, and values assumed to be artificially low are subjectively excluded.

Southern St. George Basin

The mean concentration of radon in soil gas at 82 sample sites in the southern St. George basin is 134 pCi/L (4.95×10^3 Bq/m^3) (table 1). In general, as uranium concentrations increase, radon levels also increase (figure 18). Linear regression of radon-uranium data pairs shows that they are related by the formula:

$$Rn = 52.8\ U + 7.5$$

where Rn is the concentration of soil-gas radon in pCi/L, and U is the concentration of uranium in ppm. The sample size is 82. At the 99 percent confidence level, the correlation coefficient of 0.415 exceeds the threshold value of 0.283, indicating that the correlation between radon and uranium established by linear regression is statistically significant.

Although the correlation is significant, radon values derived from the relationship appear low compared to those derived from studies elsewhere. For example, from the relationship established in the Rincon Shale of southern California (Carlisle and Azzouz, 1991), a uranium concentration of 2 ppm would yield a radon concentration in soil gas in excess of 600 pCi/L (2×10^4 Bq/m^3). In the southern St. George basin, the same uranium concentration yields a radon concentration of about 110 pCi/L (4.1×10^3 Bq/m^3). Ground-water depth and soil permeability contribute to this difference, but climate and soil moisture also have profound effects that are both perennial and seasonal.

Semi-arid areas such as the southern St. George basin are characterized by low soil moisture. Levels of iron oxidation and organic matter concentration are low in these areas, particularly at depth where water infiltration is minimal (Gundersen and others, 1993). Iron oxides and organic matter are effective adsorbants of uranium and in semi-arid areas are more abundant in thin, shallow soil horizons where uranium levels are measured with spectrometry, but deficient at depths where radon levels are measured with emanometry. This condition of disequilibrium results in relatively low levels of soil-gas radon even in areas where high uranium concentrations are measured.

Although the average level of soil moisture is low in semi-arid regions, large seasonal variations occur. This results in seasonal variations in soil-gas radon levels. In a study of radon in a semi-arid area of Colorado, soil-gas radon levels were found to vary seasonally by a factor of five or six, with lowest levels during the summer and fall (Asher-Bolinder and others, 1990). This seasonal variation is due to increased insolation in spring and summer which warms and dries the soil, limiting water infiltration and increasing soil dessication. Soil normally has enough water to absorb the kinetic energy of radon ions recoiling from the decay of radium, the immediate precursor to radon in the uranium decay series, so that radon ejected into the pores remains in the pores and is free to move (Tanner, 1989). If too little soil moisture is present, most radon ions are propelled across the pore space and into adjacent soil grains. If too much soil moisture is present, most radon ions dissolve in pore water. In either case, the amount of radon available for transport in soil gas is decreased. The fraction of radon atoms which escapes from the solid from which it formed is defined as the emanating power of the solid. As the soil dries radon emanation decreases, and deep soil cracks develop. Convective transport of soil gas through cracks increases radon flux into the atmosphere. The concentration of radon in soil gas is concurrently lowered by this combination of decreased emanation and increased flux to the atmosphere (Asher-Bolinder and others, 1990). The effects of soil cracks are greatest in soils of low permeability (Holford and others, 1993).

In the southern St. George basin, levels of radon in soil gas are highest, in excess of 200 pCi/L (7.4 x 10^3 Bq/m^3), in the Petrified Forest Member of the Chinle Formation west of St. George, and in the Washington Fields area, where a maximum level of 878 pCi/L (3.25 x 10^4 Bq/m^3) was measured (figure 20). Isolated high levels were recorded near Ivins and Washington, but levels are generally lower in these areas. Moderate levels of radon, between 100 and 200 pCi/L (3.7 x 10^3 and 7.4 x 10^3 Bq/m^3), were recorded near Bloomington. The lowest levels are in the area of eolian sand extending from Ivins to Washington in the northern part of the study area, where concentrations of radon in soil gas were routinely less than 100 pCi/L (3.7 x 10^3 Bq/m^3). This distribution is shown more clearly by exclusion isolines (figure 21), which indicate higher levels of radon in soil gas on the west, south, and east margins of the study area, and a broad area of consistently lower levels in the north and central parts of the study area.

Ogden Valley

The mean concentration of radon in soil gas at 80 sample sites in Ogden Valley is 388 pCi/L (1.44 x 10^4 Bq/m^3) (table 1). This is higher than the mean in the southern St. George basin, but is consistent with higher average uranium values and smaller positive uranium skewness for the Ogden Valley data. However, the correlation between radon and uranium in Ogden Valley, unlike that of the southern St. George basin, is poor (figure 19). Linear regression of radon-uranium data pairs shows that they are related by the formula:

$$Rn = 3.6\ U + 377.6$$

The sample size is 80. At the 99 percent confidence level, the correlation coefficient of 0.008 does not exceed the threshold value of 0.287, indicating that the correlation between radon and uranium established by linear regression is statistically insignificant. The relationship expressed by linear regression is also unrealistic because there should be essentially no decay product (Rn) if the parent material (U) is absent. If the regression is forced to zero, indicating an absence of Rn when no U is present, the data pairs are related by the formula:

$$Rn = 125.2\ U$$

Although theoretically more realistic, this correlation is also poor at the 99 percent confidence level, where the correlation coefficient of 0.278 still does not exceed the threshold value of 0.287. However, at the 95 percent confidence level, the correlation coefficient exceeds the threshold value of 0.220.

The poor correlation between soil-gas-radon and uranium concentrations may be due to the influence of soil permeability on the soil-gas sampling apparatus. Soils with the highest and lowest permeabilities are more common in Ogden Valley (figure 17) than in the southern St. George basin (figure 16), where soil permeability is commonly moderate. Atmospheric contamination of soil-gas samples may occur in permeable soils as air leaks between the probe and soil and is pumped into the sample. Clay-rich impermeable soils, particularly if moist, provide a better seal to prevent atmospheric contamination but also, if sufficiently impermeable, plug the probe perforations and prevent sampling. Both cases result in artificially low soil-gas concentrations. The influence of these factors is evident in Ogden Valley (figure 19), and to a lesser extent in the southern St. George basin (figure 18), by the presence of several sites with high uranium concentrations but low radon concentrations. The converse relationship, low uranium concentrations but high radon concentrations, is relatively rare. Tanner (1991) has designed a soil-gas sampling apparatus which, with the use of rubber packers and pressure differentials, minimizes the potential for atmospheric contamination.

Although correlation of site-specific radon-uranium data pairs is poor in the Ogden Valley, levels of radon in soil gas are highest in geologic units with high uranium concentrations. This suggests that soil-gas sampling is not adequate for a quantitative estimate of soil-gas-radon levels, but is useful for determining areas with relatively high levels. The semi-quantitative exclusion-isoline method overcomes this inadequacy. Geologic units in Ogden Valley with high radon levels include unconsolidated Quaternary alluvial-fan, fluvial, lacustrine, and deltaic deposits of northwestern Ogden Valley; and fluvial and lacustrine deposits in central and southern Ogden Valley. Radon levels in these areas commonly exceed 500 pCi/L (1.9 x 10^4 Bq/m^3) and reach a maximum of 2,269 pCi/L (8.4 x 10^4 Bq/m^3) north of Liberty (figure 22). Moderate levels of radon, between 100 and 500 pCi/L (3.7 x 10^3 and 1.9 x 10^4 Bq/m^3), are most common in the central part of the valley. The lowest levels, however, are in the east-central and southern parts of the valley, where concentrations of radon in soil gas were generally less than 100 pCi/L (3.7 x 10^3 Bq/m^3). These areas are commonly underlain by clayey soil derived from the Norwood Tuff, which plugged the sample probe and prevented collection of adequate sample volumes. Exclusion isolines (figure 23) indicate higher levels of radon in soil gas in residual soil and bedrock along north and central valley margins, and lower levels in floodplain alluvium along the North and South Fork of the Ogden River.

Indoor Radon

Geologic factors influence radon levels in soil gas, but a number of non-geologic factors influence radon levels once the gas enters the construction zone and migrates indoors. Significant non-geologic factors include foundation condition, building ventilation, construction material, and occupant lifestyles (Fleischer and others, 1982). The distribution of indoor-radon levels reflects the combined influence of both geologic and non-geologic factors.

Southern St. George Basin

Ten indoor-radon levels were measured in the southern St. George basin (table A-3). The measurements average 1.9 pCi/L

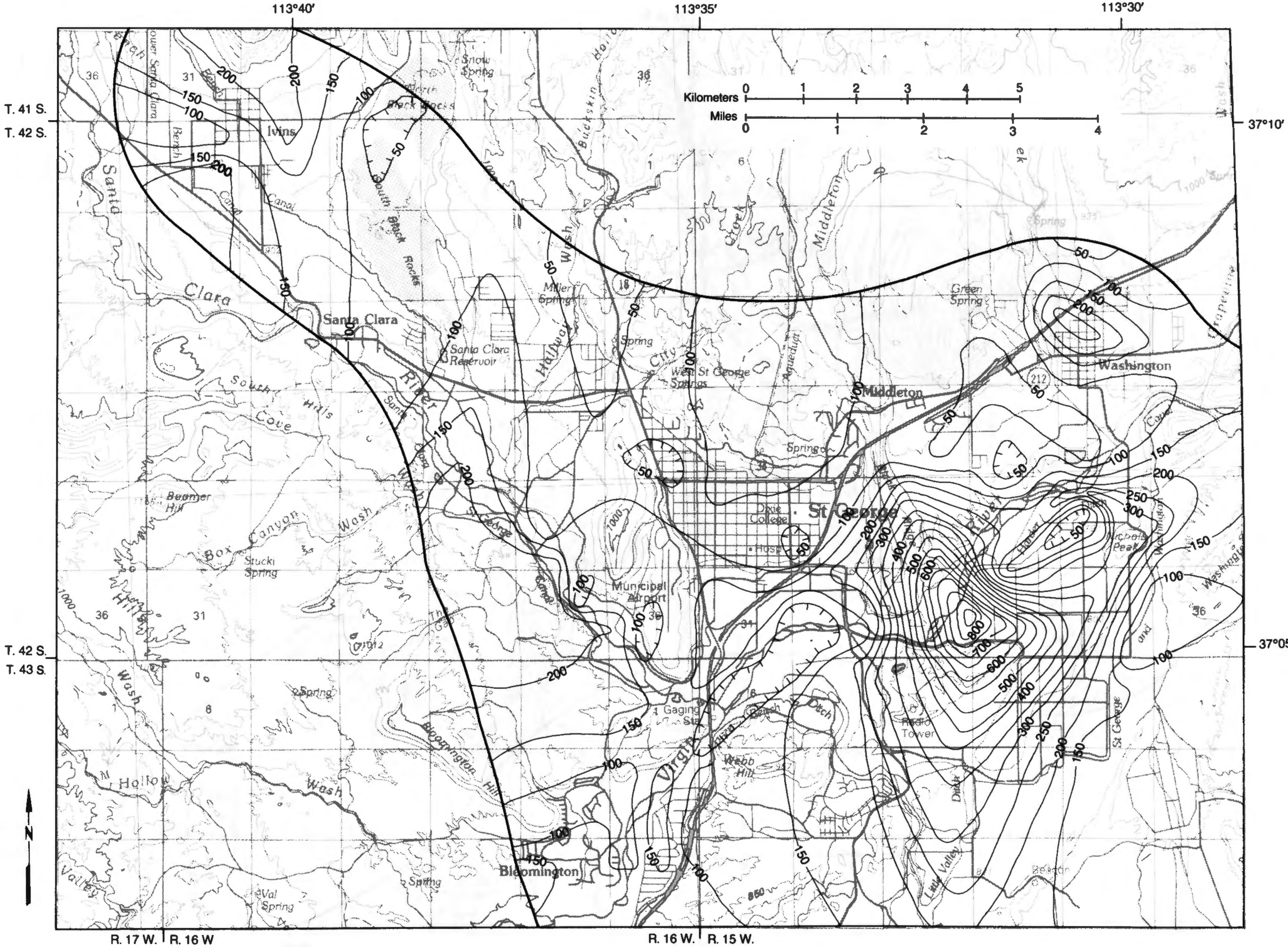


Figure 20. Radon in soil gas from radon emanometry in the southern St. George basin. Contour interval 50 pCi/L (1,850 Bq/m³). Sample locations are shown on figure 4; sample values are listed in table A-1.

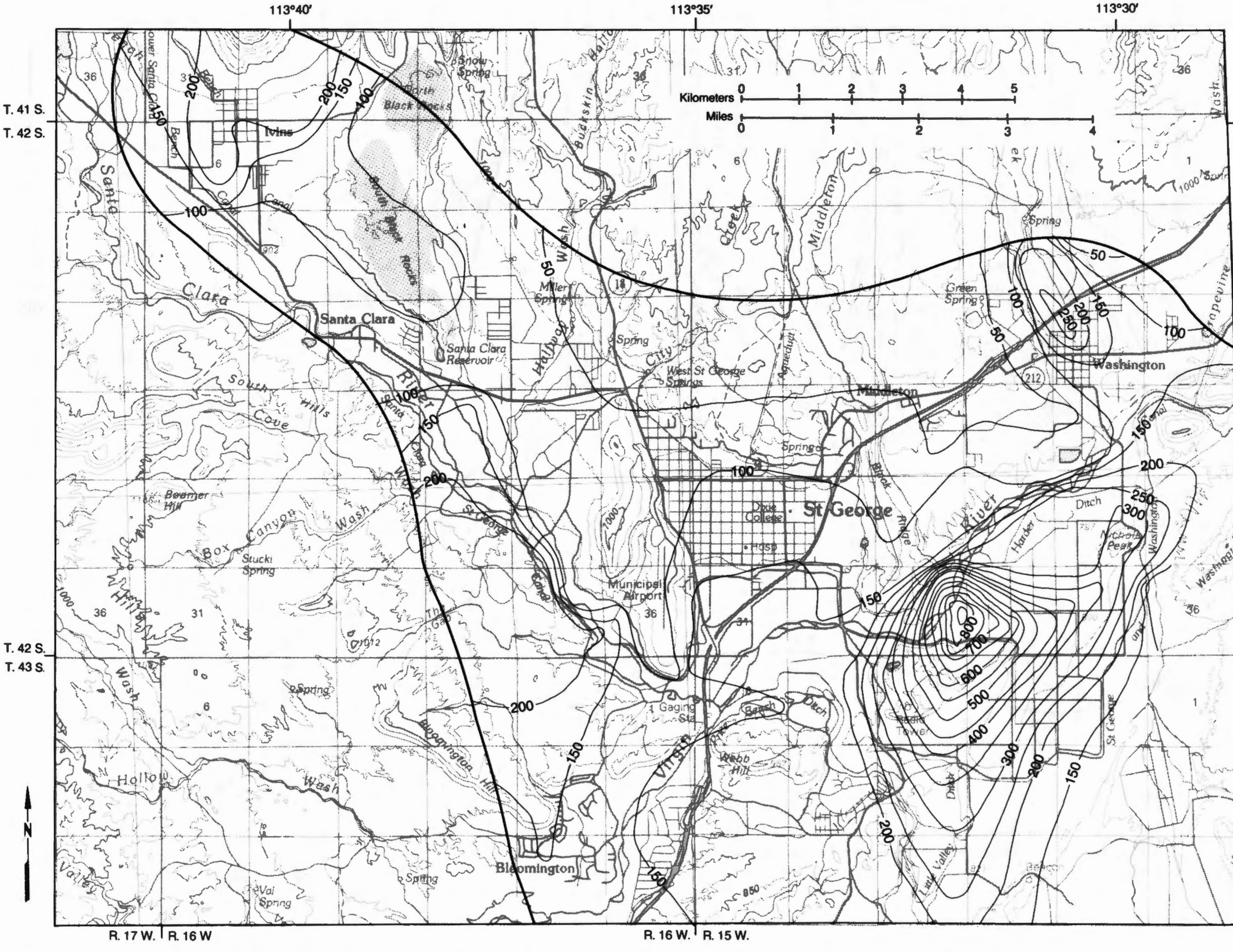


Figure 21. Exclusion isolines of radon in soil gas in the southern St. George Basin. Contour interval 50 pCi/L (1,850 Bq/m³). Sample locations are shown on figure 4; sample values are listed in table A-1.

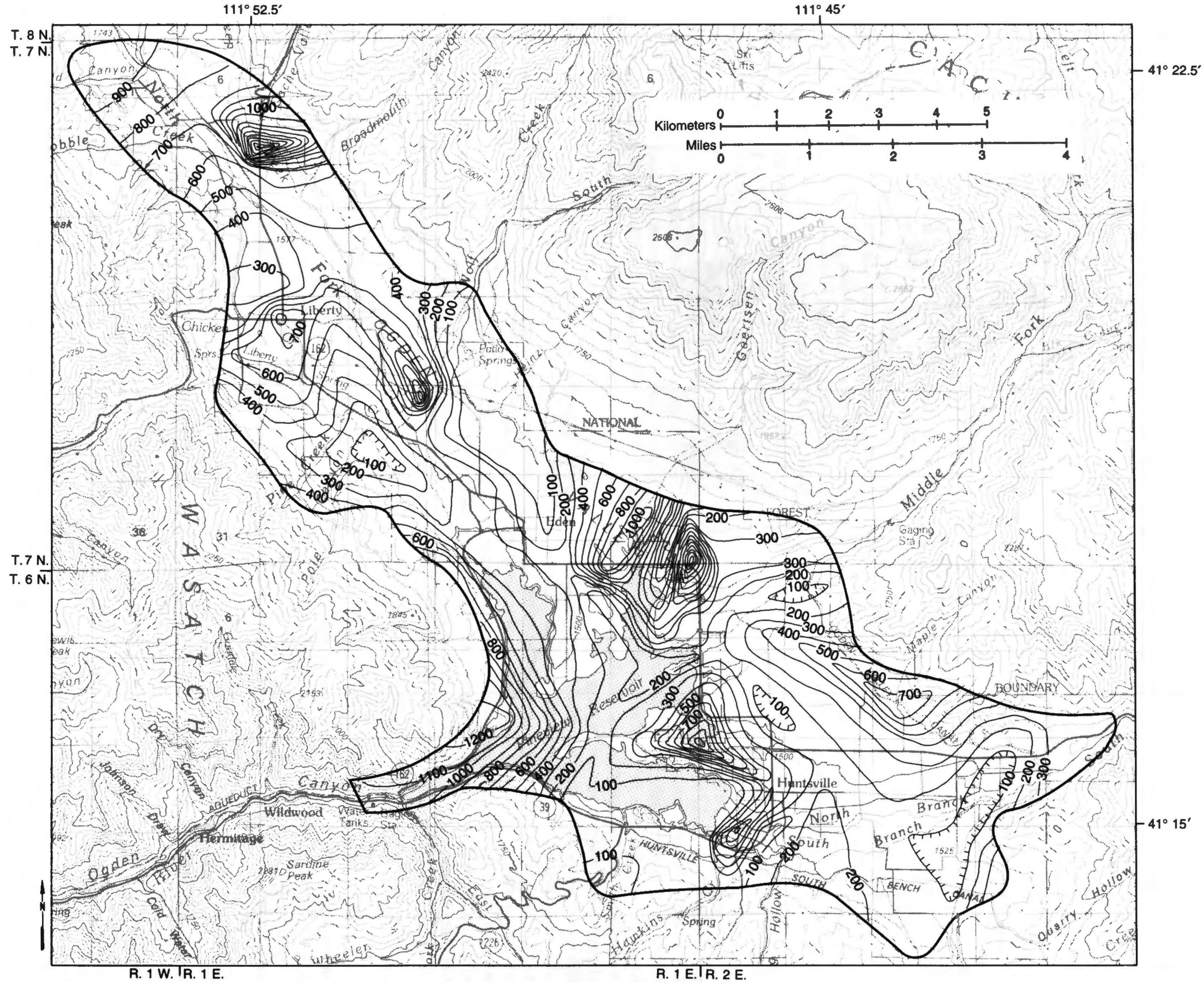


Figure 22. Radon in soil gas from radon emanometry in Odgen Valley. Contour interval 100 pCi/L (3,700 Bq/m³). Sample locations are shown on figure 5; sample values are listed in table A-1.

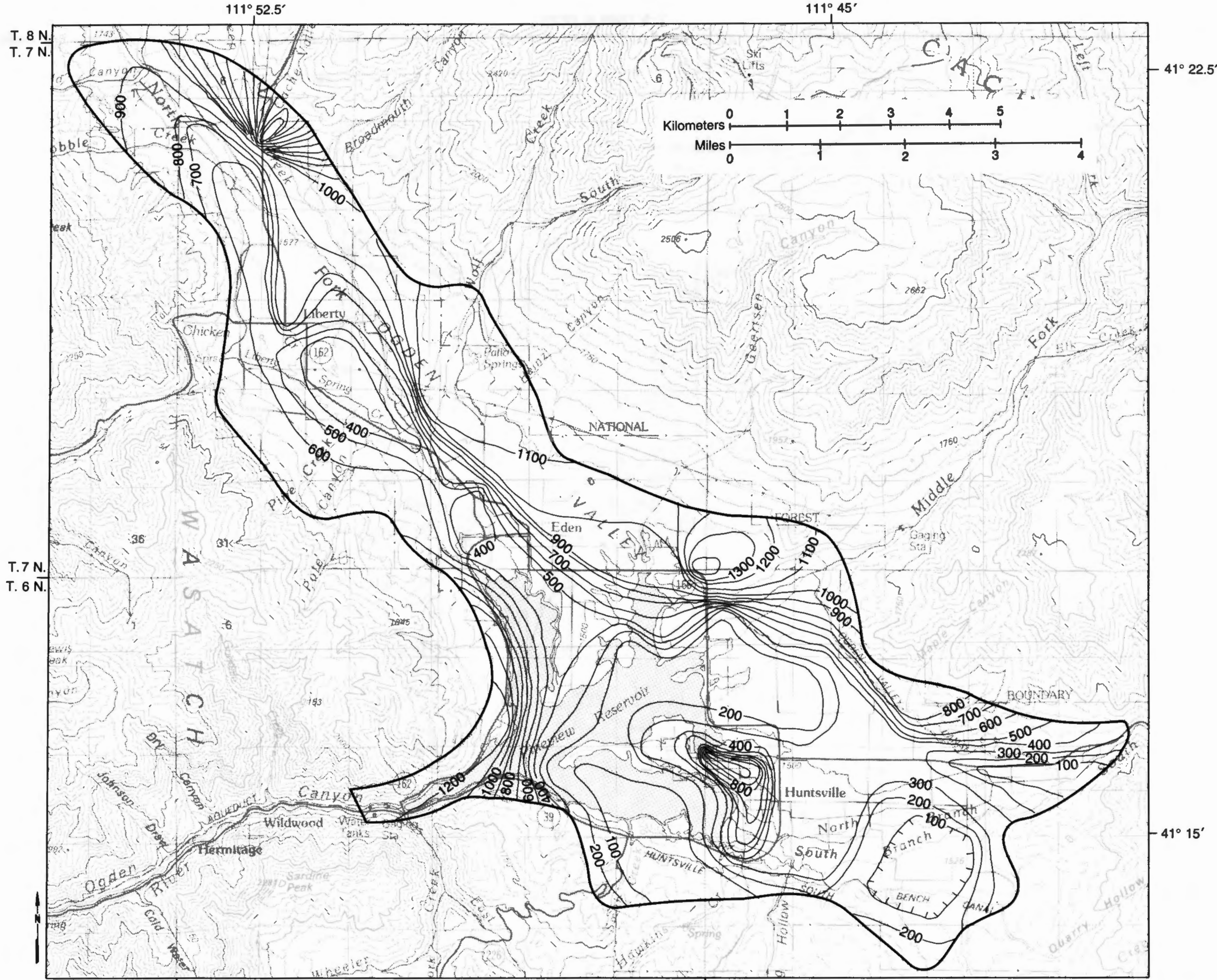


Figure 23. Exclusion isolines of radon in soil gas in Ogden Valley. Contour interval 100 pCi/L (3,700 Bq/m³). Sample locations are shown on figure 5; sample values are listed in table A-1.

(70.3 Bq/m^3)(table 1), and 80 percent are less than 4 pCi/L (148 Bq/m^3)(table 2). The highest level, 6.2 pCi/L (229.4 Bq/m^3), occurs in Bloomington, where uranium concentration and ground-water depth are moderate, and permeability is low (figure 24). Four of the ten measurements are in areas where uranium concentrations are less than 2 ppm. None of the measurements are in areas where all three geologic factors are favorable for elevated indoor-radon levels; therefore, the lack of higher levels in the data set may simply reflect the random distribution of the volunteered sample sites.

Ogden Valley

The average of 36 residential indoor-radon levels in Ogden Valley (table A-4) is 5.2 pCi/L (192.4 Bq/m^3)(table 1). Sixty-four percent of the test results are less than 4 pCi/L (148 Bq/m^3)(table 2). The average is considerably higher than in the St. George area and is likely due to higher average uranium concentration in Ogden Valley, and to the presence of highly permeable soils, particularly where high indoor-radon levels are clustered east of Huntsville. The highest level, 23.8 pCi/L (880.6 Bq/m^3), occurs north of Liberty where uranium concentration and ground-water depth are moderate, and permeability is high (figure 25). Most low measurements are in areas of shallow to moderate ground-water depth. Clusters of elevated indoor-radon levels are present in an area east of Huntsville underlain by highly permeable soils, and north of Liberty as noted previously.

Low levels of radon were measured in two schools (table 3). Valley Elementary School, with a maximum indoor-radon level of 1.5 pCi/L (55.5 Bq/m^3), is located within a cluster of low residential measurements in Huntsville where ground-water depth is shallow to moderate (figure 25). Snowcrest Jr. High School, with a maximum indoor-radon level of 0.5 pCi/L (18.5 Bq/m^3), is on low permeability soils northwest of Eden near a home with an indoor level of 5.3 pCi/L (Bq/m^3). However, construction techniques and materials differ significantly between homes and schools, as does the way in which the buildings are used. As a result, indoor-radon levels in these building types may differ considerably in the same geologic setting.

THE RADON-HAZARD POTENTIAL

Geologic factors which influence indoor-radon levels in the southern St. George basin and Ogden Valley have been used to classify relative hazard potential. Hazard-area boundaries, independent of mapped geologic units, are compiled on a composite hazard map derived from overlays of rating factors. This system is designed to accommodate the large data sets, wide value ranges, and study-area sizes. The system may not be applicable in all settings, but is suitable for a wide variety of radon-hazard assessments. This method of hazard mapping is only one of several schemes. Solomon and others (1994), for example, statistically summarize relevant geologic factors within each geologic unit to characterize its relative hazard potential. However, this method assumes uniform physical characteristics within the unit boundaries and ignores inhomogeneities. Such hazard assessments are biased toward geologic factors which may be statistically dominant but of limited areal extent. Sweden established criteria for radon-hazard assessment based on soil-gas radon levels (Akerblom, 1986; Wilson, 1987). Duval (1991) shows that more comprehensive measures of radon availability, such as those used in this study, provide more realistic estimates and demonstrate that the use of inadequate criteria can result in requirements for potentially expensive construction techniques in areas where they may not be needed.

Hazard Distribution

Three factors were included in the estimation of radon hazards: (1) uranium concentration, (2) soil permeability, and (3) ground-water depth (table 4). Numerical values from 1 to 3 were assigned to each factor, with higher values corresponding to conditions more conducive to elevated indoor-radon concentrations. Numerical values were then added and cumulative values, from 3 to 9, were grouped into three categories assigned qualitative assessments, from low to high, of the relative potential for an indoor-radon hazard (table 5). Equal weighting of each factor was used because there is insufficient evidence to weight relative contributions for individual factors. Although thorium concentration was also measured and is greater in Ogden Valley than in the southern St. George basin (table 1), thorium concentration is sufficiently low in both areas to indicate that the relative contribution of its decay product, ^{220}Rn, to the radon hazard is small (Stranden, 1984).

Southern St. George Basin

The radon-hazard potential of the southern St. George basin is shown on figure 26. The most extensive areas of high hazard potential occur southeast of Santa Clara in hills underlain by the Petrified Forest Member of the Chinle Formation, and southeast

Table 2.
Residential indoor-radon concentrations. Average concentrations for samples in each radon-hazard potential category are shown, and can be compared to predicted average concentrations shown in table 5. SG - southern St. George basin, OV - Ogden Valley, N = number of samples.

Study area	Sample size	Indoor-Radon Concentrations								Hazard Category					
		<4 pCi/L		4-10 pCi/L		10-20 pCi/L		20-30 pCi/L		Low		Moderate		High	
		N	%	N	%	N	%	N	%	N	Average Concentration (pCi/L)	N	Average Concentration (pCi/L)	N	Average Concentration (pCi/L)
SG	10	8	80	2	20	0	0	0	0	3	0.7	7	2.5	0	—
OV	36	23	64	8	22	4	11	1	3	4	4.4	26	5.2	6	5.6

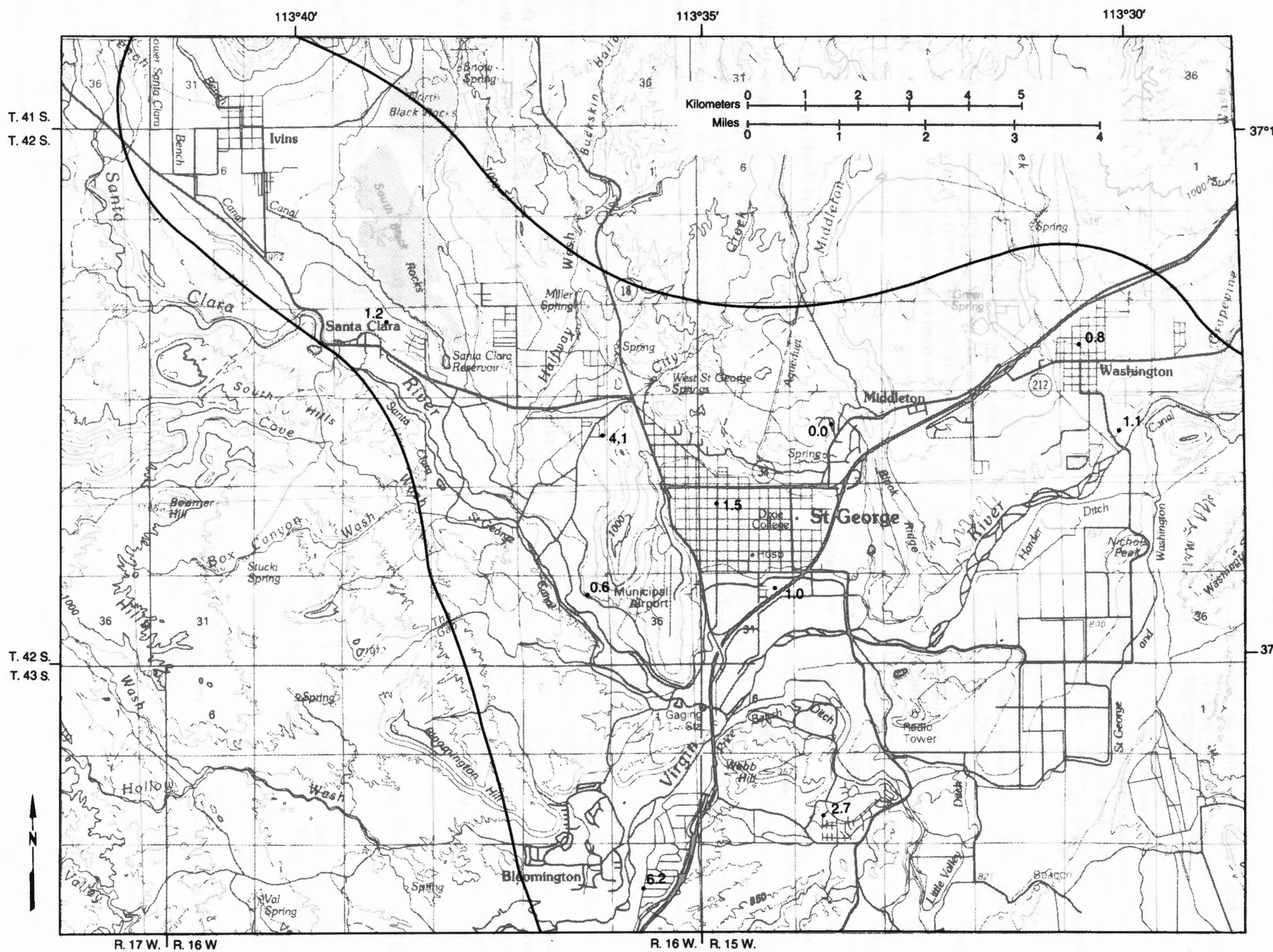


Figure 24. Indoor-radon levels, in pCi/L, in the southern St. George basin.

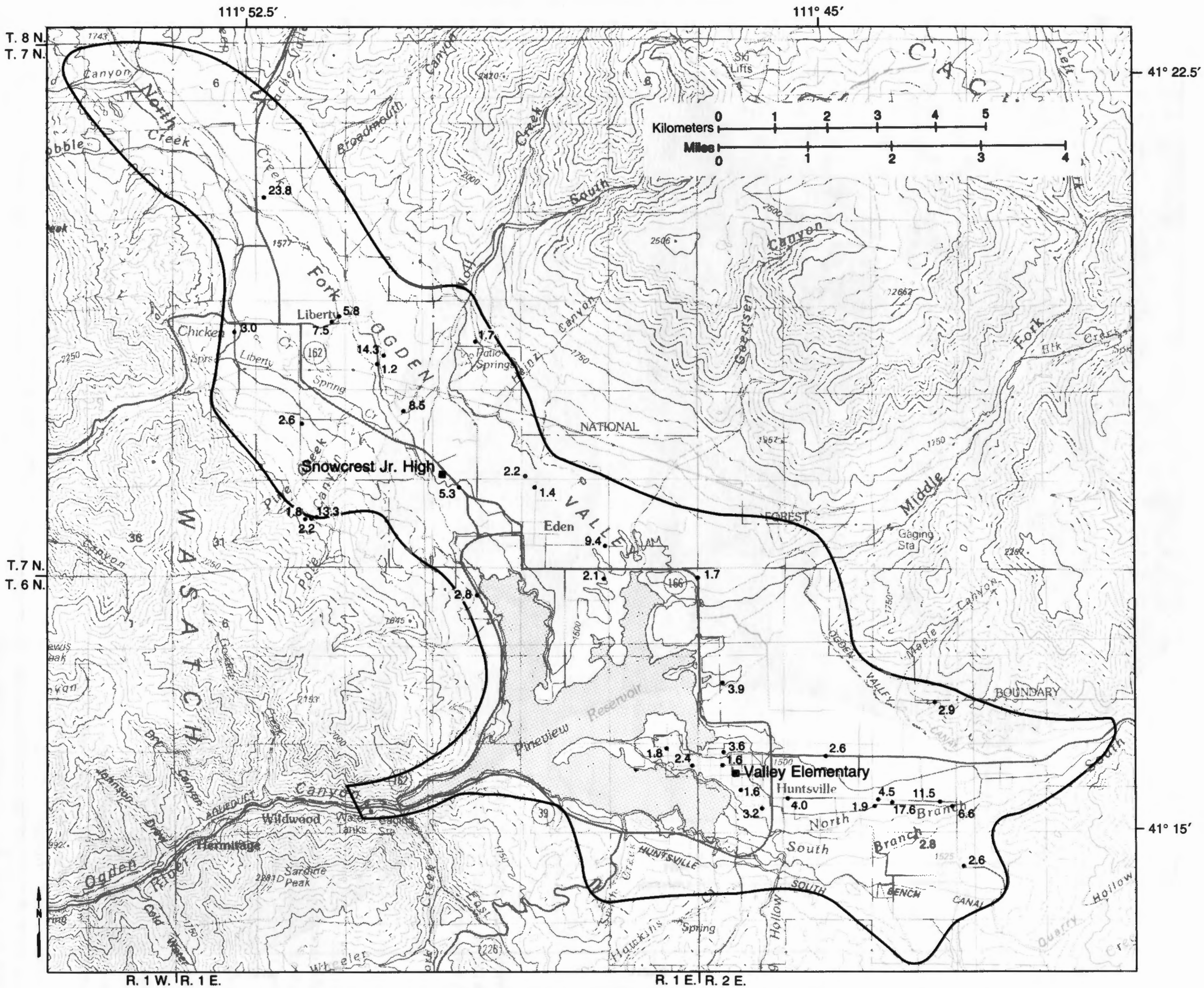


Figure 25. Indoor-radon levels, in pCi/L, in Ogden Valley. Averages of indoor measurements in schools are shown in table 3.

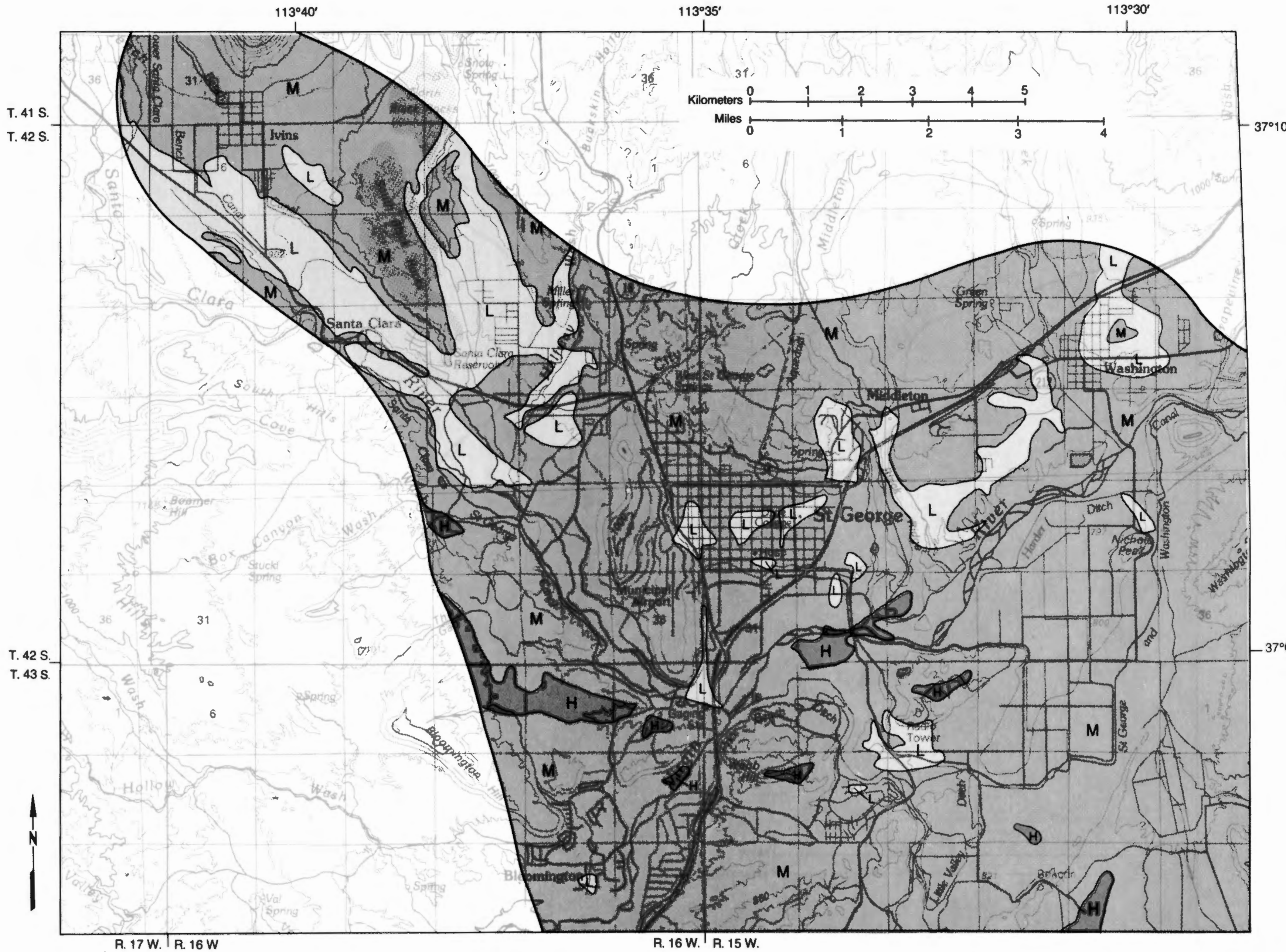


Figure 26. Indoor-radon-hazard potential in the southern St. George basin. L (light shading) - low, M (medium shading) - moderate, and H (dark shading) - high. See table 5 for definition of hazard potential categories.

Table 3.
School indoor-radon concentrations (pCi/L) in Ogden Valley.

Location	Snowcrest Jr. High	Valley Elementary
Sample size	17	17
Mean	0.1	0.3
Variance	0.0	0.2
Standard deviation	0.1	0.5
Skewness	0.0	0.1
Minimum	0.0	0.0
Median	0.0	0.0
Maximum	0.5	1.5

Table 4.
Radon-hazard potential matrix. Soil permeability classes are characterized by hydraulic conductivity, K.

Factor	Point Value		
	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 - 50	>50

Table 5.
Radon-hazard-potential categories. See table 4 for point value of factors in each category.

Category	Point Total	Probable Indoor-Rn Concentration (pCi/L)
Low	3 - 4	<2
Moderate	5 - 7	2 - 4
High	8 - 9	>4

of St. George in alluvium of the Virgin River floodplain. Smaller areas of high hazard potential are scattered throughout the southern portion of the study area. The factor common to areas of high hazard potential is a uranium level greater than 3.0 ppm. Permeability varies considerably in these areas, from relatively high in the floodplain to relatively low in shale of the Petrified Forest Member, but ground water is never less than 10 feet (3 m) below the ground surface.

In other areas where elevated uranium concentrations were measured, such as in the southern portion of Washington Fields southeast of St. George, less permeable soils and moderate ground-water depths offset the potential effects of high uranium levels. Shallow ground water offsets the potential effect of high uranium levels in much of the Virgin River floodplain. These areas, as well as others with lower uranium levels but with more permeable soils, are assigned to the moderate hazard-potential category. Extensive areas with low hazard potential include the Santa Clara Bench south and west of Ivins, the Sand Hollow area northwest of St. George, parts of central St. George, and the area between St. George and Washington. These areas all have soils with low uranium levels and ground water at shallow to moderate depths. These areas of low hazard potential lie within the belt of eolian sand which occurs in the northern part of the study area. Although uranium levels are low throughout this belt, ground water is usually too deep, and soil too permeable, to be an effective barrier to radon migration except in those portions designated with a low hazard potential. Permeable, eolian sand within the low hazard areas is generally thin, and overlies relatively impermeable soil.

Ogden Valley

In Ogden Valley, high hazard potential is most extensive on the northwest valley margin in areas underlain by unconsolidated Quaternary alluvial-fan, fluvial, and lacustrine deposits, and in bedrock outcrops of the Precambrian Formation of Perry Canyon from which nearby unconsolidated deposits are largely derived (figure 27). As in the southern St. George basin, uranium levels are consistently greater than 3.0 ppm in this and other, smaller areas of high hazard potential scattered throughout the valley. Permeability is commonly moderate in alluvial-fan deposits which underlie most high-hazard areas, but is locally high in high-hazard areas underlain by stream alluvium graded to the Provo shoreline. Ground water is deeper than 50 feet (15 m) in high-hazard areas on valley margins, but is between 10 and 50 feet (3 and 15 m) deep in more central locales.

Most other areas with elevated uranium concentrations are underlain by less permeable soils and, particularly in the central part of the valley north of Pineview Reservoir, have shallow

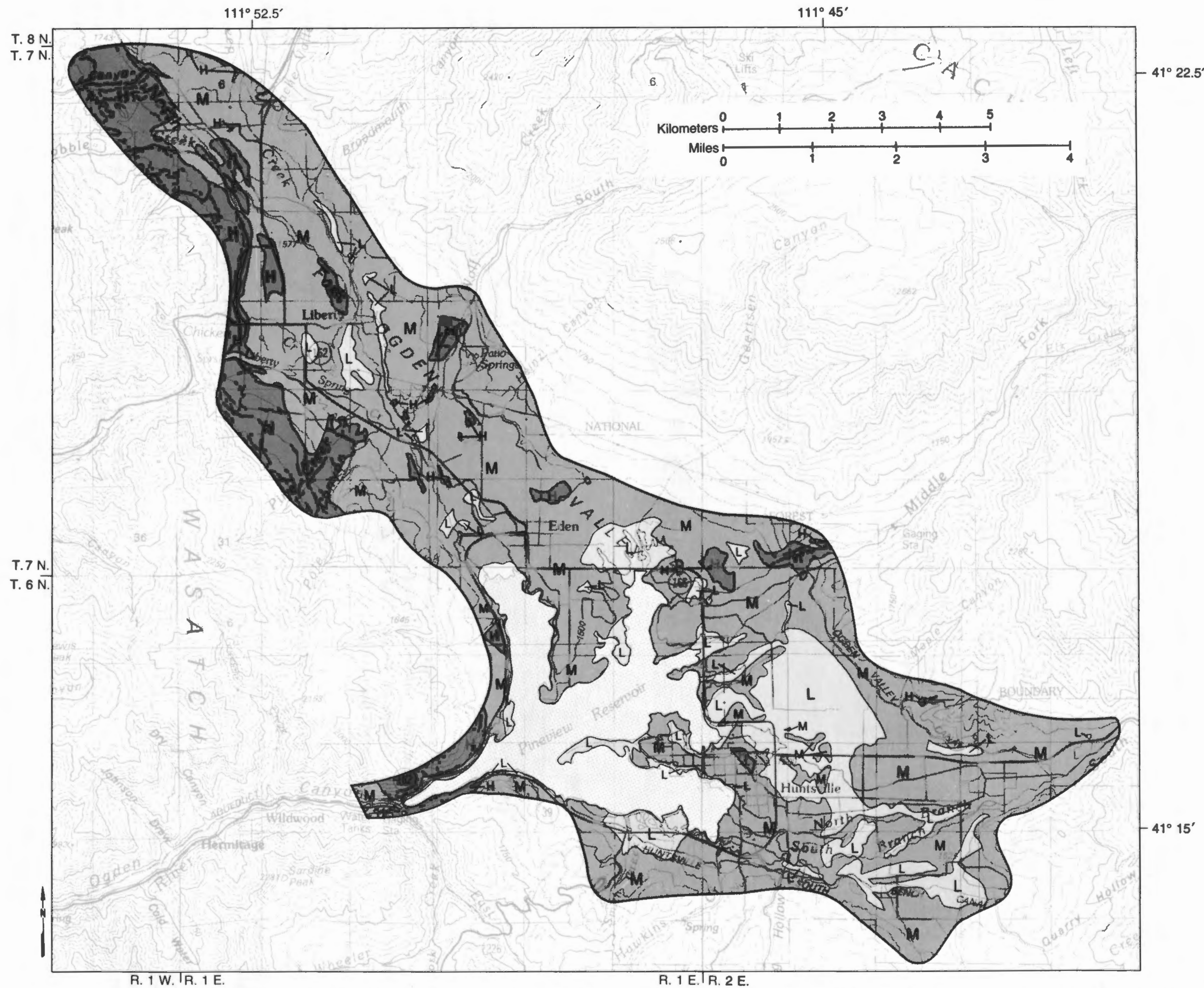


Figure 27. *Indoor-radon hazard potential in Odgen Valley. L (light shading) - low, M (medium shading) - moderate, and H (dark shading) - high. See table 5 for definition of hazard potential categories.*

ground-water depths. These areas, as well as others with lower uranium levels but with more permeable soils, have a moderate hazard potential. The most extensive area with low hazard potential occurs north and east of Huntsville, and results from soils with generally low uranium levels and permeability, and ground water at shallow depths.

Hazard Potential and Soil-Gas Radon Levels

Variations in radon-hazard potential (figures 26 and 27) approximate variations in soil-gas radon levels (figures 20 and 22) for both study areas. In the southern St. George basin, for example, the broad belt of low soil-gas radon levels in the north includes the areas of lowest hazard potential. In both study areas, highest soil-gas radon levels are generally found in areas of moderate and high hazard potential. There are, however, some conflicting data.

Anomalous levels of soil-gas radon may be attributed to several factors. For example, anomalously low levels may be caused by preferential leaching of soluble uranium under oxidizing conditions. Uranium in parts of the Petrified Forest Member in the southern St. George basin may have been mobilized by oxidizing solutions, and moved to reducing sites in adjacent units. Daughter products, however, are not leached. One daughter product, ^{214}Bi, has a more distinctive spectral peak than ^{238}U and it is this bismuth isotope that is actually measured during a spectrographic survey. The amount of measured ^{214}Bi is converted to an equivalent concentration of the parent uranium, and uranium is thus overestimated in the radiometric analysis (Nielson and others, 1991). The radon-hazard potential based upon overestimated uranium concentrations will be anomalously high, and associated soil-gas radon levels will be anomalously low.

Other inconsistencies between soil-gas radon levels and radon-hazard potential may be the result of (1) a soil-gas sampling pattern that is inadequate to detect local unique conditions, (2) atmospheric contamination of soil-gas samples resulting in low levels of soil-gas radon in high-hazard areas, or (3) the influence of physical phenomena not considered in the hazard evaluation. Unmeasured physical phenomena include meteorological effects (Kraner and others, 1964); changes in ground-water pressure, temperature, fluid solubility, and gas content (Rogers, 1958; Stoker and Kruger, 1975); and the effect of grain size on radon emanation (Tanner, 1980). The influence of these factors is difficult to quantify, however, and relevant data are not available or practical to collect for a regional hazard evaluation such as this. Exclusion isolines (figures 21 and 23) minimize the effects of these factors, and validate the hazard potential maps (figures 26 and 27) better than contoured soil-gas radon measurements (figures 20 and 22), by more accurately depicting actual soil-gas radon levels.

Hazard Potential and Indoor-Radon Levels

Even the best radon-hazard potential map based on geology cannot accurately characterize the level of indoor radon because of non-geologic factors that affect indoor-radon levels. A hazard-potential map does, however, provide an estimate of the underlying geologic basis for indoor-radon levels, which may then be modified by the effects of non-geologic factors.

The average of indoor-radon levels measured in the southern St. George basin is 1.9 pCi/L (70.3 Bq/m^3)(table 1). Of the ten measurements made there (figure 24), three were recorded in an area of low hazard potential (figure 26). Each of the three were less than 2 pCi/L (74 Bq/m^3) and within the range of probable indoor-radon concentrations in low hazard-potential areas (table 5). The other seven measurements were recorded in an area of moderate hazard potential and, although with a wider scatter of values, average 2.5 pCi/L (92.5 Bq/m^3), within the range of probable indoor-radon concentrations in moderate hazard-potential areas.

The average indoor-radon level in Ogden Valley, 5.2 pCi/L (192.4 Bq/m^3), is considerably higher than in the southern St. George basin (table 1) and indoor-radon levels in Ogden Valley have a wider range of values within hazard-potential categories (figures 25 and 27). These differences are likely due to the higher average uranium concentration in Ogden Valley, and to local factors not detectable within the survey scale or timeframe.

Although the average level measured in areas of each hazard category increases with hazard potential, only the average of measurements in the area of high hazard potential, 5.6 pCi/L (207.2 Bq/m^3), is in agreement with the probable concentration of that hazard category. The average of four measurements in the area of low hazard potential is 4.4 pCi/L (162.8 Bq/m^3), but this is highly skewed by two high values, and is probably not statistically representative of the area because indoor-radon levels were not measured in a large area northeast of Huntsville. The average of 26 measurements in the area of moderate hazard potential is 5.2 pCi/L (192.4 Bq/m^3) (table 2), but this value is also highly skewed by large values in two relatively small parts of the moderate-hazard potential area northwest of Eden and east of Huntsville. Eighteen of the 26 measurements in the area of moderate hazard potential, 69 percent, were collected outside of the anomalous clusters of indoor measurements and all of the 18 are less than 4 pCi/L (148 Bq/m^3). The anomalous clusters of high indoor-radon values are found where ground water is shallow, and suggest a relationship between water levels and radon emanation. Steele and others (1982) propose that shallow ground water may locally contribute to increased radon concentration at the surface by two mechanisms: (1) outgassing of the sediments in response to seasonal rises in water levels, and (2) upward transport of radon or its precursors from deeper levels by the rising water. Although seasonal increases in radon were not detected in the soil-gas survey of Ogden Valley because it was conducted during a limited time period, such increases were accounted for by integration of year-long results in the indoor survey.

Inconsistencies between the hazard assessment and indoor measurements arise because of the influence of unmeasured geologic and non-geologic factors, the presence of anomalies in measured factors not detected because of map scale, and the lack of a statistically valid sample of indoor measurements due to reliance on volunteers. However, an assessment of the hazard potential based on easily obtainable geologic information is recommended to concentrate testing efforts on those areas for which geologic criteria indicate the greatest hazard potential and to guide the use of radon-resistant techniques in new construction where indoor testing is not possible. Once sufficient indoor data are obtained, average indoor-radon concentrations should better correlate with probable concentrations predicted by the geologic assessment.

Cautions When Using This Report

This report can not be used to predict specific indoor-radon levels, because a quantitative relationship between geologic factors and indoor-radon levels does not exist. Factors not considered in this study can strongly affect indoor-radon levels. Small localized areas of higher or lower radon potential are likely within any given area. All map boundaries between radon-hazard categories are approximate and gradational. Radon-hazard categories are relative, and are specific to the southern St. George basin and Ogden Valley.

CONCLUSIONS

The uranium content of soil and shallow bedrock is the primary factor controlling indoor radon in both the southern St. George basin and Ogden Valley. Uranium and radon in soil gas exhibit a grossly linear relationship, and soil-gas radon is the immediate precursor to indoor radon. However, numerous geologic and non-geologic factors also influence radon levels in both soil gas and indoors. Soil permeability and ground-water levels are two geologic factors which are easily characterized, and affect migration of radon in geologic materials. These factors, and uranium concentrations measured in a ground-based survey, were used in a numerical matrix to create radon-hazard-potential maps. The map of the southern St. George basin shows that parts of the basin have the potential for indoor-radon levels greater than the EPA action level of 4 pCi/L (148 Bq/m^3), despite low uranium concentrations measured during the NURE aerial radiometric survey which imply that no significant hazard potential likely exists. The map of Ogden Valley confirms the implication of the NURE survey that parts of the valley have potential for elevated indoor-radon levels, and adds considerable detail to the distribution of hazard areas implied by NURE uranium concentrations.

In the southern St. George basin, areas of high hazard potential are found along the Virgin River in the southern part of the study area where soils with high uranium concentrations are present. A local primary source of uranium is tuffaceous, fine-grained rock in the Petrified Forest Member of the Chinle Formation. A distant primary source of uranium is granitic rocks in the Pine Valley Mountains to the north. Secondary uranium mobilization, suggested by high U/Th ratios, resulted in uranium enrichment in local areas of rock and soil. Shallow ground water in southern St. George and the Virgin River floodplain inhibits the potential for elevated indoor-radon levels in these areas, and relatively impermeable soils inhibit the potential for elevated indoor-radon levels in other areas with high uranium concentrations. The lowest hazard potential occurs in permeable eolian sands in the northern part of the study area, derived from uranium-deficient Jurassic and Triassic sandstones. Here, low hazard potential is also the result of shallow ground water.

In Ogden Valley, areas of high hazard potential also coincide with areas of high soil-uranium concentrations. These areas are most common on the northwest valley margin, where high uranium levels originate both from bedrock outcrops of the Precambrian Formation of Perry Canyon and unconsolidated Quaternary alluvial-fan, fluvial, and lacustrine deposits largely derived from that rock. High uranium levels are also present in the central and southern parts of the valley, associated with the Tertiary Norwood Tuff and residual soils, but lower permeability and, in the central valley, shallow ground water results in a moderate hazard potential. Low hazard potential is north and east of Huntsville, where low uranium levels, low permeability, and shallow ground water combine to inhibit both soil-gas radon levels and migration.

The relative hazard potential in both study areas can be used to prioritize indoor testing and to evaluate the need for radon-resistant new construction. The hazard-potential maps, however, are only reconnaissance tools. Detailed characterization and testing of specific sites are required to evaluate actual hazards.

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APPENDIX

Ground-Survey Data

Table A-1.
Radiometric data, southern St. George basin, exclusive of indoor-radon measurements. Sample locations are plotted on figure 4.

Sample Number	Total Counts (ppm)	K %	eU (ppm)	eTh (ppm)	eU/eTh	Soil-Gas Rn (pCi/L)
G-001	8.8	1.1	3.4	4.6	0.74	69.86
G-002	10.7	2.0	1.8	7.4	0.24	57.28
G-003	11.3	1.8	2.8	6.6	0.42	125.42
G-004	11.8	2.2	2.1	6.3	0.33	98.22
G-005	8.8	1.8	1.3	4.7	0.28	66.75
G-006	6.4	1.1	1.6	4.5	0.36	36.92
G-007	7.1	1.1	1.9	3.2	0.59	26.97
G-008	8.0	1.3	2.5	5.8	0.43	91.13
G-009	11.1	1.9	2.6	6.0	0.43	—
G-010	10.9	1.6	3.0	7.0	0.43	185.23
G-011	9.8	1.5	3.0	5.0	0.60	118.96
G-012	10.7	1.7	3.1	6.3	0.49	173.12
G-013	9.3	1.8	1.6	6.5	0.25	55.94
G-014	10.1	1.8	2.4	4.6	0.52	56.35
G-015	8.4	1.4	2.2	4.0	0.55	38.45
G-016	9.4	1.7	1.9	7.4	0.26	72.22
G-017	12.2	1.7	3.7	8.4	0.44	178.84
G-118	8.4	1.4	1.9	6.0	0.32	—
G-119	10.6	1.6	2.9	7.9	0.37	137.42
G-020	12.4	2.1	3.3	7.0	0.47	187.26
G-021	12.2	1.9	3.6	8.9	0.40	72.43
G-022	12.2	1.8	3.3	6.7	0.49	110.07
G-023	7.5	1.2	2.3	3.2	0.72	55.10
G-024	13.2	1.9	3.3	8.9	0.37	152.23
G-025	10.3	1.4	3.4	6.9	0.49	201.11
G-026	3.5	0.3	1.8	1.5	1.20	—
G-027	8.5	1.2	3.4	4.1	0.83	—
G-028	13.0	1.9	2.9	9.4	0.31	—
G-029	9.0	1.2	2.8	5.6	0.50	168.06
G-030	8.1	0.9	3.0	5.5	0.55	—
G-031	13.6	2.2	3.4	7.9	0.43	101.32
G-032	8.4	1.3	2.8	4.7	0.60	—
G-033	7.2	1.1	2.6	3.5	0.74	85.28
G-034	14.5	2.3	3.7	9.2	0.40	140.14
G-035	11.8	1.8	3.2	5.5	0.58	189.08
G-036	13.4	2.1	3.7	8.3	0.45	177.16
G-037	8.6	1.2	2.3	6.7	0.34	—
G-038	12.7	2.3	2.3	7.9	0.29	80.57
G-039	7.6	1.1	2.0	5.0	0.40	—
G-040	8.7	1.3	2.3	4.2	0.55	119.95
G-041	9.0	1.6	1.4	5.6	0.25	132.99
G-042	10.4	1.7	2.6	7.2	0.36	149.97
G-043	8.6	1.4	2.0	5.6	0.36	91.53
G-044	13.6	2.3	2.4	10.2	0.24	131.71
G-045	11.5	1.8	2.2	9.7	0.23	187.56
G-046	11.7	1.9	2.5	8.0	0.31	88.46
G-047	11.2	1.9	2.0	9.0	0.22	198.45
G-048	11.8	1.8	2.8	9.7	0.29	94.70
G-049	11.3	1.6	3.2	8.5	0.38	89.47
G-050	11.9	1.6	3.2	9.9	0.32	229.19
G-051	11.7	1.4	3.2	10.0	0.32	227.70
G-052	11.0	1.7	2.9	6.4	0.45	—

Sample Number	Total Counts (ppm)	K %	eU (ppm)	eTh (ppm)	eU/eTh	Soil-Gas Rn (pCi/L)
G-053	9.4	1.6	1.5	6.8	0.22	—
G-054	10.4	1.6	1.6	8.6	0.19	—
G-055	7.6	1.0	2.4	5.0	0.48	—
G-056	11.2	2.2	2.0	6.5	0.31	—
G-057	7.0	1.3	1.8	4.4	0.41	—
G-058	6.0	0.9	2.0	3.3	0.61	—
G-059	6.7	1.0	1.1	4.7	0.23	—
G-060	5.9	1.0	1.0	4.0	0.25	—
G-061	9.2	1.4	2.1	5.8	0.36	148.91
G-062	11.4	1.8	2.2	8.2	0.27	—
G-063	10.0	1.5	2.6	6.5	0.40	—
G-064	7.2	1.3	1.2	5.4	0.22	34.93
G-065	5.6	1.0	1.3	4.6	0.28	—
G-066	11.9	2.4	1.8	7.7	0.23	91.56
G-067	12.7	2.1	1.5	12.7	0.12	83.26
G-068	4.6	0.8	1.2	2.6	0.46	—
G-069	4.6	0.8	0.7	4.1	0.17	—
G-070	7.3	1.5	0.9	5.3	0.17	—
G-071	8.7	1.6	1.1	5.1	0.22	105.75
G-072	5.2	1.0	1.0	2.8	0.36	40.10
G-073	9.8	1.7	1.4	5.9	0.24	—
G-074	4.9	0.8	1.4	1.7	0.82	—
G-075	5.4	0.9	1.1	2.5	0.44	79.31
G-076	5.8	1.0	1.4	3.3	0.42	49.46
G-077	9.4	1.9	1.2	5.6	0.21	97.37
G-078	8.0	1.6	1.4	4.7	0.30	—
G-079	9.4	1.6	2.0	5.2	0.38	—
G-080	9.0	2.0	2.0	3.5	0.57	—
G-081	6.9	1.5	0.2	2.2	0.09	—
G-082	9.9	1.6	2.2	6.5	0.34	—
G-083	3.3	0.7	0.2	2.1	0.10	—
G-084	6.3	0.9	2.2	3.3	0.67	—
G-085	7.2	1.2	1.6	5.4	0.30	—
G-086	4.1	0.8	1.2	1.7	0.71	22.34
G-087	3.8	0.1	1.1	1.4	0.79	—
G-088	5.9	1.1	1.2	3.0	0.40	—
G-089	10.9	1.7	2.5	7.9	0.32	—
G-090	5.3	0.6	2.0	3.6	0.56	—
G-091	10.7	1.9	1.8	8.4	0.21	286.87
G-092	9.9	1.6	2.1	7.4	0.28	136.59
G-093	5.5	1.0	1.4	3.3	0.42	—
G-094	8.1	1.7	1.7	4.3	0.40	31.33
G-095	15.1	2.6	2.7	11.0	0.25	—
G-096	6.9	0.9	1.8	5.9	0.31	—
G-097	6.3	0.9	2.3	3.1	0.74	—
G-098	4.9	0.7	1.6	3.3	0.48	—
G-099	6.2	0.9	1.2	5.4	0.22	—
G-100	8.9	1.8	2.0	5.6	0.36	128.93
G-101	5.4	0.8	2.3	1.8	1.28	28.14
G-102	7.7	1.3	1.9	3.1	0.61	49.55

Table A-1 (continued)

Sample Number	Total Counts (ppm)	K %	eU (ppm)	eTh (ppm)	eU/eTh	Soil-Gas Rn (pCi/L)
G-103	8.8	1.6	1.8	7.2	0.25	58.60
G-104	6.3	1.2	1.1	3.4	0.32	42.39
G-105	7.5	1.0	1.3	6.4	0.20	—
G-106	7.9	1.4	1.2	5.2	0.23	—
G-107	14.5	2.7	2.0	11.3	0.18	—
G-108	13.0	1.3	3.5	13.2	0.27	—
G-109	7.2	1.5	0.6	4.2	0.14	30.70
G-110	8.6	1.4	2.2	5.4	0.41	—
G-111	11.2	1.9	2.0	7.9	0.25	—
G-112	10.3	1.6	2.4	7.2	0.33	296.06
G-113	14.5	2.4	3.3	10.5	0.31	—
G-114	6.8	1.2	0.9	5.6	0.16	—
G-115	15.1	2.6	2.9	9.5	0.31	—
G-116	5.7	1.0	1.6	4.0	0.40	—
G-117	6.2	1.1	1.3	3.4	0.38	—
G-118	13.5	1.8	4.6	9.8	0.47	334.77
G-119	10.6	1.4	4.4	4.7	0.98	302.14
G-120	8.2	1.2	2.4	3.4	0.71	297.70
G-121	11.6	1.9	3.3	6.7	0.49	62.26
G-122	13.2	2.1	3.0	11.6	0.26	220.78
G-123	8.0	1.1	2.1	4.4	0.48	—
G-124	8.9	1.2	2.6	5.3	0.49	—
G-125	13.6	2.2	2.6	9.7	0.27	—
G-126	9.8	0.9	3.0	9.2	0.33	—
G-127	11.0	1.6	3.4	6.5	0.52	128.78
G-128	10.5	1.7	3.3	5.9	0.56	—
G-129	9.7	1.4	3.5	3.7	0.95	—
G-130	8.4	1.2	2.8	5.9	0.47	—
G-131	10.1	0.7	3.6	8.7	0.41	—
G-132	10.5	2.3	1.5	4.2	0.36	—
G-133	16.7	3.0	1.8	13.5	0.13	—
G-134	4.4	0.9	1.3	2.3	0.57	—
G-135	10.1	0.7	2.9	12.6	0.23	—
G-136	7.8	1.0	2.6	4.4	0.59	—
G-137	8.9	1.4	2.4	4.6	0.52	72.66
G-138	8.5	1.2	3.8	3.9	0.97	97.15
G-139	9.8	1.4	3.4	5.0	0.68	—
G-140	13.2	2.0	3.4	9.4	0.36	878.43
G-141	8.9	0.8	3.4	7.6	0.45	—
G-142	8.1	1.0	3.3	5.1	0.65	—
G-143	8.5	1.5	2.3	5.4	0.43	—
G-144	14.2	2.4	2.7	11.9	0.23	—
G-145	11.4	2.0	2.4	7.6	0.32	118.93
G-146	10.9	1.5	2.5	8.5	0.29	171.73
G-147	8.9	1.4	3.4	5.6	0.61	246.72
G-148	8.7	1.2	3.1	4.8	0.65	—
G-149	7.8	0.9	3.1	6.4	0.48	—
G-150	9.8	1.0	5.3	4.6	1.15	—
G-151	8.0	0.4	6.7	1.6	4.19	—
G-152	11.6	1.6	5.9	6.0	0.98	—

Sample Number	Total Counts (ppm)	K %	eU (ppm)	eTh (ppm)	eU/eTh	Soil-Gas Rn (pCi/L)
G-153	12.1	1.7	4.7	4.0	1.18	—
G-154	9.0	1.3	2.8	5.0	0.56	—
G-155	11.2	1.7	2.7	6.7	0.40	—
G-156	6.7	1.4	2.1	3.6	0.58	—
G-157	9.3	1.4	2.1	6.9	0.30	—
G-158	12.4	2.1	2.4	8.7	0.28	104.53
G-159	6.7	1.1	2.1	4.2	0.50	—
G-160	9.1	1.7	2.1	4.3	0.49	—
G-161	7.6	1.3	1.0	7.0	0.14	—
G-162	10.2	2.2	1.6	5.0	0.32	—
G-163	9.5	1.9	2.0	3.9	0.51	172.64
G-164	9.5	1.8	1.6	5.3	0.30	57.34
G-165	6.7	1.3	1.9	3.2	0.59	232.00
G-166	4.9	0.9	1.1	2.7	0.41	—
G-167	4.8	0.8	1.8	2.6	0.69	—
G-168	9.5	1.4	2.8	5.4	0.52	—
G-169	7.5	1.2	1.9	4.0	0.48	—
G-170	2.4	0.4	0.5	1.1	0.45	—
G-171	8.5	1.3	1.8	8.4	0.21	—
G-172	6.9	1.3	1.1	3.6	0.31	116.62
G-173	10.5	2.1	2.2	4.8	0.46	96.45
G-174	9.0	1.8	1.9	4.4	0.43	218.72
G-175	7.7	1.6	0.6	4.8	0.13	141.32
G-176	6.0	1.0	1.4	3.7	0.38	—
G-177	3.2	0.5	1.0	2.1	0.48	—
G-178	3.8	0.5	1.1	2.5	0.44	—
G-179	9.5	1.4	1.7	9.1	0.19	—
G-180	10.7	1.4	1.9	11.1	0.17	—
G-181	9.0	1.2	3.7	5.3	0.70	—
G-182	8.3	1.1	3.1	4.4	0.70	—
G-183	6.6	0.9	2.7	4.0	0.68	—
G-184	7.7	1.1	1.3	7.4	0.18	—
G-185	6.4	0.8	2.1	4.4	0.48	—
G-186	6.6	1.3	1.2	4.5	0.27	—
G-187	7.7	1.2	2.0	5.0	0.40	—
G-188	8.9	1.4	1.7	6.8	0.25	—
G-189	10.1	1.6	2.3	6.9	0.33	—
G-190	17.5	3.7	2.3	10.7	0.21	—
G-191	8.6	1.5	2.4	4.1	0.59	—
G-192	6.9	1.1	1.2	5.2	0.23	—
G-193	6.4	1.0	1.7	3.1	0.55	—
G-194	6.2	1.0	1.4	3.3	0.42	—

Table A-2.
Radiometric data, Ogden Valley, exclusive of indoor-radon measurements. Repeat samples were collected at sites 13 and 88 to test the reproducibility of data, and are denoted by letters following the sample number (for example, OV-13A). Sample locations are plotted on figure 5.

Sample Number	Total Counts (ppm)	K %	eU (ppm)	eTh (ppm)	eU/eTh	Soil-Gas Rn (pCi/L)
OV-001	19.4	2.3	6.1	14.8	0.41	22.04
OV-002	14.8	1.9	3.7	13.8	0.27	2.83
OV-003	10.3	0.9	3.5	11.8	0.30	0.00
OV-004	9.2	1.0	2.7	9.9	0.27	389.48
0V-005	7.3	0.8	2.2	7.5	0.29	—
OV-006	8.4	1.0	1.8	8.7	0.21	57.70
0V-007	7.3	0.9	2.3	5.5	0.42	67.28
0V-008	8.4	1.0	3.0	7.3	0.41	409.45
0V-009	11.6	1.5	2.1	9.9	0.21	1059.30
0V-010	8.5	0.8	2.6	8.5	0.31	316.67
0V-011	9.6	1.3	3.3	5.8	0.57	603.46
0V-012	6.5	0.8	1.1	7.3	0.15	236.19
0V-013	10.7	1.5	2.3	8.7	0.26	1431.81
0V-13A	10.2	1.3	2.7	8.1	0.33	299.13
0V-13B	—	—	—	—	—	27.22
0V-13C	—	¤	¤	¤	—	96.30
0V-13D	—	¤	¤	¤	—	425.73
0V-13E	11.8	1.5	2.9	11.3	0.26	113.45
0V-13F	12.4	1.5	2.9	10.8	0.27	309.10
0V-014	11.6	1.4	2.0	11.8	0.17	378.62
0V-015	13.8	1.9	3.0	12.0	0.25	810.86
0V-016	14.1	1.7	3.7	14.3	0.26	2268.66
0V-017	7.6	0.8	1.3	7.2	0.18	—
0V-018	9.8	1.3	1.2	11.4	0.11	—
0V-019	6.3	0.7	1.8	4.6	0.39	—
0V-020	7.5	1.0	1.9	5.7	0.33	—
0V-021	8.9	1.3	2.7	5.4	0.50	—
0V-022	6.5	0.8	1.4	6.8	0.21	—
0V-023	6.2	0.8	1.9	4.9	0.39	—
0V-024	6.5	0.6	1.8	5.8	0.31	—
0V-025	13.8	1.9	2.7	12.4	0.22	259.70
0V-026	7.5	0.9	2.1	7.1	0.30	—
0V-027	8.9	1.0	2.5	8.5	0.29	0.00
0V-028	13.9	1.7	3.0	12.8	0.23	252.61
0V-029	12.7	1.6	2.5	9.9	0.25	—
0V-030	13.6	1.7	2.7	14.1	0.19	357.35
0V-031	15.0	1.9	2.8	16.3	0.17	934.22
0V-032	12.6	1.6	2.9	11.3	0.26	—
0V-033	9.7	1.2	3.2	7.5	0.43	—
0V-034	8.7	1.1	2.4	6.4	0.38	—
0V-035	9.8	1.4	1.5	8.9	0.17	—
0V-036	9.2	1.2	2.3	6.9	0.33	—
0V-037	13.2	1.6	4.0	10.5	0.38	15.52
0V-038	12.6	1.7	2.0	13.3	0.15	334.55
0V-039	12.5	1.6	2.4	10.9	0.22	698.06
0V-040	15.4	2.0	3.3	12.8	0.26	352.79
0V-041	6.6	0.9	1.9	5.5	0.35	421.17
0V-042	6.7	0.9	1.4	5.3	0.26	—
0V-043	9.0	1.2	1.9	8.5	0.22	—

Sample Number	Total Counts (ppm)	K %	eU (ppm)	eTh (ppm)	eU/eTh	Soil-Gas Rn (pCi/L)
OV-044	14.0	2.0	2.4	10.7	0.22	—
OV-045	12.8	1.6	3.4	12.6	0.27	—
OV-046	5.9	0.8	1.1	6.6	0.17	—
OV-047	12.6	1.4	2.9	13.3	0.22	1213.09
0V-048	14.3	2.0	2.9	13.8	0.21	—
OV-049	15.5	1.9	3.7	13.3	0.28	386.47
0V-050	14.1	2.2	1.7	13.1	0.13	760.77
0V-051	9.5	1.1	2.6	8.6	0.30	384.68
0V-052	15.4	2.0	3.5	12.3	0.28	366.41
0V-053	10.8	1.3	2.3	12.0	0.19	—
0V-054	12.4	1.7	2.8	11.4	0.25	—
0V-055	14.1	2.0	3.1	11.5	0.27	—
0V-056	6.7	1.0	1.6	6.7	0.24	—
0V-057	6.5	0.9	1.6	4.6	0.35	—
0V-058	6.2	0.7	2.2	5.8	0.38	163.47
0V-059	14.4	2.1	2.7	12.8	0.21	802.22
0V-060	6.9	0.8	2.5	5.2	0.48	76.55
0V-061	13.1	1.6	2.7	13.0	0.21	699.09
0V-062	15.9	1.8	3.3	16.0	0.21	—
0V-063	17.7	2.4	4.1	13.1	0.31	—
0V-064	18.3	2.4	2.6	19.7	0.13	301.36
0V-065	14.1	1.9	3.7	11.0	0.34	—
0V-066	13.6	1.6	3.0	13.7	0.22	—
0V-067	14.3	1.7	4.1	13.0	0.32	—
0V-068	13.3	1.8	1.8	14.7	0.12	—
0V-069	14.3	1.6	2.5	15.8	0.16	288.04
0V-070	7.3	1.0	1.4	6.9	0.20	158.93
0V-071	10.2	1.3	2.2	13.5	0.16	148.97
0V-072	9.7	1.4	2.6	7.6	0.34	336.42
0V-073	6.0	0.9	0.8	5.5	0.15	—
0V-074	6.7	1.0	1.4	6.1	0.23	290.34
0V-075	15.6	2.0	2.8	15.0	0.19	—
0V-076	8.7	1.2	1.5	9.2	0.16	—
0V-077	14.3	1.7	3.9	11.3	0.35	—
0V-078	14.2	1.7	2.8	13.5	0.21	—
0V-079	12.7	1.7	2.7	11.5	0.23	—
0V-080	12.1	1.6	2.8	10.6	0.26	1.15
0V-081	10.5	1.2	3.6	7.2	0.50	4.09
0V-082	14.8	1.7	3.8	13.1	0.29	134.55
0V-083	14.7	1.9	3.4	13.4	0.25	21.73
0V-084	9.6	1.3	2.8	7.0	0.40	4.78
0V-085	10.8	1.5	2.1	9.3	0.23	—
0V-086	12.4	1.6	1.3	12.2	0.11	—
0V-087	7.6	1.0	1.5	7.5	0.20	—
0V-088	9.8	1.4	2.6	8.0	0.33	—
0V-88A	10.1	1.3	2.4	9.4	0.26	355.36
0V-089	12.9	1.6	3.6	12.5	0.29	508.35
0V-090	14.4	2.0	3.6	14.2	0.25	932.85
0V-091	7.7	0.9	2.1	6.6	0.32	22.08

Table A-2 (continued)

Sample Number	Total Counts (ppm)	K %	eU (ppm)	eTh (ppm)	eU/eTh	Soil-Gas Rn (pCi/L)
OV-092	7.2	0.8	2.0	6.7	0.30	171.69
OV-093	15.3	1.7	5.4	11.2	0.48	387.46
OV-094	9.0	1.1	3.1	6.6	0.47	—
OV-095	12.0	1.4	3.8	10.9	0.35	44.66
0V-096	10.1	1.2	2.9	7.2	0.40	39.65
OV-097	10.6	1.4	1.9	10.9	0.17	1054.03
0V-098	10.1	1.3	2.4	8.8	0.27	75.60
0V-099	7.2	0.9	1.9	6.2	0.31	—
0V-100	7.7	1.0	2.1	5.7	0.37	—
0V-101	7.3	1.0	1.3	6.6	0.20	—
0V-102	7.0	0.9	1.6	7.2	0.22	546.40
0V-103	16.3	1.7	3.4	18.1	0.19	—
0V-104	14.3	1.8	2.8	15.3	0.18	634.69
0V-105	8.3	1.1	1.8	6.5	0.28	—
0V-106	14.8	1.9	3.6	12.9	0.28	558.27
0V-107	13.3	1.5	3.8	11.8	0.32	963.36
0V-108	15.3	1.9	4.2	12.5	0.34	631.89
0V-109	14.8	1.9	2.6	12.9	0.20	487.42
0V-110	14.1	2.0	2.2	12.6	0.17	1137.82
0V-111	9.3	1.2	2.3	6.5	0.35	68.34
0V-112	14.6	2.0	2.9	12.4	0.23	297.95
0V-113	19.1	2.7	4.4	16.2	0.27	338.68
0V-114	19.0	3.0	3.7	14.9	0.25	635.43
0V-115	20.4	2.4	4.6	17.8	0.26	374.66
0V-116	16.4	2.2	3.7	13.3	0.28	402.63
0V-117	13.7	1.7	2.9	11.3	0.26	0.00
0V-118	11.4	1.4	2.6	10.2	0.25	392.87
0V-119	15.9	1.9	3.7	17.0	0.22	—
0V-120	15.4	1.9	3.7	14.2	0.26	—
0V-121	15.1	2.1	3.1	13.7	0.23	41.03
0V-122	12.4	1.5	2.1	12.0	0.18	117.71
0V-123	8.1	1.0	2.3	7.3	0.32	—
0V-124	23.8	2.5	4.8	25.7	0.19	—
0V-125	9.1	1.0	2.4	7.0	0.34	132.19
0V-126	8.1	0.9	2.0	7.9	0.25	182.04

Table A-3

Indoor-radon measurements, southern St. George basin, listed by community and postal zip code. Sample locations are plotted on figure 24.

Sample Number	Indoor Radon (pCi/L)
Santa Clara - 84765	
483338	1.2
St. George - 84770	
483344	6.2
35175	4.1
35022	2.7
35429	1.5
35050	1.0
35405	0.6
35145	0.0
Washington - 84780	
483234	1.1
634604	0.8
35458	Detector not returned

Table A-4.

Indoor-radon measurements, OgdenValley, listed by community and postal zip code. Sample locations are plotted on figure25.

Sample Number	Indoor Radon (pCi/L)
Eden - 84310	
35148	13.3
35456	9.4
483758	8.5
35246	5.3
35083	2.8
35201	2.2
35245	2.2
483511	2.1
35157	1.8
34988	1.7
35037	1.4
34971	1.2
35168	Detector not returned
Liberty - 84310	
35231	23.8
35108	14.3
35007	7.5
35001	5.8
35069	3.0
35212	2.6
35165	1.7
35254	Detector not returned
Huntsville - 84317	
483180	17.6
35132	11.5
35135	6.6
35440	4.5
35232	4.0
35033	3.9
35031	3.6
35019	3.2
35017	2.9
35149	2.8
483588	2.6
35010	2.6
35144	2.4
35096	1.9
35071	1.8
34967	1.6
35146	1.6
35194	Detector not returned
35197	Detector not returned
35243	Detector not returned