1993 - 22

GEOLOGIC MAPPING OF RADON-HAZARD POTENTIAL IN UTAH

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ABSTRACT

Geologic data were used to map potential radon-hazard areas in Utah. The first statewide map identified rock uranium† sources, but did not systematically evaluate populated areas underlain by unconsolidated valley fill. Subsequent indoor testing identified high radon levels in some of this valley fill. Detailed geologic studies and targeted indoor surveys were performed in six areas with high indoor-radon levels. Initially, these studies assigned hazard potentials to Quaternary geologic units, assuming that each unit was relatively homogeneous. Indoor-radon levels were used for model validation. Later studies used overlays of specific geologic factors (uranium content, permeability, and ground-water depth) to derive a composite hazard map, with hazard categories independent of geologic units. Soil-gas radon concentrations were used for validation with exclusion isolines, a semiquantitative analysis technique that minimizes the effect of factors which differentially reduce soil-gas radon concentrations. Hazard-potential maps derived from overlays effectively identify potential hot spots, and do not rely upon either geologic or artificial political boundaries to constrain hazard interpretations. The overlay method was used to revise the statewide radon-hazard-potential map, and assessments of hazard potential from detailed field investigations correlate well with those on the revised statewide map. Central Utah has the highest radon-hazard potential, primarily due to uranium-enriched Tertiary volcanic rocks. Western Utah has the lowest radon-hazard potential, due to limitations on radon emanation and migration imposed by impermeable soils and shallow ground water common in basins.

INTRODUCTION

A preliminary, qualitative geologic assessment of potential radon hazards in Utah (Sprinkel 1987), based predominantly on bedrock geology, indicated areas which could be generalized sources of radon. A survey of indoor-radon levels was conducted in these source areas (Sprinkel and Solomon 1990) to identify clusters of indoor levels greater than 4 pCi L^{-1}. Several clusters were found, and six were targeted for detailed geologic and indoor surveys. Two hazard classification methods were used to accomodate geologic factors that influence indoor-radon levels in specific geologic settings. The first method, used in the study of two areas along the populous Wasatch Front (Solomon et al. 1991), assumes that geologic conditions are relatively uniform within geologic units and assigns numerical ratings to geologic factors considered for each unit. The second method, used in the study of four areas elsewhere in Utah (Solomon 1992; Black in preparation; Solomon in preparation[a,b]), assumes that geologic

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† For this report radon and uranium refer to ^{222}Rn which forms from the decay of ^{238}U, thorium refers to ^{232}Th, and potassium refers to ^{40}K. Gamma-ray spectrometer measurements of these uranium and thorium isotopes refer to equivalent uranium (eU) and equivalent thorium (eTh) measured from progeny with distinctive spectral peaks.

conditions vary within geologic units and boundaries are gradational rather than discrete, and assigns numerical ratings to geologic factors mapped on overlays. The latter method was modified to re-evaluate the statewide radon-hazard potential (Black 1993), and results of detailed geologic field investigations are in close agreement with the revised statewide assessment.

PRELIMINARY ESTIMATE OF THE RADON-HAZARD POTENTIAL OF UTAH

Sprinkel (1987) first mapped potential radon-hazard areas in Utah using regional geologic data (Fig. 1). However, some important geologic factors in areas underlain by thick sequences of unconsolidated valley fill, such as permeability and ground-water depth, were not considered. The type and scale of geologic data used in the compilation made the map very generalized. A later, statewide survey of indoor-radon levels showed that they are consistently higher in areas where favorable geologic conditions exist. This was the first indication of the extent of Utah's indoor-radon problem.

Geologic Considerations

Potential radon-hazard areas in the preliminary radon-hazard assessment (Sprinkel 1987) were identified by known uranium occurrences (possible point sources for radon); uranium-enriched rocks (generalized sources) at the surface or beneath well-drained, porous, and permeable soils; anomalous surficial uranium concentrations; and the surface trace of the Wasatch fault zone. Uranium occurrences included uranium mines, uranium mill sites, and geothermal areas. The distribution of uranium-enriched rocks was compiled from published maps. A 1:1,000,000 scale computer-generated map of apparent surface concentration of uranium in Utah, derived from a national map (Duval et al. 1989) and compiled from airborne radiometric surveys of the National Uranium Resource Evaluation (NURE) program, outlined uraniferous rocks not otherwise shown by geologic mapping. Sprinkel (1987) considered the Wasatch fault zone a likely source of increased radon emanation and a permeable route for radon migration. Quaternary units were not included in the compilation unless documented in publications to be a radon source.

Sprinkel (1987) shows potential radon-hazard areas scattered throughout the state (Fig. 1), but some areas are of particular significance. Much of the Wasatch Front, a linear, north-trending region in central Utah which includes the majority of Utah's population, is shown as an area of relatively high hazard potential. The largest area of high hazard potential includes a belt of volcanic rocks extending northeastward across southwestern Utah. Sprinkel (1987) shows numerous localized sources of enriched uranium and radium in southern Utah, but they do not occur in areas of uraniferous rocks mapped as generalized sources of radon.

The Utah Indoor-Radon Study

Volunteers for indoor testing were solicited from residents of radon-hazard areas identified by Sprinkel (1987). Indoor testing was conducted in two phases. The first phase involved participants from throughout the state and commenced in late 1987. Elevated indoor levels were concentrated in particular geographic locations, and a second phase of targeted indoor surveys commenced in early 1991 in six of these locations (Fig. 2). Homes selected to participate in both phases were owner-occupied, single-family dwellings. Volunteers placed alpha track-etch monitoring devices in the lowest livable area of their homes, and monitored their homes for twelve months. There were 631 devices returned for analysis from the statewide survey, and an additional 502 devices from the targeted surveys. The distribution of monitors reflects population density, and thus the populous Wasatch Front counties (Davis, Salt Lake, Utah, and Weber) received most of the monitors (Table 1).

The average indoor-radon level measured in these surveys was 2.7 pCi L^{-1} (Table 1), with 15.8 percent of measurements greater than 4 pCi L^{-1}. This is considerably higher than the comparable figures for the United States of 1.7 pCi L^{-1} and 6 percent, respectively (Sextro 1988). The county-by-county distribution of average indoor-radon levels (Table 1, Fig. 2) broadly parallels the preliminary geologic estimate of radon-hazard areas (Fig. 1). Elevated indoor-radon levels are clustered in Beaver, Piute, and Sevier Counties, and roughly coincide with the volcanic terrane in southwestern Utah identified by Sprinkel (1987) as a potential hazard area. Low average indoor levels were measured in Kane, Millard, and Tooele Counties, in which few sources of radon were identified. Geologic

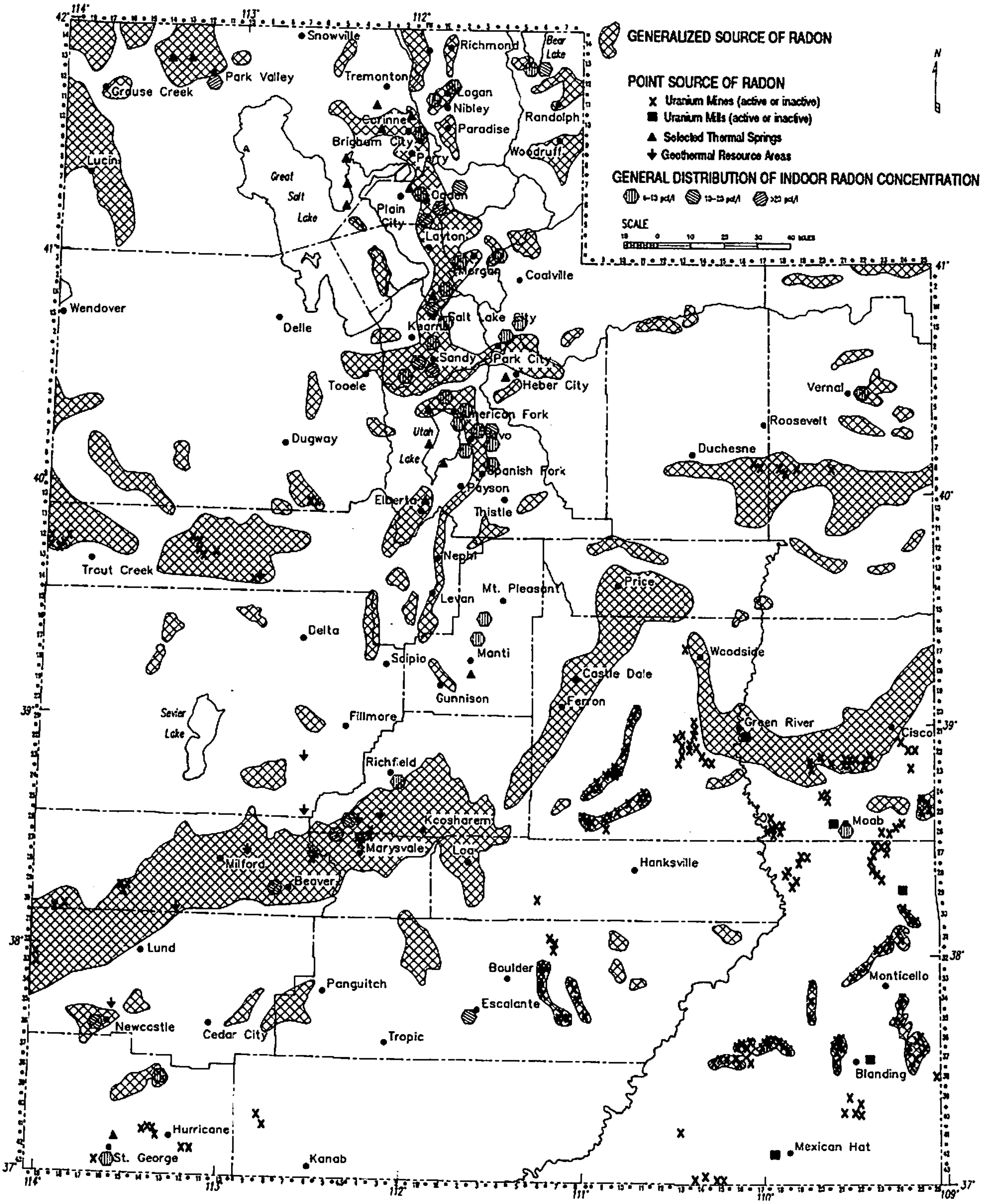

Fig. 1. Preliminary estimate of potential radon-hazard areas in Utah (modified from Sprinkel 1987).

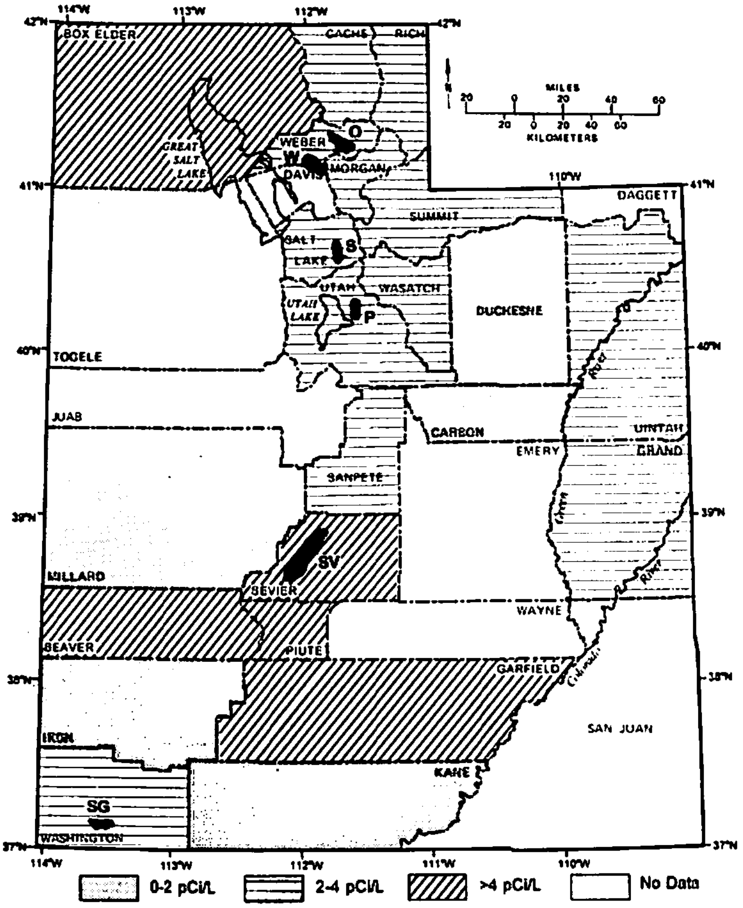

Fig. 2. Average indoor-radon concentrations in Utah counties. Locations of targeted indoor surveys and detailed geologic studies are shown in black: O - Ogden Valley, P - Provo, S - Sandy, SG - St. George, SV - Sevier Valley, W - Weber River area.

characteristics conducive to elevated indoor-radon levels in other counties varied, and this is reflected by variations in indoor-radon measurements.

Whereas the map of average indoor-radon levels (Fig. 2) is a useful aid to visualize levels within political boundaries, it is not suitable to determine the potential hazard in any particular area. Utah is characterized by many large, sparsely populated counties and a few small, densely populated counties. Population density is often concentrated within small regions of each county. If hazard potential is based on average levels of indoor radon in political units, hazard assessments may be biased toward factors of local extent not necessarily characteristic of population centers, or toward factors characteristic of the population center but not of the remainder of the county. For example, sixteen indoor measurements were collected in Box Elder County in northwestern Utah. Only three of the sixteen (18.8 percent) are greater than 4 pCi L^{-1}, one of which is 52.0 pCi L^{-1}. This single high measurement causes the countywide average to double from 2.9 to 5.9 pCi L^{-1}. Two of the three elevated levels were measured in homes in the rural northwestern part of the county; the average of the 13 measurements in a more densely populated strip along the eastern border of Box Elder County is only 2.5 pCi L^{-1}. This latter average is most representative of the potential hazard exposure of most county residents. Conversely, Salt Lake County occupies less than 1 percent of Utah's area, but 42.1 percent of the state's population live mostly in the eastern half of the county. Countywide average indoor-radon levels, biased toward populous areas in which the greatest number of measurements are recorded, may inaccurately suggest to residents outside of the urban corridor a level of potential hazard to which they may not actually be subjected. A more representative sampling grid is desirable, but may be difficult to obtain. Geologic studies, though, do not depend upon resident participation, and the relative hazard potential can be accurately mapped by characterizing a few significant factors. The areal hazard distribution is mapped without bias toward population density.

DETAILED GEOLOGIC STUDIES

Detailed characterization of geologic factors which influence indoor-radon levels were conducted in the six areas of targeted indoor surveys (Fig. 2). Three of the areas are in the Wasatch Front urban corridor and the other three are rural communities experiencing rapid growth: (1) Sandy, a suburb of Salt Lake City in southern Salt Lake County, and the state's fourth most populous city; (2) Provo, in northern Utah County, the state's third most

Table 1. Indoor-radon concentrations in Utah. Values in pCi L^{-1}.

County	Sample Size	Mean	Variance	Standard Deviation	Minimum	Maximum	%≥4 pCi L^{-1}	% State Area	% State Population
Beaver	2	6.7	14.4	3.8	2.9	10.5	50.0	3.2	0.3
Box Elder	16	5.9	144.7	12.0	0.9	52.0	18.8	6.8	2.1
Cache	17	2.6	3.4	1.8	0.5	7.1	23.5	1.4	4.1
Carbon	1	0.4	0.0	0.0	0.4	0.4	0.0	1.8	1.2
Daggett	0	0.0	0.0	0.0	0.0	0.0	0.0	0.9	0.0
Davis	45	1.6	1.0	1.0	0.2	4.3	4.4	0.3	10.9
Duchesne	14	1.8	2.1	1.4	0.3	5.7	7.1	4.0	0.7
Emery	0	0.0	0.0	0.0	0.0	0.0	0.0	5.4	0.6
Garfield	2	4.8	2.6	1.6	3.2	6.4	50.0	6.4	0.2
Grand	2	3.2	6.0	2.5	0.7	5.6	50.0	4.5	0.4
Iron	6	1.8	1.0	1.0	0.6	3.8	0.0	4.0	1.2
Juab	0	0.0	0.0	0.0	0.0	0.0	0.0	4.2	0.3
Kane	2	1.2	0.5	0.7	0.5	1.9	0.0	5.0	0.3
Millard	2	0.7	0.1	0.4	0.3	1.0	0.0	8.1	0.7
Morgan	4	3.9	1.7	1.3	2.2	5.7	50.0	0.7	0.3
Piute	2	10.6	72.3	8.5	2.1	19.1	50.0	0.9	0.1
Rich	10	3.5	10.2	3.2	1.6	12.1	20.0	1.2	0.1
Salt Lake	456	2.6	7.4	2.7	0.0	26.2	15.8	0.9	42.1
San Juan	0	0.0	0.0	0.0	0.0	0.0	0.0	9.6	0.7
Sanpete	7	3.7	3.2	1.8	1.8	7.3	42.9	1.9	0.9
Sevier	38	4.9	23.9	4.9	0.3	22.4	44.7	2.4	0.9
Summit	15	2.9	2.1	1.4	0.6	4.9	26.7	2.3	0.9
Tooele	2	0.8	0.0	0.2	0.6	1.0	0.0	8.4	1.5
Uintah	10	3.4	7.9	2.8	0.7	8.5	30.0	5.4	1.3
Utah	192	2.6	4.6	2.1	0.2	13.6	14.1	2.4	15.3
Wasatch	1	3.6	0.0	0.0	3.6	3.6	0.0	1.5	0.6
Washington	16	3.1	12.2	3.5	0.0	14.3	31.3	3.0	2.8
Wayne	0	0.0	0.0	0.0	0.0	0.0	0.0	3.0	0.1
Weber	271	2.5	25.2	5.0	0.0	68.2	11.1	0.7	9.2
All	1133	2.7	13.9	3.7	0.0	68.2	15.8	100.0	100.0

populous city; (3) the Weber River area of northern Davis and southern Weber Counties, a suburban area south of Ogden, the state's sixth most populous city; (4) Ogden Valley, east of Ogden in eastern Weber County; (5) St. George, in Washington County, southwestern Utah; and (6) Sevier Valley, in Sevier County, central Utah. These areas were selected for study because each had clusters of indoor-radon levels in excess of 4 pCi L^{-1} and, in some cases, average levels greater than the statewide average.

Two techniques were used to map the potential radon hazard in the study areas. The first, used in Sandy and Provo, assumes that physical characteristics of each geologic unit are relatively uniform. This method assigns average data values to each unit, with discrete changes in values at unit boundaries. The second method, used in the other four study areas, assumes that the natural variation of physical characteristics within geologic units is not adequately represented by average values. This method maps physical characteristics irrespective of unit boundaries. The Sandy and Ogden Valley studies are summarized as examples of these two techniques. Radiometric measurements collected in all study areas are summarized in Table 2.

Table 2. Statistical summary of radiometric data. O - Ogden Valley, P - Provo, S - Sandy, SG - St. George, SV - Sevier Valley, W - Weber River area.

	Soil						Soil Gas		Indoor	
Study Area	Sample Size	Total Count (ppm)	K (%)	eU (ppm)	eTh (ppm)	eU/ eTh	Sample Size	Rn (pCi L^{-1})	Sample Size	Rn (pCi L^{-1})
O	130	11.6	1.5	2.7	10.5	0.27	80	388	36	5.2
P	99	9.2	1.2	2.6	6.8	0.39	57	449	152	2.5
S	131	20.6	2.4	5.6	13.2	0.43	56	528	206	3.0
SG	194	9.1	1.4	2.3	5.9	0.45	82	134	10	1.9
SV	202	14.3	1.9	3.6	11.1	0.37	99	240	38	4.9
W	169	11.0	1.4	2.5	9.2	0.30	90	280	179	2.1

Hazard Potential Assuming Discrete Boundary Conditions

The radon-hazard potential of Sandy was estimated using three geologic factors: (1) uranium content of soils, (2) concentration of radon in soil gas, and (3) depth to ground water (Solomon et al. 1991). Numerical scores from 1 to 4 were applied to each factor, with higher scores corresponding to conditions favorable for elevated indoor-radon concentrations. Scores were summed, with each factor weighted equally because there is no quantitative evidence indicating the relative importance of individual factors to the radon hazard. Three radon-hazard-potential categories were established based on the cumulative totals of the three factors, and the categories were used to characterize the hazard potential for each major Quaternary geologic unit. NURE airborne radiometric measurements were interpreted for Sandy and the adjacent Wasatch Range for rapid hazard-potential evaluation.

In Sandy, the Wasatch fault zone separates unconsolidated deposits in Salt Lake Valley from bedrock in the Wasatch Range. The valley is underlain by a complex sequence of unconsolidated Quaternary alluvial, deltaic, lacustrine, and eolian basin-fill deposits dominated by latest Pleistocene Lake Bonneville surficial materials (Personius and Scott 1992). Although a wide variety of bedrock types occur in the Wasatch Range east of Sandy, only two lithologies provide source material with elevated uranium levels to the Quaternary deposits in the study area:

(1) Oligocene granitic rocks of the Little Cottonwood, Alta, and Clayton Peak stocks (Crittenden 1976); and (2) Precambrian metamorphic rocks, including the Mineral Fork Formation (Condie 1967). In the study area ground water is found in unconsolidated, unconfined valley aquifers at depths greater than 50 feet to the east, but less than 10 feet to the west (Anderson et al. 1986).

Published ground-water data were supplemented by collected field data, which includes: (1) uranium, thorium, and potassium concentrations in shallow soil, (2) soil-gas radon levels, (3) soil moisture and density, and (4) soil texture. Gamma-ray spectrometry shows that average uranium levels are significantly higher in Sandy than in other areas studied in detail (Table 2). This uranium anomaly, which averages 5.6 ppm in unconsolidated deposits, is evident in the NURE data, as are anomalies associated with uranium-enriched bedrock in the Wasatch Range. The highest uranium levels are found in upper Pleistocene sand and gravel of the Provo (regressive) shoreline of the Bonneville lake cycle, and in upper Pleistocene gravelly alluvium of terraces graded to this shoreline. Elevated uranium levels are reflected in high concentrations of radon in soil gas, averaging 528 pCi L^{-1} with a maximum of 2,398 pCi L^{-1}. There are considerable geographic variations in the distribution of uranium and soil-gas radon that coincide with Pleistocene drainage patterns. Highest levels are present near the mouth of Little Cottonwood Canyon, which drains granitic terrane. Lowest levels are present near the mouth of Big Cottonwood Canyon, which drains terrane predominantly underlain by quartzite, shale, and slate of the Precambrian Big Cottonwood Formation.

Geologic units with the highest relative radon-hazard potential are upper Pleistocene lacustrine sediments related to the Bonneville (transgressive) phase of the Bonneville lake cycle, as well as regressive and other younger deposits overlying the transgressive units. Here, uranium levels as high as 10.6 ppm and soil-gas radon levels as high as 2,398 pCi L^{-1} occur in well-drained sediments on benches near the mountain front (Fig. 3). Although indoor-radon levels were not used to evaluate hazard potential, the clustering of elevated indoor-radon levels within the area of highest hazard potential serves to validate the hazard map. The average indoor-radon level in Sandy is 3.0 pCi L^{-1}, with 18 percent of measurements greater than 4 pCi L^{-1} (Table 2). However, in the area of Sandy with the highest hazard potential the average indoor-radon level is 3.5 pCi L^{-1}, with 27 percent of measurements greater than 4 pCi L^{-1}, compared to the state average of 2.7 pCi L^{-1} and 15.8 percent (Table 1). A 4-square-mile portion of the high-hazard area has an average indoor-radon level of 9.1 pCi L^{-1}. Of 28 indoor measurements in this "hot spot," all were greater than 4 pCi L^{-1}, with a maximum measurement of 26.2 pCi L^{-1}.

Some low levels of indoor radon were measured in the area of highest relative hazard potential, outside of the "hot spot." Whereas non-geologic factors such as weather, construction type, and resident lifestyle undoubtedly contributed to this variability, the application of average values for each geologic unit, and the assumption of discrete changes in values across geologic-unit boundaries, may account for some of the scatter in the data. A hazard-assessment technique which assumes variability of geologic factors within units, and gradational changes of geologic factors across unit boundaries, reduces this shortfall. This latter technique is also applicable to a wider variety of geologic settings which either lack published mapping or sufficiently differentiated mapped units.

Hazard Potential Assuming Gradational Variation

The radon-hazard potential of Ogden Valley (Solomon in preparation[a]) was also estimated using three geologic factors, although soil permeability was used rather than concentration of radon in soil gas because of greater permeability contrasts in Ogden Valley than in Sandy. Soil-gas radon was used for validation of the hazard assessment. As in Sandy, numerical scores were applied to each factor, equal weighting was used, and radon-hazard-potential categories were calculated to estimate the hazard potential. However, the three radon-hazard-potential categories in Ogden Valley were compiled by overlaying basic-data maps developed for each of the three geologic factors, summing hazard ratings, and tracing contacts based on summed ratings for all three geologic factors. Hazard categories are independent of the boundaries of Quaternary geologic units.

Unconsolidated Quaternary units in Ogden Valley 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). Bedrock units on the valley margin include low-grade metasedimentary rocks of Middle Proterozoic to Cambrian age; Mississippian carbonates;

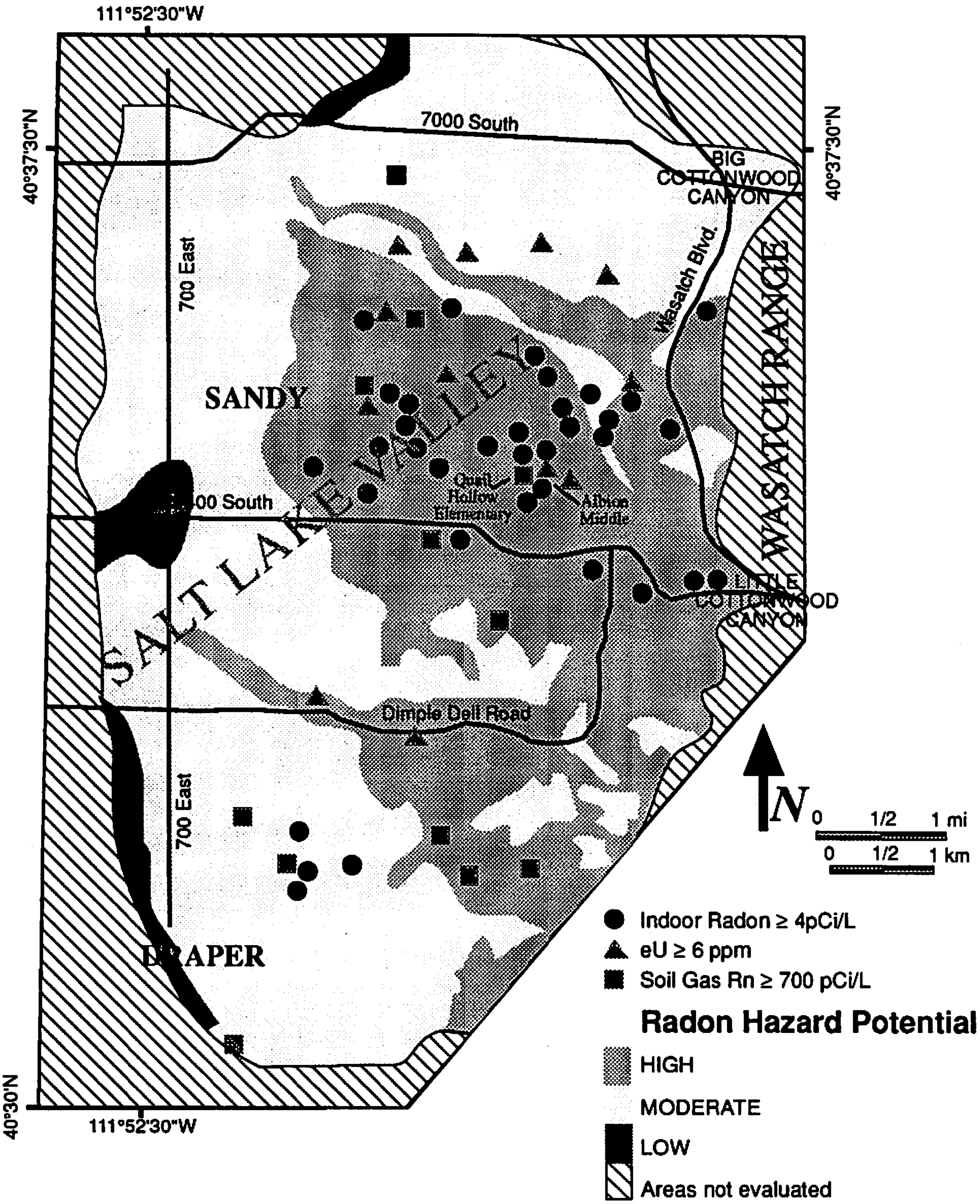

Fig. 3. Radon-hazard potential of Sandy, Utah (modified from Solomon et al. 1991).

Upper Cretaceous to Eocene coarse, clastic sedimentary rocks; and the Eocene to Oligocene Norwood Tuff. Detritus and residual soils from the Norwood Tuff are the predominant source of uranium in the valley, and a secondary source are metasedimentary rocks in the Proterozoic Formation of Perry Canyon. Permeability in the valley is highest in flood plains along the valley axis and lowest in residual soils on the Norwood Tuff on valley margins (Carley et al. 1980). Ground water is found in unconsolidated, unconfined aquifers at depths greater than 50 feet on valley margins, but less than 10 feet in flood plains (Leggette and Taylor 1937). A deeper, unconsolidated artesian aquifer is present in the western portion of the valley (Doyuran 1972).

Published permeability and ground-water data were supplemented by collected field data, which includes: (1) uranium, thorium, and potassium concentrations in shallow soil, (2) soil-gas radon levels, and (3) soil texture. Soil moisture and density data were not collected because gravelly soils prevented drilling of augered access holes. Gamma-ray spectrometry shows that average uranium levels are not as high as in Sandy but, with an average of 2.7 ppm (Table 2) and a maximum of 6.1 ppm, are sufficiently high to be associated with excessive indoor-radon levels (Muessig 1988). The highest uranium levels are found in unconsolidated Quaternary alluvial-fan, fluvial, and lacustrine deposits in northwestern Ogden Valley; and fluvial and lacustrine deposits in central and southern Ogden Valley.

Soil-gas radon levels did not correlate well with uranium concentrations because of disequilibrium between shallow soils tested for uranium content and deeper soils tested for radon content, and atmospheric contamination of some soil-gas samples when air leaks between the probe and dry, permeable soil. These influences can be overcome to some extent with the use of a semiquantitative interpretation method originally developed for analysis of radon concentrations measured in surface-water surveys (Durrance 1978). This method is based on the premise that many factors can act to reduce the radon concentration of a sample, but only an influx of radon will result in high concentrations. If an area of uniformly high radon input is considered, the results of a survey in which sample points have an irregular distribution will show an apparently random pattern of high and low values, the high values being the true indicators and the low values being the result of factors which produce artificially low concentrations. It may be inferred, therefore, that only the high values have significance. 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. Areas of consistently high concentrations may then be taken as geologically meaningful. Exclusion isolines in Ogden Valley indicate higher levels of soil-gas radon, up to 2,269 pCi L^{-1}, in residual soil and bedrock along north and central valley margins; lower levels occur in flood-plain alluvium (Fig. 4). Variations in hazard potential (Fig. 5) approximate variations in soil-gas radon levels. Although elevated indoor-radon levels were measured in all three hazard-potential categories (Fig. 5), average indoor levels are greatest in the areas of highest hazard potential. The average indoor-radon level in these areas is 5.6 pCi L^{-1} with 50 percent of measurements greater than 4 pCi L^{-1}. As in Sandy, some low levels of indoor radon were measured in the area of highest relative hazard potential, and some high levels were measured in areas of lower relative hazard potential. However, the distribution of soil-gas radon levels shown by exclusion isolines, and average indoor-radon levels in hazard-potential categories, validate the utility of the overlay method to identify the potential indoor-radon hazard.

THE RADON-HAZARD-POTENTIAL MAP OF UTAH

The radon-hazard mapping technique used in Ogden Valley was also used to revise the statewide radon-hazard-potential map (Black 1993) (Fig. 6). Basic-data maps were developed for each of three geologic factors: (1) uranium concentration, (2) soil permeability, and (3) ground-water depth. Uranium concentration in Utah, compiled from the computer-generated uranium contour map derived from the national NURE airborne radiometric map of Duval et al. (1989), was grouped into three categories with concentrations of: (1) less than 1.5 ppm; (2) 1.5 ppm or greater, but less than 2.5 ppm; and (3) 2.5 ppm or greater. Soils in Utah have been mapped and classified by the U.S. Soil Conservation Service (SCS) (Wilson et al. 1973). Based on SCS permeability data, Utah soils were grouped into categories with hydraulic conductivities of: (1) less than 0.6 inches/hour; (2) 0.6 inches/hour or greater, but less than 6.0 inches per hour; and (3) 6.0 inches/hour or greater. Ground-water depths were taken from Hecker et al. (1988), which groups depths to ground water into three categories: (1) less than 10 feet; (2) 10 feet or greater,

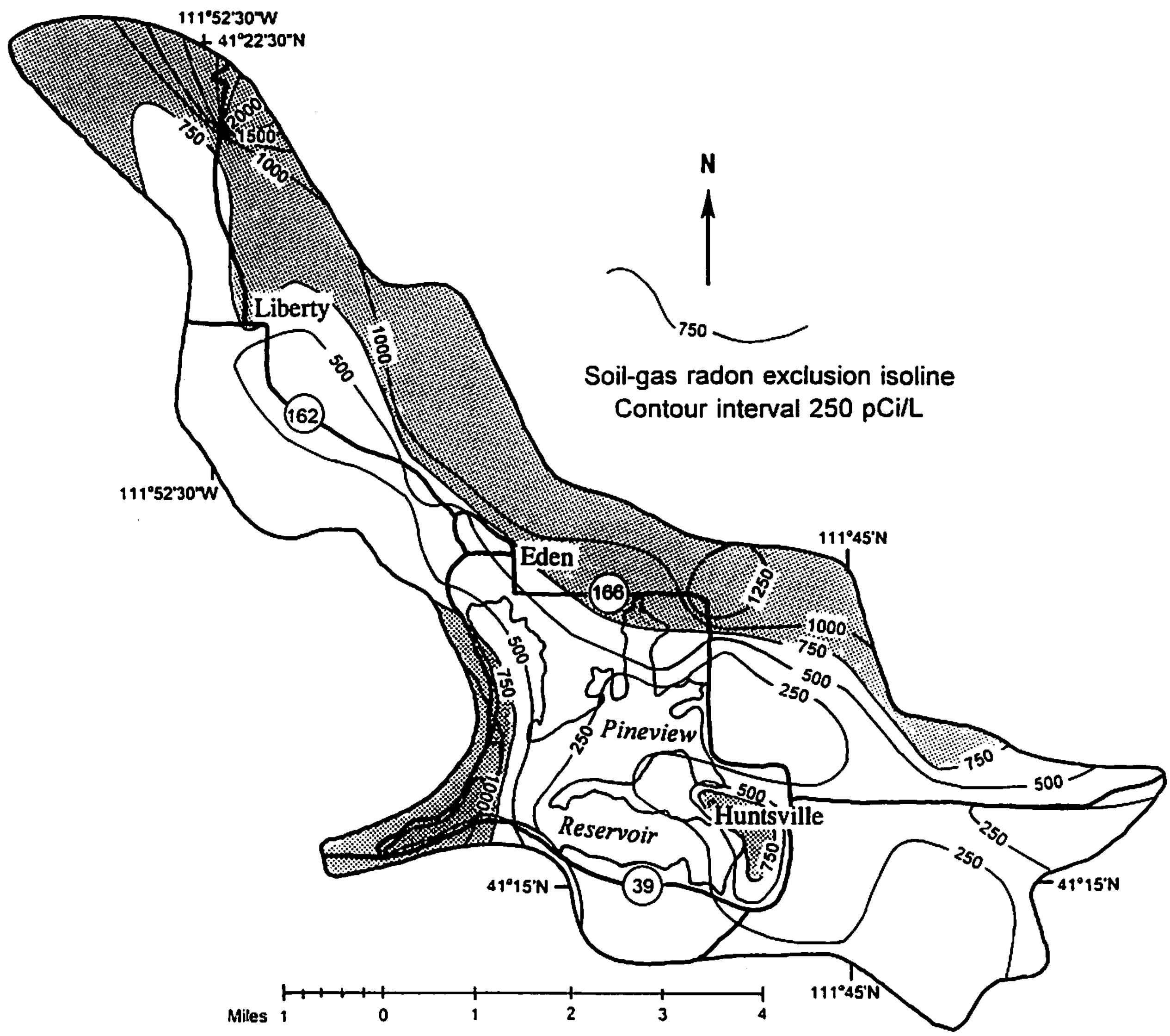

Fig. 4. Exclusion isolines of soil-gas radon, Ogden Valley, Utah (modified from Solomon in preparation[a]). Areas which yield greater that 750 pCi L^{-1}, shown by shading, generally correspond to areas with high hazard potential (Fig. 5).

but less than 30 feet; and (3) 30 feet or greater. Local perched ground-water conditions and seasonal ground-water fluctuations were not considered. The radon-hazard-potential map was derived by overlaying the three basic-data maps, summing equally-weighted hazard ratings, and tracing contacts based on summed ratings for all three geologic factors. Three radon-hazard-potential categories were established based on the cumulative totals of the three factors.

The Basin and Range-Colorado Plateau transition zone (Fig. 7) has the highest overall radon-hazard potential in the state. In this area, high hazard potential commonly occurs where uranium-enriched Tertiary volcanic rocks are found, such as in the volcanic plateaus of south-central Utah. Low hazard potential occurs in central parts of valleys where shallow ground water and low permeability soils are found. The Colorado Plateau Province has a

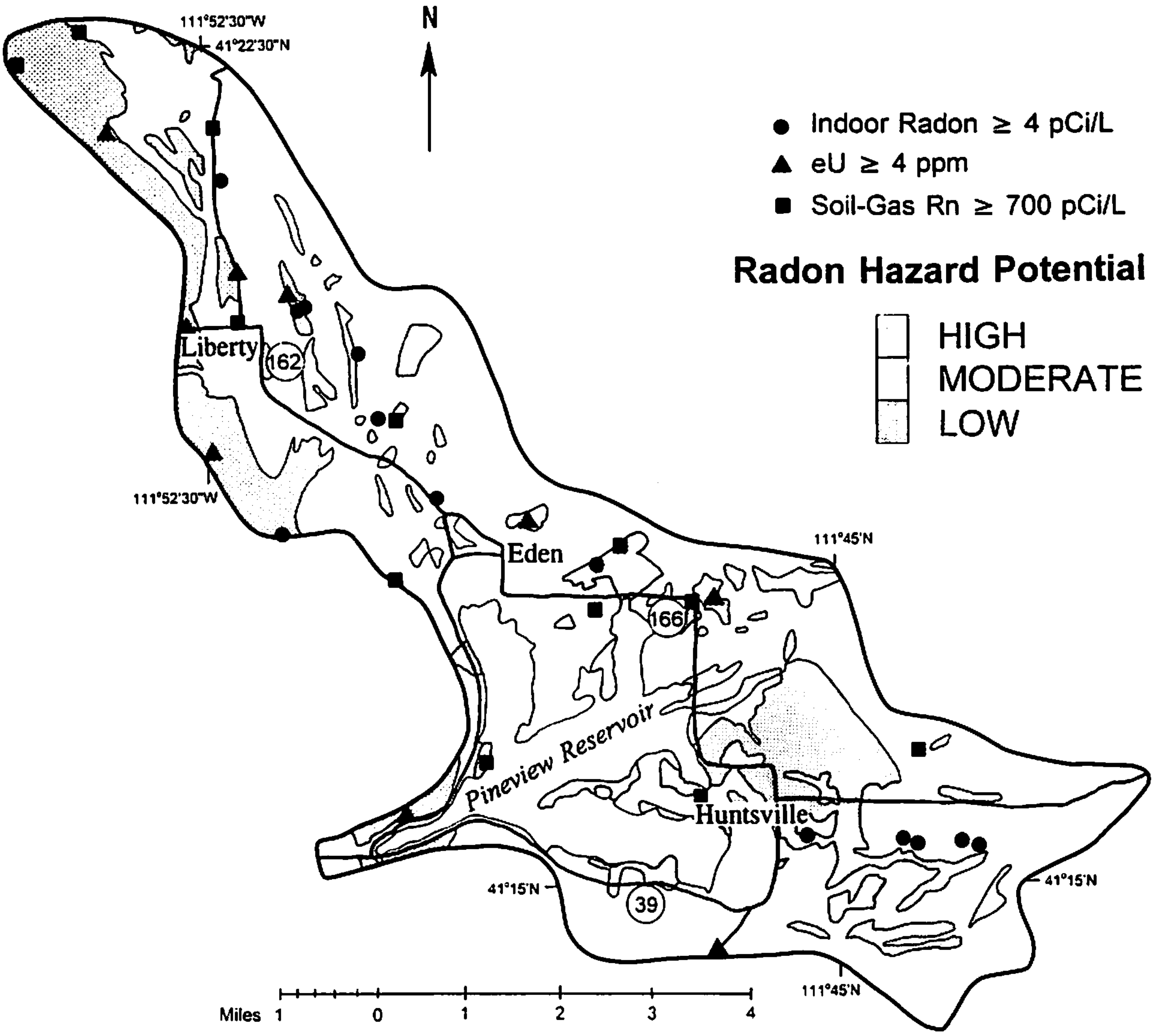

Fig. 5. Radon-hazard potential of Ogden Valley, Utah (modified from Solomon in preparation[a]).

moderate to high radon-hazard potential. Areas of high radon-hazard potential either have moderate uranium levels but permeable soils and deep ground water, or are associated with uranium-enriched sedimentary rocks such as the Triassic Chinle and Jurassic Morrison Formations. Areas of low potential are few. The Middle Rocky Mountains Province has a generally moderate radon-hazard potential. Much of this province has low uranium levels, but areas with moderate to high uranium levels associated with Tertiary volcanic rocks and Precambrian metamorphic rocks have high radon-hazard potentials. The Basin and Range Province has the lowest overall radon-hazard potential, but moderate to high potential is present along the urbanized Wasatch Front, where benches along the mountain front have favorable soil and ground-water conditions. High radon-hazard potential also commonly occurs in mountain ranges of the province, where soil and ground-water conditions are favorable for indoor-radon hazards and where Tertiary volcanic rocks are found. A low hazard potential is common in basin bottoms of northwestern Utah

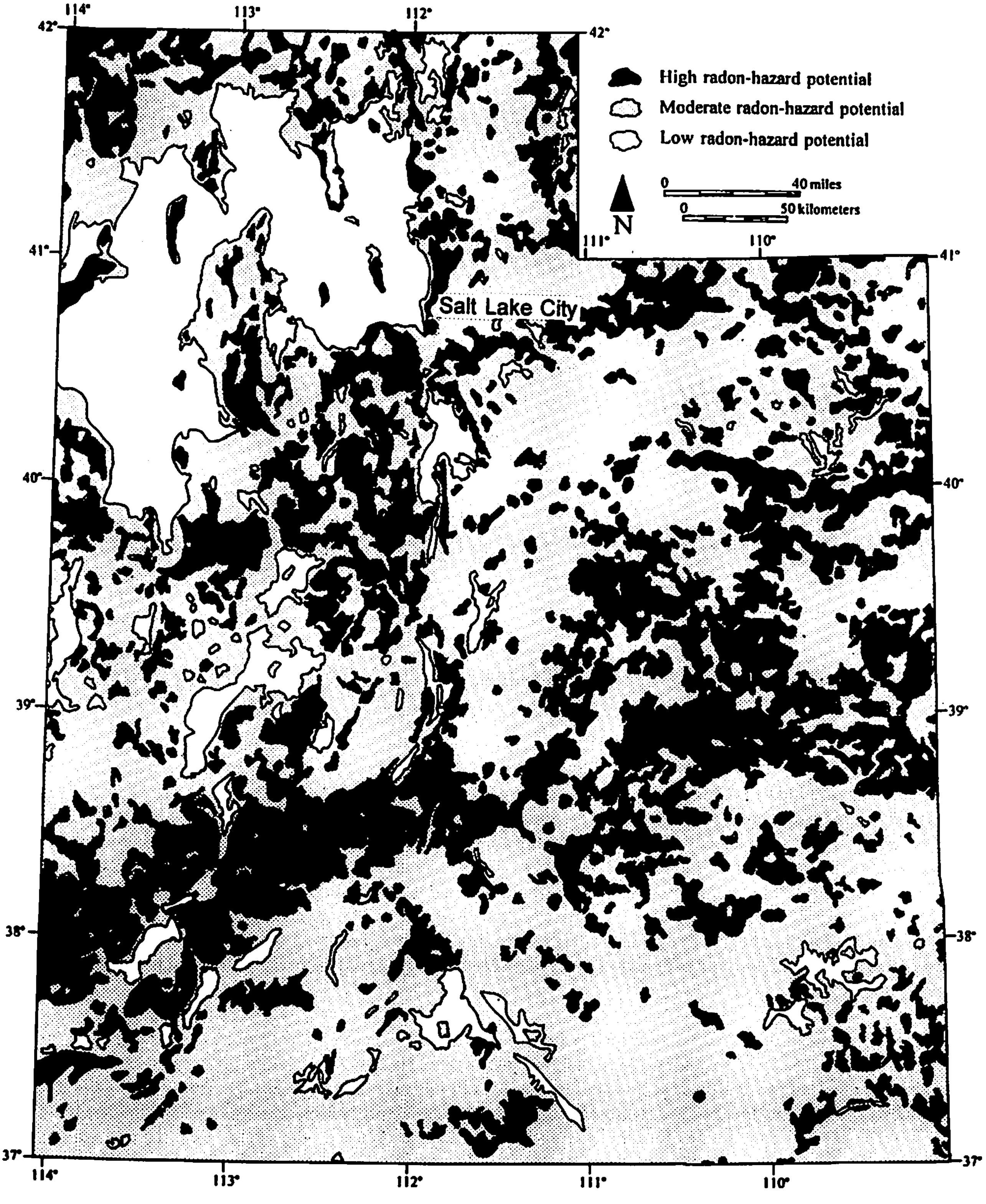

Fig. 6. Radon-hazard-potential map of Utah (modified from Black 1993).

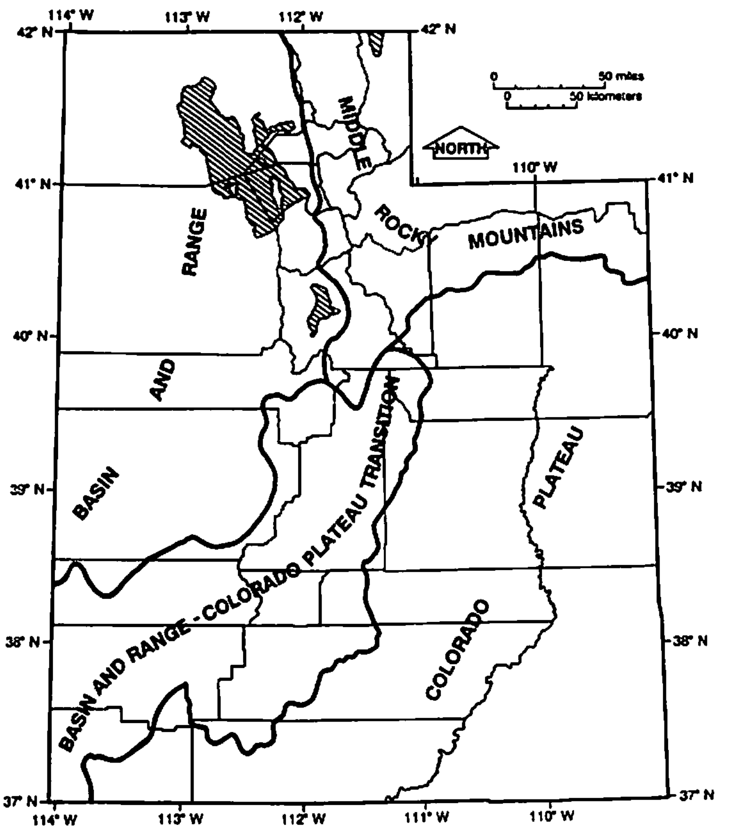

Fig. 7. Physiographic subdivisions of Utah (modified from Stokes 1977).

underlain by poorly drained, impermeable, clay-rich soils low in uranium.

CONCLUSIONS

Airborne-radiometric measurements, in conjunction with regional geologic maps, can be used to define broad areas with the potential for high concentrations of indoor radon. This is an efficient method for making rapid determinations of potential hazard areas, and was used to construct the first statewide estimate of the radon-hazard in Utah (Sprinkel 1987). However, a complex relationship of geologic and non-geologic factors controls indoor-radon levels. Although the effects of non-geologic factors are difficult to quantify and characterize regionally, the effects of geologic factors can be estimated. A more detailed map of the statewide radon-hazard potential (Black 1993) was compiled using three geologic factors: (1) uranium concentration, (2) soil permeability, and (3) depth to ground water. Results of a statewide survey of indoor levels validate this hazard-potential map.

Hazard assessments were performed in the field to increase the level of detail in high-hazard areas identified in the statewide indoor-radon survey. Two methods of hazard mapping were used in the field studies. In the Sandy and Provo areas, boundaries of hazard classifications were based on geologic units, assuming that the three factors used in the classification are relatively uniform within each geologic unit. In four other study areas, boundaries of hazard classifications are independent of geologic units, and are based on the assumption that the three factors vary within geologic units and have gradational boundaries. The second method is more generally applicable and can be used in all geologic settings, particularly in areas where detailed geologic maps do not exist. Indoor-radon levels, because they are only in part the result of geologic factors, are not considered in the hazard classification but were used to validate both methods. Exclusion isolines, a semiquantitative interpretation method which minimizes the effects of factors that act to reduce the radon concentration of soil-gas samples, can also be used to validate hazard-potential maps.

Relative hazard potential determined in both statewide and targeted studies can be used to prioritize indoor testing and evaluate the need for radon-resistant new construction. Hazard maps should not be used to predict actual indoor-radon levels because of map scale and the complex relationships between geologic and non-geologic factors controlling indoor-radon levels. The scale of the maps preclude identification of small areas of higher or lower radon-hazard potential contained within the hazard-potential areas depicted on the maps. Detailed characterization and testing of specific sites are required to evaluate the influence of other factors, and to overcome the limitation of map scale.

REFERENCES

Anderson, L.R.; Keaton, J.R.; Spitzley, J.E.; Allen, A.C. Liquefaction potential map for Salt Lake County, Utah. Logan: Utah State University, Department of Civil and Environmental Engineering; and Salt Lake City: Dames & Moore Consulting Engineers: 1-48; 1986.

Black, B.D. The radon-hazard-potential map of Utah. Utah Geological Survey Map 149: 1-12; scale 1:1,000,000; 1993.

Black, B.D. Radon-hazard-potential map of the Weber River area, Davis and Weber Counties, Utah. Utah Geological Survey Map: in preparation.

Carley, J.A.; Jensen, E.H.; Campbell, L.B.; Barney, M.; Fish, R.H.; Chadwick, R.S.; Winkelaar, P. Soil survey of Morgan area, Utah, Morgan County and eastern part of Weber County. U.S. Department of Agriculture, Soil Conservation Service and Forest Service; in cooperation with Utah Agricultural Experiment Station: 1-300; 1980.

Condie, K.C. Petrology of the late Precambrian tillite(?) association in northern Utah. Geological Society of America Bulletin 78: 1317-1344; 1967.

Crittenden, M.D., Jr. Stratigraphic and structural setting of the Cottonwood area, Utah. In: Symposium on geology of the Cordilleran Hingeline. Hill, J.G., editor. Denver: Rocky Mountain Association of Geologists: 363-379; 1976.

Doyuran, V. Geology and ground-water resources of Ogden Valley, Utah. Salt Lake City: University of Utah, unpublished Ph.D. thesis: 1-134; 1972.

Durrance, E.M. Radon in the stream waters of East Devon. In: Proceedings of the 17th Ussher Society Conference 4. Edwards, R.A., editor. Pt. 2: 220-228; 1978.

Duval, J.S.; Jones, W.J.; Riggle, F.R.; Pitkin, J.A. Equivalent uranium map of the conterminous United States. U.S. Geological Survey Open-File Report 89-478: 1-12; 1989.

Hecker, S.; Harty, K.M.; Christenson, G.E. Shallow ground water and related hazards in Utah. Utah Geological and Mineral Survey Map 110: 1-17; scale 1:750,000; 1988.

Leggette, R.M.; Taylor, G.H. Geology and ground-water resources of Ogden Valley, Utah. U.S. Geological Survey Water Supply Paper 796-D: 1-161; 1937.

Lowe, M. Surficial geology of Ogden Valley, Weber County, Utah. Utah Geological Survey Open-File Report: in preparation.

Muessig, K.W. Correlation of airborne radiometric data and geologic sources with elevated indoor radon in New Jersey. In: The 1988 Symposium on Radon and Radon Reduction Technology, preprints. Research Triangle Park, North Carolina: U.S. Environmental Protection Agency, Air and Energy Environmental Research Laboratory: V-1; 1988.

Personius, S.F.; Scott, W.E. Surficial geologic map of the Salt Lake City segment and parts of adjacent segments of the Wasatch fault zone, Davis, Salt Lake, and Utah Counties, Utah. U.S. Geological Survey Miscellaneous Investigations Map I-2106: scale 1:50,000; 1992.

Sextro, R. Radon in dwellings. In: Radon and the environment. Makofske, W.J.; Edelstein, M.R., editors. Park Ridge, New Jersey: Noyes Publications: 71-82; 1988.

Solomon, B.J. Environmental geophysical survey of radon-hazard areas in the southern St. George basin, Washington County, Utah. In: Engineering and environmental geology of southwestern Utah. Harty, K.M., editor. Utah Geological Association Publication 21: 173-191; 1992.

Solomon, B.J. Radon-hazard-potential areas in the southern St. George basin, Washington County, and Ogden Valley, Weber County, Utah. Utah Geological Survey Special Studies: in preparation(a).

Solomon, B.J. Radon-hazard-potential map of the Sevier Valley, Sevier County, Utah. Utah Geological Survey Map: in preparation(b).

Solomon, B.J.; Black, B.D.; Nielson, D.L.; Cui, L. Identification of radon-hazard areas along the Wasatch Front, Utah, using geologic techniques. In: Proceedings of the 27th Symposium on Engineering Geology and Geotechnical Engineering. McCalpin, J.P., editor. Logan: Utah State University: 40-1 - 40-16; 1991.

Stokes, W.L. Subdivisions of the major physiographic provinces of Utah. Utah Geology 4: 1-17; 1977.

Sprinkel, D.A. The potential radon hazard map, Utah. Utah Geological and Mineral Survey Open-File Report 108: 1-4; scale 1:1,000,000; 1987 (revised 1988).

Sprinkel, D.A.; Solomon, B.J. Radon hazards in Utah. Utah Geological and Mineral Survey Circular 81: 1-24; 1990.

Wilson, L.; Olsen, M.E.; Hutchings, T.B.; Southard, A.R.; Erickson, A.J. Soils of Utah. Logan: Utah State University, Agricultural Experiment Station Bulletin 492: 1-94; scale 1:1,000,000; 1973.