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IDENTIFICATION OF RADON-HAZARD AREAS ALONG THE WASATCH FRONT, UTAH, USING GEOLOGIC TECHNIQUES

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ABSTRACT

This study evaluates the geologic conditions responsible for high indoor radon concentrations along portions of the Wasatch Front, Utah, and develops geologic techniques for assessing radon-hazard potential. The hazard potential was estimated by determining the nature of three geologic factors which affect indoor radon levels: 1) uranium content of soils; 2) concentration of radon in soil gas; and 3) depth to ground water. These were determined by airborne and ground radiometric measurements, and by geologic data compilation. Numerical scores are applied to each rating factor, and composite ratings are calculated to estimate the hazard potential for major Quaternary geologic units. In the two areas studied, east Sandy and east Provo, units with the highest potential for elevated indoor radon concentrations are upper Pleistocene lacustrine sediments related to the transgressive phase of the Bonneville lake cycle, as well as younger deposits overlying the transgressive units. This hazard potential reflects sediment provenance, transport mechanisms, and ground-water levels. Geologic characterization of large areas can be accomplished rapidly with techniques used for this study, and can serve as a predictive indicator of the potential for high indoor radon levels.

INTRODUCTION

Concentrations of indoor radon (Rn) are a function of a number of aspects including weather, building construction, and ventilation. Ultimately, however, the source of radon is uranium (U) in the geologic units surrounding the building's foundation. 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. Subsequent references to radon and uranium refer to these isotopes.

Sprinkel (1987) used regional geologic data to map potential radon-hazard areas in Utah. These areas were identified by known uranium occurrences; uranium-enriched rocks at the surface or beneath well-drained, porous and permeable soils; anomalous surficial uranium concentrations; and the surface trace of the Wasatch fault zone. Quaternary units were not included in the compilation unless documented in publications to be a radon source.

In late 1987, the Utah Bureau of Radiation Control (UBRC) conducted a survey to assess indoor radon levels statewide (Sprinkel and Solomon, 1990). Volunteers were solicited from cities or towns within radon-hazard areas, and the homes selected to participate in the study were owner-occupied, single-family dwellings. Alpha-track monitoring devices were placed in 631 homes. The statewide average indoor radon level was 2.7 picocuries per liter (pCi/L) (100 Becquerels per cubic meter; Bq/m^3), with 14 percent of measurements greater than 4 pCi/L (148 Bq/m^3), the level above which mitigation procedures are suggested (U.S. Environmental Protection Agency and U.S. Department of Health and Human Services, 1986). Clusters of high indoor radon values occur in several areas of the state. Two of these areas, east Sandy and east Provo, occur along the populous Wasatch Front and were selected for detailed investigation (figure 1). Interpretations of airborne radiometric data were conducted for an area which includes east Sandy.

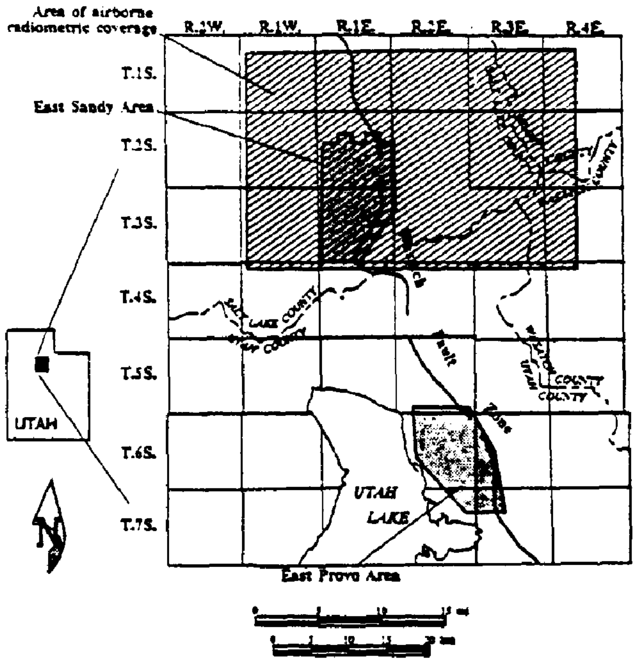

Figure 1. Index map showing location of study areas.

The objectives of this investigation were: 1) to define the distribution and magnitude of specific geologic factors which influence areal radon distribution, 2) to establish field techniques for rapid and inexpensive definition of radon-hazard areas in future investigations, and 3) to provide a tool to achieve a more efficient allocation of resources devoted to testing and mitigation in existing construction, and to hazard prevention in new construction. Additional indoor radon measurements within the study areas are now being coordinated by the UBRC. Results will be incorporated in an expanded version of this paper to be published by the UGMS.

LOCATION AND GEOLOGY OF STUDY AREAS

The east Sandy study area in eastern Salt Lake County extends from the mouth of Big Cottonwood Canyon on the north to the town of Draper on the south, and is approximately bounded by State Street on the west and the Wasatch Range on the east (figure 1). The average indoor radon level within the east Sandy study area is 3.2 pCi/L (118 Bq/m^3), with 17 percent of measurements greater than 4 pCi/L (148 Bq/m^3) (table 1). Airborne radiometric measurements were interpreted for the east Sandy study area and adjacent portions of the southern Salt Lake Valley and Wasatch Range.

The active Wasatch fault zone separates unconsolidated deposits of the Salt Lake Valley from bedrock within the Wasatch Range. The valley is underlain by a complex sequence of Quaternary unconsolidated alluvial, deltaic, lacustrine, and eolian deposits (Personius and Scott, 1990). The dominant influence on surficial geology and physiography was the last cycle of Pleistocene Lake Bonneville, which was present from about 10,000 to 30,000 years ago (Currey and others, 1983). The lake underwent several major periods of stability resulting in the creation of four basin-wide shorelines. Two of these, the transgressive Bonneville and the regressive Provo shorelines, are significant to this study. A compound delta was formed at the mouths of Big and Little Cottonwood Canyons by rivers which drained into the lake from the Wasatch Range. Holocene alluvial fans and eolian deposits overlie the older material. Coarser deposits in the valley generally occur to the east along the range front. Ground water occurs at depths greater than 50 feet (15 m) to the east, but is less than 10 feet (3 m) deep to the west and in active and abandoned alluvial channels which originate in the mountains (Anderson and others, 1986b).

A wide variety of bedrock compositions occur within the Wasatch Range, but three lithologies have the potential to provide source material high in uranium to Quaternary deposits in the valley. Of primary importance are Oligocene granitic rocks of the Little Cottonwood, Alta, and Clayton Peak stocks, which underlie extensive parts of the drainage basin of Little Cottonwood Canyon, and smaller parts of the drainage basin of Big Cottonwood Canyon (Crittenden, 1976). Of secondary importance are Precambrian

Table 1. Statistical summary of field data, factor ratings, and hazard ratings for major Quaternary geologic units in the east Sandy and east Provo areas. Geologic units are summarized from Machette (1989) and Personius and Scott (1990). Area S - east Sandy; P - east Provo. Soil textures are described using the classification of SCS, 1951, and are the predominant texture of material at sample sites. Textures do not necessarily correspond to unit descriptions. N for eU and Rn is the number of sample sites; N for ground-water depth is the number of sites with ground-water depth greater than 50 feet (15 m). No soil gas samples were collected for units lbg in Provo and es in Sandy; factor ratings were estimated from eU and ground-water levels. See table 2 for a description of the rating factors and hazard ratings.

Geologic Unit	Area	Soil Texture	eU N	eU %≥3ppm	eU Ave ppm	eU Max ppm	eU Rating	Rn in soil gas N	Rn %≥500pCi/L	Rn Ave pCi/L	Rn Max pCi/L	Rn Rating	Depth to ground water N	%≥50ft	Depth Rating	Indoor Rn N	%≥4pCi/L	Ave pCi/L	Max pCi/L	Hazard Ratings
Lacustrine Deposits																				
Regressive-Phase Deposits of Bonneville Lake Cycle																				
Deltaic Deposits (lpd)	S	Sg	7	86	7.1	9.0	4	3	33	315.35	612.90	2	1	11	1	2	0	1.1	1.3	7 - Moderate
	P	Lg	2	0	2.1	2.2	1	2	0	189.99	205.48	1	0	0	1	3	0	1.4	2.2	3 - Low
Lacustrine Gravel (lpg)	S	Sg	33	76	4.8	10.6	3	19	47	539.39	1433.70	3	20	40	2	17	12	2.2	8.8	8 - Moderate
	P	Lg	3	0	1.9	2.4	1	2	0	384.38	419.73	2	0	0	1	8	0	1.9	2.5	4 - Low
Lacustrine Sand (lps)	P	CLg	4	0	2.3	2.9	1	4	50	421.08	619.49	2	0	0	1	2	0	1.3	1.7	4 - Low
Transgressive-Phase of Bonneville Lake Cycle																				
Lacustrine Gravel (lbg)	S	Sg	17	82	4.8	8.6	3	8	38	564.79	1198.37	3	15	75	4	3	67	10.6	26.2	10 - High
	P	Lg	2	50	3.1	3.8	2	-	-	-	-	3	4	100	4	2	0	2.6	2.7	9 - Moderate
Lacustrine Sand (lbs)	P	Lg	9	44	2.7	3.4	1	3	0	153.77	206.56	1	15	94	4	7	14	2.5	9.9	6 - Moderate
Lacustrine Silt and Clay (lbm)	P	Lg	10	50	2.9	3.6	1	7	57	601.46	1463.41	3	10	53	3	9	22	3.9	13.6	7 - Moderate
Stream Alluvium																				
Unit 1 (al1)	S	Sg	6	83	6.8	9.0	4	3	0	270.15	482.13	2	0	0	1	-	-	-	-	7 - Moderate
Unit 2 (al2)	P	SLg	8	13	2.4	3.9	1	3	67	604.10	886.51	3	0	0	1	2	50	3.8	6.5	5 - Low
Regressive-Phase Alluvium (alp)	S	LSg	34	97	6.7	8.7	4	16	50	640.92	2397.57	3	29	60	3	14	29	4.5	12.7	10 - High
	P	Lg	24	17	2.3	3.3	1	11	27	394.20	733.54	2	21	38	2	31	10	2.5	6.3	5 - Low
Fan Alluvium																				
Unit 2 (af2)	S	Sg	6	67	4.0	6.0	2	1	0	119.52	119.52	1	4	44	2	3	0	2.5	3.2	5 - Low
	P	Lg	8	25	2.5	3.4	1	6	33	679.12	1454.45	3	0	0	1	1	100	8.2	8.2	5 - Low
Younger Alluvium (afy)	P	Lg	19	32	2.9	4.6	1	11	45	516.85	1404.85	3	14	45	2	12	25	3.1	10.2	6 - Moderate
Regressive-Phase Alluvium (afp)	P	Lg	6	33	2.8	3.6	1	5	0	233.64	468.02	1	1	14	1	1	0	0.5	0.5	3 - Low
Eolian Deposits																				
Sand and Silt (es)	S	S	8	88	5.1	8.2	3	-	-	-	-	2	11	65	3	9	0	1.8	3.0	8 - Moderate
	P	SCL	2	0	1.8	1.8	1	2	0	419.43	490.07	2	0	0	1	5	0	2.0	3.8	4 - Low
Colluvial Deposits																				
Colluvium and Alluvium, Undivided (ca)	S	Sg	8	100	5.9	8.4	4	2	0	374.65	466.45	2	2	22	1	1	0	2.2	2.2	7 - Moderate
Study Area Summaries																				
East Sandy	-	-	131	86	5.6	10.6	-	56	41	528.19	2397.57	-	92	50	-	53	17	3.2	26.2	-
East Provo	-	-	99	26	2.6	4.6	-	57	32	449.26	1463.41	-	68	37	-	86	13	2.6	13.6	-

metamorphic rocks and the Precambrian Mineral Fork Formation, a diamictite derived from older granitic rocks (Condie, 1967). These units underlie small parts of the drainage basins of both canyons. Quartzite, shale, and slate are widespread in the Precambrian Big Cottonwood Formation in the drainage basin of Big Cottonwood Canyon (James, 1979), and provide source material low in uranium to Quaternary sediments.

The east Provo study area in central Utah County extends from the city of Orem on the north to Provo on the south, and is approximately bounded by Interstate 15 on the west and the Wasatch Range on the east (figure 1). The average indoor radon level within the east Provo study area is 2.6 pCi/L (96 Bq/m^3), with 12 percent of measurements greater than 4 pCi/L (148 Bq/m^3) (Sprinkel and Solomon, 1990). Although the average indoor radon level within the study area is lower than the statewide average, Sprinkel and Solomon (1990) demonstrated that east Provo does contain areas with average indoor radon concentrations in excess of the statewide average.

The east Provo study area lies within the eastern portion of Utah Valley. As in the Sandy area, the Wasatch fault zone separates unconsolidated deposits of the valley from bedrock within the mountains. The valley is underlain by Quaternary sediments deposited in similar paleoenvironments to those of east Sandy (Machette, 1989). Ground water occurs at depths greater than 50 feet (15 m) to the east, but is less than 10 feet (3 m) deep to the west and in active and abandoned alluvial channels which originate in the mountains (Anderson and others, 1986a). A wide variety of bedrock composition occurs within the Wasatch Range adjacent to the east Provo area, but two units have the potential to provide source material high in uranium to Quaternary deposits in the valley: 1) the Pennsylvanian to Mississippian Manning Canyon Shale, a dark shale with abundant organic material which underlies a large portion of the range front; and 2) diamictite, similar to that of the east Sandy area, of the Precambrian Mineral Fork Formation which underlies the drainage basins of Rock and Slate Canyons (Baker, 1964, 1972, 1973). Limestone and quartzite of the Pennsylvanian and Permian Oquirrh Formation provide source material low in uranium to Quaternary units, and is transported from the interior of the Wasatch Range by drainage through Provo Canyon. The Provo River delta was formed at the mouth of Provo Canyon at the time of Lake Bonneville.

DATA COLLECTION AND INTERPRETATION

Airborne Radiometric Measurements

Sampling and Analytical Techniques – The airborne radiometric survey completed under the National Uranium Resource Evaluation (NURE) program provides an excellent data base for the delineation of large areas of high surface uranium concentrations, and can be used as an indicator of areas that have the potential for indoor radon hazards (Duval and Otton, 1990). 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. NURE data interpretation, therefore, serves as a reconnaissance tool for regional studies, but requires more detailed follow-up surveys such as ground-based gamma-ray spectrometry, soil radon emanometry, and indoor radon measurements.

Data from the NURE program (EG&G Geometrics, 1979) were compiled for the portion of the Salt Lake City 1:250,000-scale quadrangle which includes the southern Salt Lake Valley and adjacent parts of the Wasatch Range (figure 1). This area includes east Sandy, which was studied in detail using ground radiometric techniques. The airborne survey was performed using a GeoMetrics GR-800 gamma-ray spectrometer mounted in an SA315B Lama helicopter. The GR-800 system contained 37,760 cubic centimeters (2,304 cubic in.) of NaI crystals. Navigation of the helicopter was with visual techniques and 1:24,000 topographic maps, but the flight path was also documented using a 35-millimeter tracking camera. The survey was flown at a terrain clearance of between 60 and 210 meters (200 and 700 ft), with an average clearance of 120 meters (400 ft). Data were collected at 1 second intervals along the flight lines. Data reduction techniques are described in the NURE report (EG&G Geometrics, 1979).

Data and Discussion – Corrected values for equivalent uranium (eU), equivalent thorium-232 (eTh), and potassium-40 (K) were read from the NURE tapes and used to plot eU, eTh, and K concentration, total gamma, and eU/eTh, eU/K, and eTh/K contour maps. The contour maps were generated by computer and have no geologic bias. Only the uranium contour map is shown in this report (figure 2). The average apparent uranium concentration for the entire quadrangle is 1.65 parts per million (ppm) (EG&G Geometrics, 1979). The area of principal interest for this study is uranium anomaly A in the Sandy area. This area contains uranium concentrations greater than 4 ppm in an area where high levels of indoor radon were detected (Sprinkel and Solomon, 1990). The anomaly is located over Quaternary unconsolidated deposits. High uranium values in the Wasatch Range to the east of anomaly A are located over outcrops of the Little Cottonwood, Alta, and Clayton Peak stocks (anomaly B) and suggest that a significant portion of anomaly A results from material eroded from the stocks.

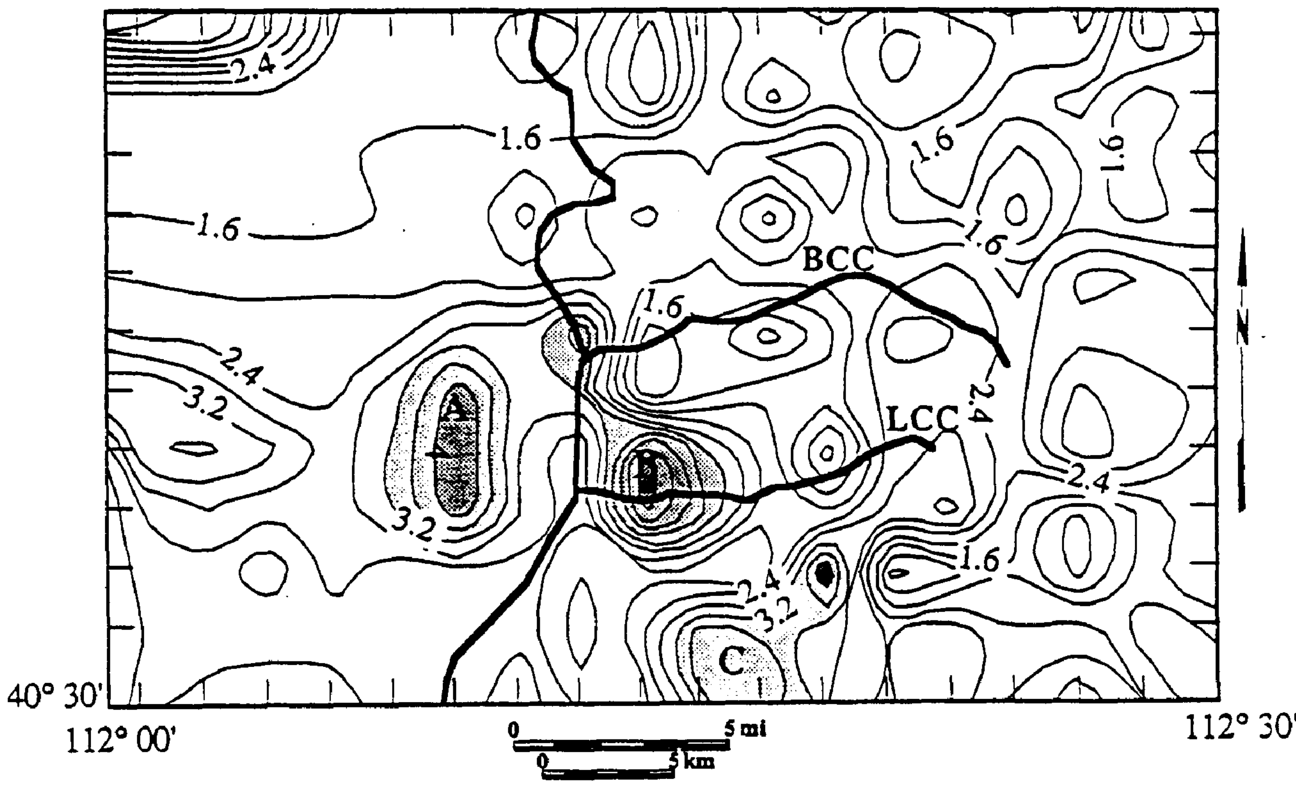

Figure 2. Uranium concentrations from the airborne radiometric survey. The heavy line is the range front. BCC is Big Cottonwood Canyon; LCC is Little Cottonwood Canyon. Contour interval 0.4 ppm.

The map of eTh concentrations shows that uranium anomaly A is also coincident with a thorium anomaly that reaches values greater than 13 ppm. The thorium anomaly is broader than the uranium anomaly and even higher values of thorium are found over the granitic stocks. The map of K concentrations shows similar relationships, but the patterns are more diffuse. The data are compatible with the process of concentration of U, Th, and K in more siliceous igneous rocks.

The total gamma count represents gamma radiation in the entire 0.4 to 3.0 million electron volts (MeV) range. The total gamma anomalies are much broader than the eU anomalies, suggesting that the total gamma data are not as useful as the eU data for delineating areas that require ground survey follow-up.

Ratio maps are commonly used in uranium exploration surveys to define areas having the potential for ore deposits. An eU/eTh contour map does not show any remarkable values in the area of anomaly A. This is to be expected given the high concentrations of both uranium and thorium in this area. Likewise, maps of eU/K and eTh/K show no unusual values for the area. If the uranium had resulted from non-igneous processes, it should have been concentrated relative to both Th and K and the ratio maps would have been more useful.

Because high indoor radon values have been associated with uranium anomaly A, which has greater than

4 ppm eU, other areas with similar eU concentrations should be field checked. Anomaly C (figure 2) has such concentrations, is located over the same granitic stock that produces anomaly B, and is also coincident with an eTh anomaly. Anomaly C is located in an uninhabited area; however, drainage is to the south into the northern part of Utah Valley in the vicinity of the town of Alpine. Thus, there is the potential for eU and related high indoor radon concentrations in the Alpine area of northern Utah Valley, to the south of figure 2, analogous to those found in anomaly A in the east Sandy area of Salt Lake Valley.

Ground Measurements

Sampling and Analytical Techniques – Four types of ground data were collected during the field study. These types included: 1) gamma-ray spectrometry, 2) levels of radon in soil gas, 3) soil moisture and density, and 4) soil texture. Gamma-ray spectrometry determines the amount of radioactive parent material in the soil available to decay into radon. The level of radon in soil gas determines the amount of radon available for migration into buildings. Soil moisture, density, and texture affect the ability of radon to migrate through pathways in the soil to building foundations. Data were collected at 131 sites in the east Sandy area, and at 100 sites in the east Provo area.

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 contained a 3 x 3 inch (7.5 x 7.5 cm) NaI crystal. Values for total gamma, K, eU, and eTh were collected. Peak energy levels used for measurement were 1.46 MeV for K (K has only one emission line), 1.76 MeV for eU (corresponding to ^{214}Bi), and 2.62 MeV for eTh (corresponding to ^{208}Tl).

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, resulting from the decay of ^{222}Rn. The individual scintillator cells were calibrated using the UNC Geotech Alpha-track Chamber in Grand Junction, Colorado. 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, is within the lower B or upper C soil horizons, and is close to sampling depths which provided consistent and reproducible data to other researchers (Hesselbom, 1985; Reimer and Gundersen, 1989).

Wet density, dry density, and moisture content of soils were determined in situ using a Campbell Pacific Nuclear 501DR portable probe. The probe contains a gamma source and a gamma-measuring detector for density measurements, and a fast neutron source and thermal neutron detector for moisture measurements.

Soil texture of samples was classified into one of twelve categories used by the U.S. Soil Conservation Service (1951). Classification is based upon the less than 2-millimeter (0.08-in.) fraction, and is modified by estimates of the volume percent of gravel. Soil texture was only estimated for those sites where soil gas samples were collected and, where possible, estimates were based upon soil from the depth of gas sample collection.

Data and Discussion – Data from the ground spectrometer survey (table 1) shows that uranium levels are significantly higher in the east Sandy area (5.6 ppm) than in the east Provo area (2.6 ppm). The distribution of uranium in the two areas, however, is not uniform. In east Sandy, the highest average uranium levels were found in upper Pleistocene gravel and sand of the Provo (regressive) shorelines of the Bonneville lake cycle (7.1 ppm). Uranium levels in the upper Pleistocene gravelly alluvium of terraces graded to the Provo (regressive) shoreline showed a bimodal distribution; low levels (4.1 ppm) occur west of the mouth of Big Cottonwood Canyon, while higher levels (6.9 ppm) are present elsewhere. In east Provo, the highest average uranium levels were found in upper Pleistocene lacustrine gravel of the Bonneville (transgressive) shoreline (3.1 ppm). Total gamma, eTh, and K data were also collected and analyzed, but data are not presented in this report. The distribution of total gamma, eTh, and K parallels that of eU in east Sandy and is consistent with derivation primarily from siliceous igneous rocks. In east Provo, eU is more concentrated relative to both eTh and K in areas of high eU anomalies, indicating a more significant contribution from non-igneous sources.

Average levels of radon in soil gas (table 1) were also higher in east Sandy (528 pCi/L; 1.95 x 10^4 Bq/m^3) than in east Provo (449 pCi/L; 1.66 x 10^4 Bq/m^3). In east Sandy, the highest average levels of radon in soil gas were found in the upper Pleistocene terrace deposits noted above (641 pCi/L; 2.37 x 10^4 Bq/m^3). Average levels were lower in the Bonneville (transgressive) shoreline lacustrine gravel (565 pCi/L; 2.09 x 10^4 Bq/m^3), but levels were lowest where it occurs west of the mouth of Big Cottonwood Canyon (296 pCi/L; 1.10 x 10^4 Bq/m^3) compared to similar deposits elsewhere in east Sandy (654 pCi/L; 2.42 x 10^4 Bq/m^3). In east Provo, the highest levels of radon in soil gas were found in middle Holocene to upper Pleistocene alluvial fans (679 pCi/L; 2.51 x 10^4 Bq/m^3).

Once radon gas is formed, it migrates through the soil and into buildings. The rate of migration is a function of the soil permeability. Soil gas permeability can be estimated from measurements of moisture, porosity, and particle diameter (Rogers and Nielson, 1990). An attempt was made to measure moisture and density (from which porosity may be calculated) for this study with the moisture-density gauge. However, gravels commonly prevented the necessary access holes from being augered. The few moisture and density measurements that were made are biased toward the relatively small amount of finer-grained soils. An estimate of permeability may be made from textural classification of the soil. Because soil texture did not significantly change between geologic units, permeability estimates of the various units within each area were not attempted. Soils from east Sandy, however, are generally gravelly sands, and are more permeable than the abundant gravelly loams of the east Provo area.

Pore water effectively traps radon and tends to inhibit radon migration. Conversely, low water saturation above the ground-water table facilitates diffusion of radon to the air. This phenomenon is graphically illustrated in east Sandy where Quaternary units high in uranium, but with shallow ground water, have low levels of radon in soil gas (see units ca, al1, and lpd on figure 3; this phenomenon also occurs in units west of the mouth of Big Cottonwood Canyon, where ground-water levels are shallower than near the mouth of Little Cottonwood Canyon). The relationship is not as clear in east Provo, possibly because uranium levels are lower (figure 4). A measure of the depth to ground water in the survey area is shown in table 1, which includes the number of sample sites with ground-water depths greater than 50 feet (15 m). The 50-foot (15-m) depth was arbitrarily chosen to estimate the relative depth to ground water in each geologic unit, and does not necessarily indicate a threshold depth that affects radon migration or diffusion.

Levels of indoor radon reported in Sprinkel and Solomon (1990) also reflect differences between the two areas, and among the various geologic units (table 1). The average indoor radon level in east Sandy is 3.2 pCi/L (118 Bq/m^3), while in east Provo the average level is 2.6 pCi/L (96 Bq/m^3). The highest average indoor radon levels in both areas occur in houses on upper Pleistocene deposits of the Bonneville and transgressive shorelines. In east Sandy, however, these deposits are predominantly gravel (10.6 pCi/L; 392 Bq/m^3), while in east Provo they are predominantly silt and clay (3.9 pCi/L; 144 Bq/m^3) (fan alluvium, unit 2, has higher indoor radon levels, but the sample size is small). In east Sandy, homes west of the mouth of Big Cottonwood Canyon have lower indoor radon levels than homes near Little Cottonwood Canyon. Many of the geologic units with high average indoor radon levels also have relatively high levels of uranium and radon in soil gas, as well as deeper ground-water levels (table 1).

Radon-Hazard Potential of Quaternary Geologic Units

A method has been devised to rate the relative hazard potential of geologic units. Three factors were included to estimate the radon hazard: 1) soil uranium concentration, 2) soil gas radon concentration, and 3) ground-water level (table 2; figures 3 and 4). Normal probability plots were constructed of measured values for the first two factors, and factor ratings were assigned to groups of values bounded by breaks on the probability plot. Factor ratings were arbitrarily assigned to the ground-water factor based upon the percentage of sample sites with a depth to ground water of greater than 50 feet (15 m). Four ratings were assigned numerical values of from 1 to 4 for each factor. Numerical values were then added for each geologic unit, and cumulative ratings, from 3 to 12, were assigned qualitative assessments of the relative potential for an indoor radon hazard. Equal weighting of each factor was used, since there is insufficient evidence to support the assignment of a relative amount of contribution for individual factors.

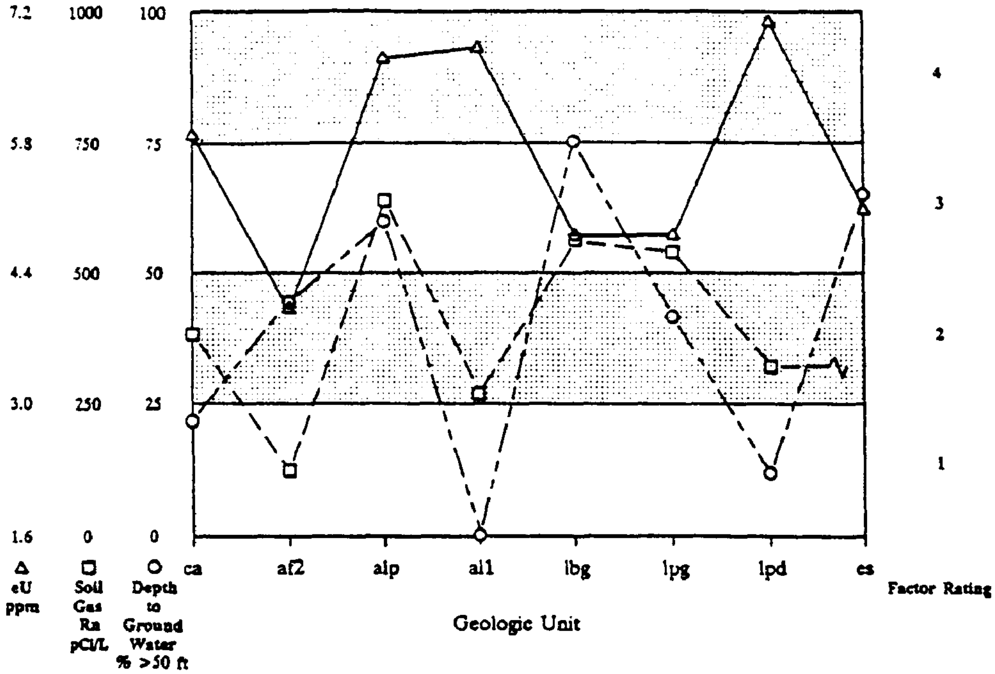

Figure 3. Average levels of hazard rating factors in major Quaternary geologic units of the east Sandy area. These are the factors used to compile the potential radon hazard ratings in table 1; factor ratings are shown at right. The lines which connect the symbols are for clarity and do not imply a spatial relationship between the units. See table 1 for explanation of geologic units.

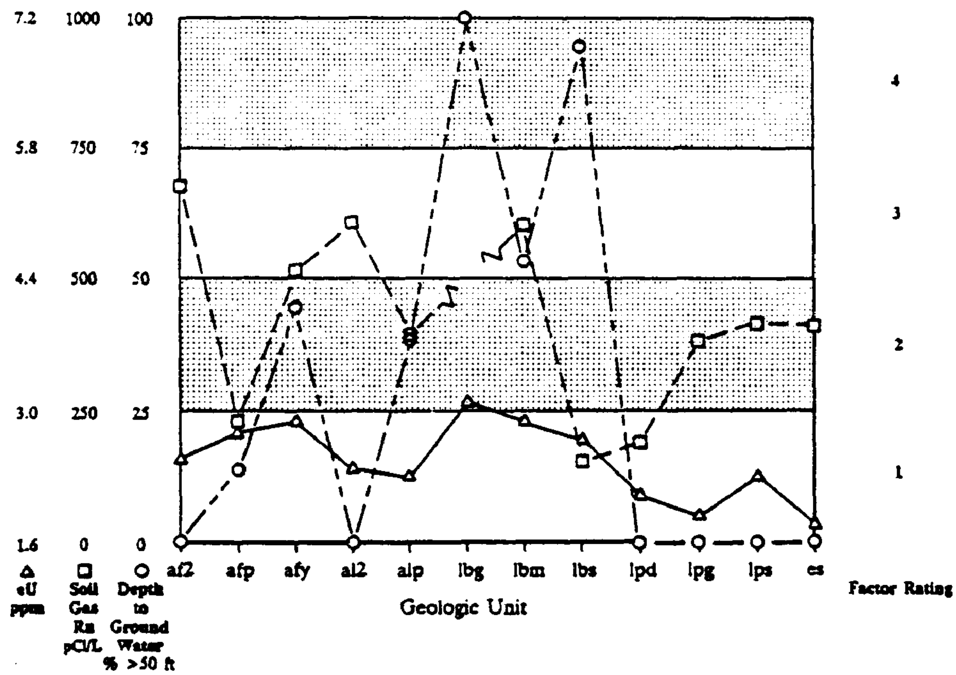

Figure 4. Average levels of hazard rating factors in major Quaternary geologic units of the east Provo area. These are the factors used to compile the potential radon hazard ratings in table 1; factor ratings are shown at right. The lines which connect the symbols are for clarity and do not imply a spatial relationship between the units. See table 1 for explanation of geologic units.

Table 2. Summary of the scheme used to estimate the relative potential for the indoor radon hazard along the Wasatch Front. Each of three factors are given ratings which range from 1 (lowest potential for contributing to high indoor radon levels) to 4 (highest potential). Ratings for the three factors are then added, and the composite rating is used to define three relative hazard potential groups.

Factor Rating	eU ppm	Soil Rn pCi/L	GW Depth %>50 ft
1	<3.0	<250	<25
2	3.0-4.4	250-500	25-50
3	4.4-5.8	500-750	50-75
4	>5.8	>750	>75

Hazard Rating	Hazard Potential
3-5	Low
6-9	Moderate
10-12	High

The radon-hazard potential is shown on figures 5 and 6, and hazard ratings are listed in table 2. Boundaries between areas of equal hazard potential are modified from contacts of Quaternary geologic units mapped by Machette (1989) and Personius and Scott (1990). Each geologic unit listed in table 2 has a rating that applies to the unit wherever it occurs in the study areas, with two exceptions near the mouth of Big Cottonwood Canyon in east Sandy. There, upper Pleistocene gravelly alluvium of terraces graded to the Provo (regressive) shoreline has a low hazard potential, and upper Pleistocene lacustrine gravel of the Bonneville (transgressive) shoreline has a moderate hazard potential. Elsewhere in east Sandy these units have high hazard potentials. Lower ratings for these units near the mouth of Big Cottonwood Canyon are primarily a reflection of shallower ground water and lower levels of radon in soil gas. The terrace deposits also have a lower level of eU near the canyon mouth than elsewhere in east Sandy. This is a reflection of the uranium-deficient source rock within the canyon.

Variations in the trend of hazard potential between geologic units closely parallels variations in the trend of average indoor radon levels, although the magnitude of variations of indoor radon levels is different in the two study areas (figures 7 and 8). These parallel trend changes, in a factor based only on geologic criteria and in levels of the contaminant caused by the geology, support the utility of the rating scheme to predict the relative potential of the indoor radon hazard in areas without the benefit of extensive indoor testing. The difference in magnitude of indoor radon levels in the two areas, however, indicates an inconsistency which should be explained. The rating scheme shows that the east Provo area is at significantly less risk from a potential indoor radon hazard than is east Sandy. This difference may be somewhat overstated because the lower numerical scores of east Provo are influenced primarily by the significantly lower uranium content of east Provo soils. Although the average indoor radon level in east Provo is only 19 percent less than in east Sandy, the average uranium content in east Provo is 54 percent less.

Obviously, other factors which have not been taken into account influence indoor radon levels. Several were noted above, but their characteristics vary both spatially and temporally and their effects cannot accurately or efficiently be determined for large geographic areas. One difference between the two study areas is readily amenable to regional analysis if proper data exists. Although soils in both areas are gravelly, the soil matrix in the east Provo area is significantly finer grained than in the east Sandy area. It is easier for radon atoms to escape from the solid in which they are produced if that solid has a large ratio of surface area to volume (Tanner, 1980). The ratio of surface area to volume increases in finer grained soil. On first impression, this effect could be taken into account by assigning numerical scores for a "grain size" factor, with the highest score for the finest grain size. Such a factor, though, would contradict another potential factor, permeability. Greater permeability facilitates radon migration and, hence, the potential for elevated indoor radon levels. But permeability generally increases with increasing grain size. Thus, if a single factor was used with soil texture as a surrogate for permeability, a high score for permeability in a coarse-grained soil would ignore the effect of the ratio of surface area to volume. The solution would be to use two factors, both grain size and permeability, but direct measurement of permeability is time consuming. Many

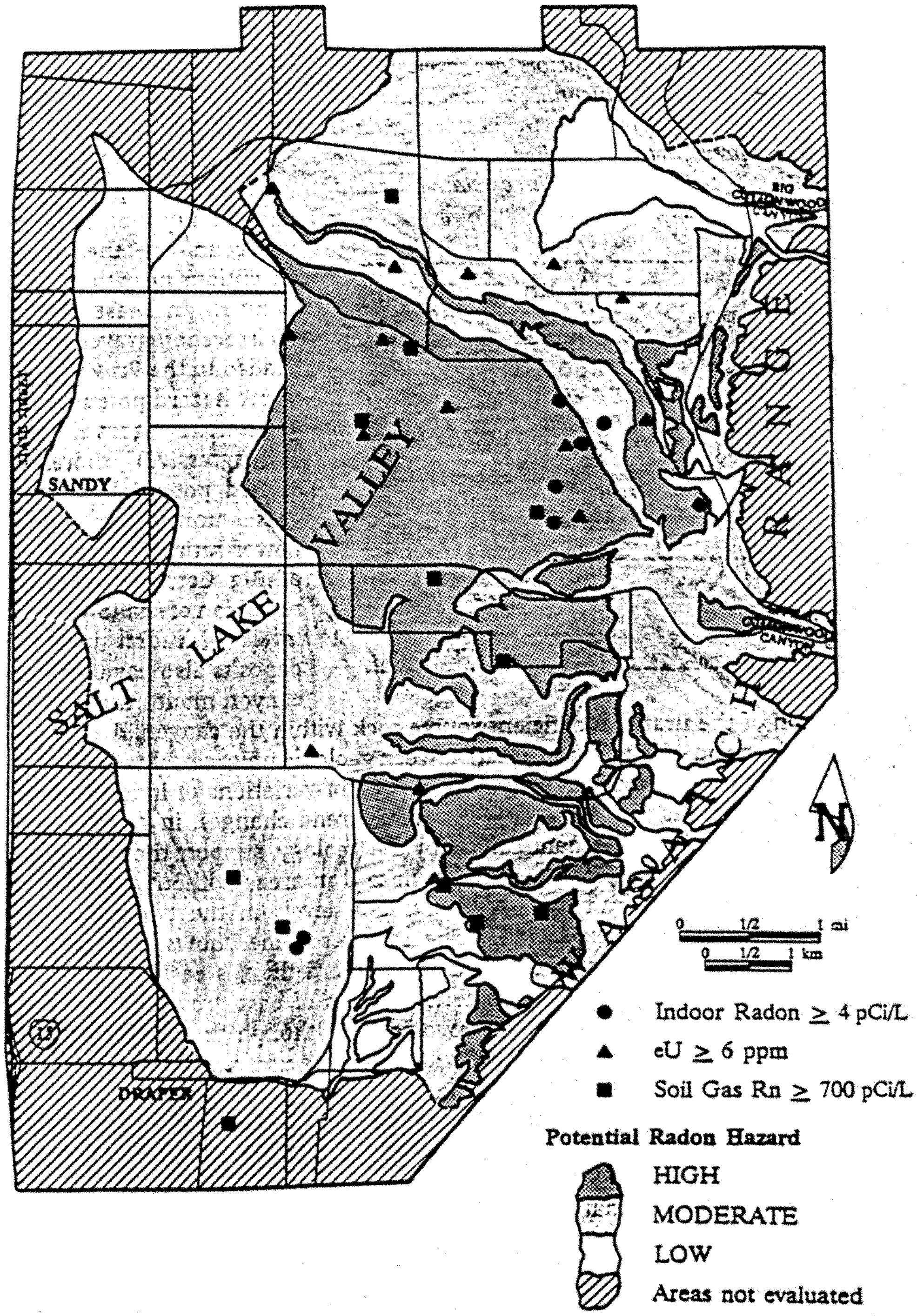

Figure 5. Map of the potential radon hazard, east Sandy. Approximate locations are shown for measurements of eU, Rn in soil gas, and indoor Rn in excess of threshold values. Threshold values of eU and Rn in soil gas were arbitrarily chosen to illustrate the geographic relationship between high measured values and hazard ratings, and do not coincide with threshold values of factor ratings in table 2 or with threshold values in figure 6. Areas of radon hazard potential are based upon the data summarized in table 1, and the ratings scheme shown in table 2. Hazard area boundaries are modified from the contacts of Quaternary geologic units mapped by Personius and Scott (1990).

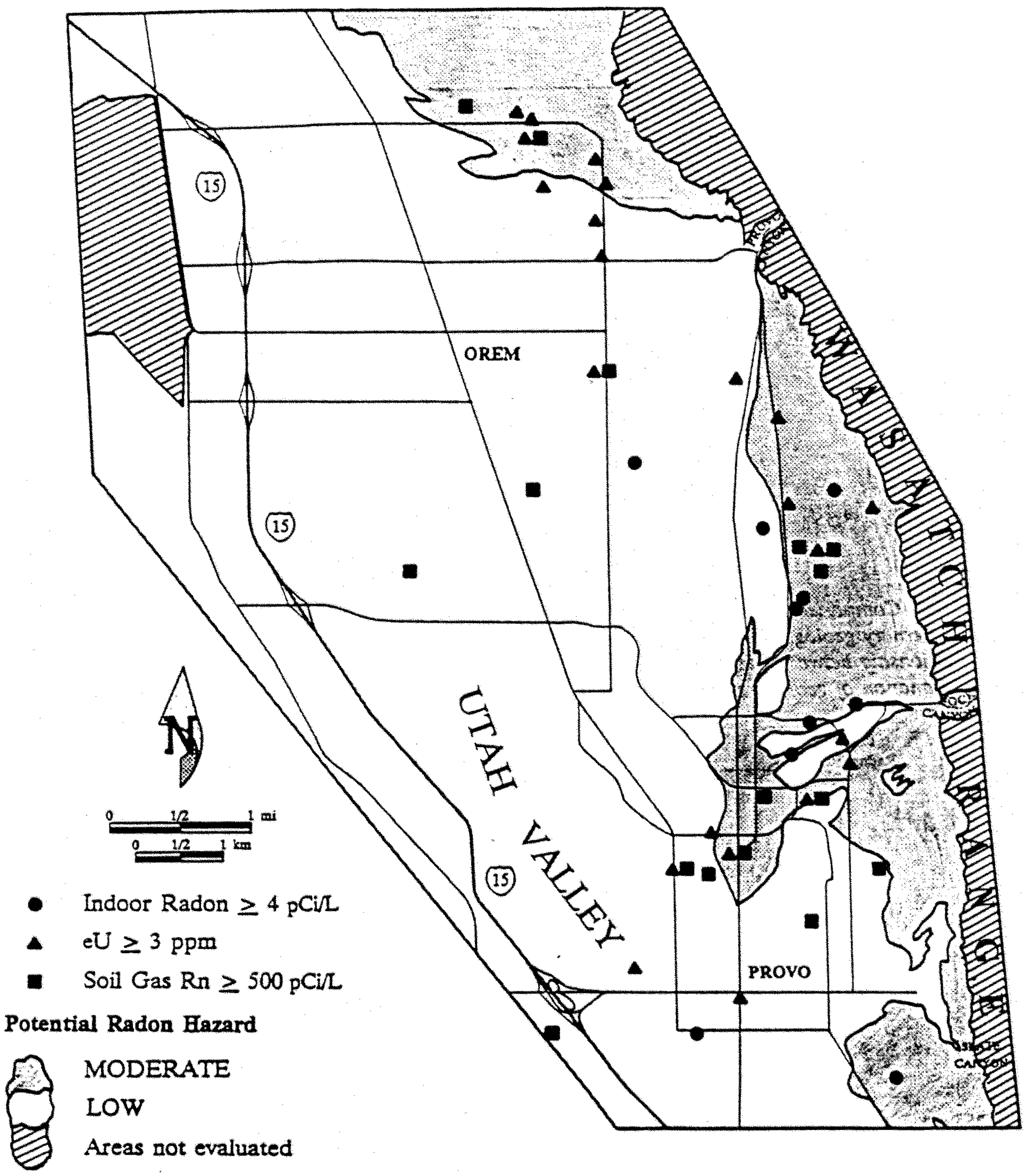

Figure 6. Map of the potential radon hazard, east Provo. Approximate locations are shown for measurements of eU, Rn in soil gas, and indoor Rn in excess of threshold values. Threshold values of eU and Rn in soil gas were arbitrarily chosen to illustrate the geographic relationship between high measured values and hazard ratings, and do not coincide with threshold values of factor ratings in table 2 or with threshold values in figure 5. Areas of radon hazard potential are based upon the data summarized in table 1, and the ratings scheme shown in table 2. Hazard area boundaries are modified from the contacts of Quaternary geologic units mapped by Machette (1989).

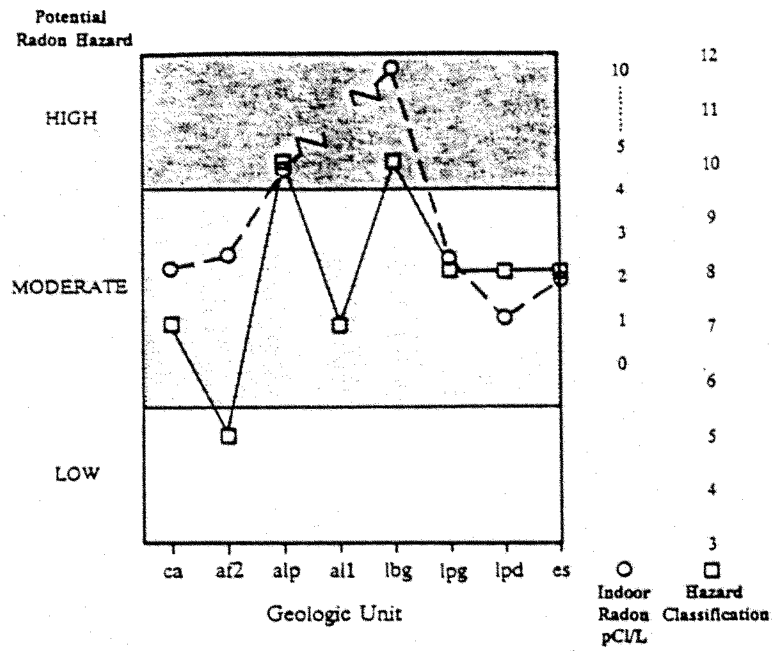

Figure 7. Comparison of average indoor radon concentrations and potential radon hazard ratings of major Quaternary geologic units in the east Sandy area. The vertical scales have been adjusted to illustrate the relationship between the trend of the two curves, but no quantitative relationship is implied. See table 1 for explanation of geologic units.

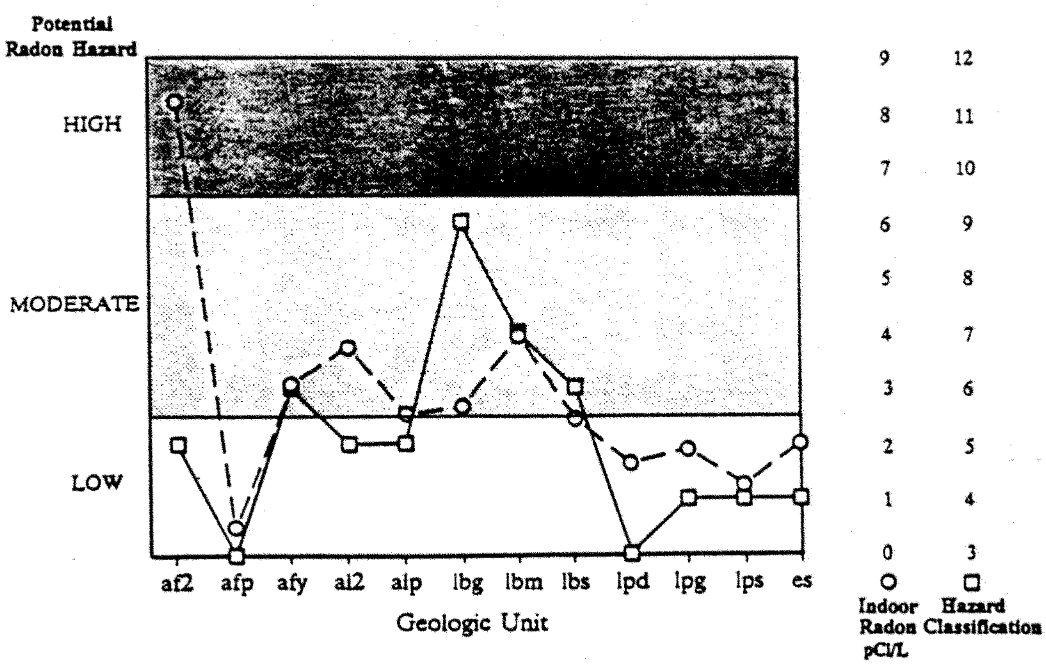

Figure 8. Comparison of average indoor radon concentrations and potential radon hazard ratings of major Quaternary geologic units in the east Provo area. The vertical scales have been adjusted to illustrate the relationship between the trend of the two curves, but no quantitative relationship is implied. See table 1 for explanation of geologic units.

investigators use permeabilities estimated from percolation tests conducted for U.S. Soil Conservation Service soil surveys (see, for example, Otton and others, 1988). In the east Sandy and east Provo areas, however, soil survey permeabilties (Swenson and others, 1972; Woodward and others, 1974) are in insufficient detail to indicate permeability contrasts between Quaternary geologic units.

Cautions When Using This Report

Hazard ratings in this report should not be used to indicate actual indoor radon levels because a quantitative relationship between measured factors and indoor radon levels does not exist. Factors not considered such as building construction techniques, lifestyle, and weather can strongly affect indoor radon levels. Small localized areas of higher or lower radon potential are likely to occur because of these effects, and because the map scale precludes identification of small areas. All map boundaries between radon-hazard areas are approximate due to the gradational nature of geologic contacts. Radon-hazard ratings are relative and are specific to the east Sandy and east Provo study areas. Indoor radon statistics used in this study are based upon volunteer data, and are not based upon a true random sampling.

A GEOLOGIC MODEL FOR PREDICTION OF THE INDOOR RADON HAZARD ALONG THE WASATCH FRONT

The rating scheme used for assessment of the potential indoor radon hazard in the east Sandy and east Provo areas indicates common depositional patterns and physical conditions that influence the hazard in both areas. Such patterns and conditions, as well as the techniques used in this study to identify them, are applicable to the identification of areas susceptible to an indoor radon hazard elsewhere in the Wasatch Front region.

In both areas, geologic units with the highest rating scores were upper Pleistocene lacustrine sediments related to the transgressive phase of the Bonneville lake cycle, as well as younger deposits overlying the transgressive units. In east Sandy, drainage from Little Cottonwood Canyon has transported material derived principally from Oligocene granitic rocks with a relatively high uranium content to the Little Cottonwood delta (figure 9). Material transported through Big Cottonwood Canyon to the Big Cottonwood delta is derived from a mixed source whose principal component is the Big Cottonwood Formation which is relatively deficient in uranium, but whose secondary components include Oligocene granitic rocks and Precambrian metamorphic and sedimentary rocks with higher uranium contents. Material high in uranium was deposited at both the Bonneville (transgressive) and Provo (regressive) levels of the Little Cottonwood delta, while material low in uranium was deposited at both levels of the Big Cottonwood delta. Sediments below the Provo level toward the valley interior, though, are not well drained and a significant portion of radon gas derived from the uranium at this level migrates with shallow ground water rather than with soil gas.

Uranium levels in east Sandy, even on the Big Cottonwood delta, are considerably higher than in east Provo due to differences in source material. There, uranium-enriched sediment was derived from bedrock with significant contributions from the Mineral Fork Formation and Manning Canyon Shale, was transported locally through Rock and Slate Canyons as well as smaller drainages, and was deposited at the Bonneville (transgressive) level on elevated benches along the range front (figure 10). Uranium-deficient sediment was derived from the Oquirrh Formation, was transported through Provo Canyon, and was deposited on the Provo River delta. As in east Sandy, Quaternary geologic units with the highest potential for an indoor radon hazard in east Provo contain well-drained sediments along the range front.

This combination of distinct source areas with contrasting uranium contents, routes of sediment transport, stratigraphic differentiation in the depositional area, and geomorphic position of well-drained sediments along the range front is a pattern that is likely repeated elsewhere along the Wasatch Front. Techniques used in this study may be applied with equal success in analogous areas.

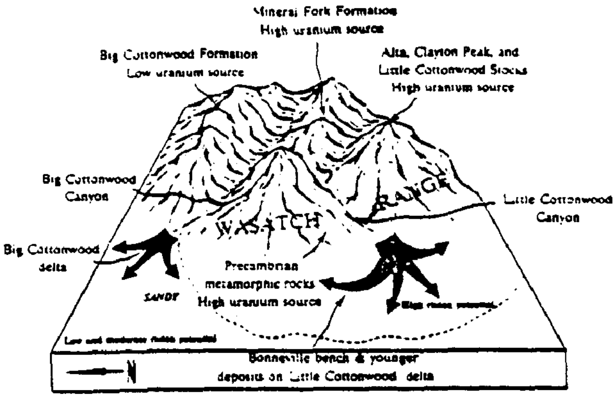

Figure 9. Sketch of regional geology showing relationship between source and depositional areas, east Sandy. Material from granitic stocks and Precambrian diamictite and metamorphic rocks with a relatively high uranium content was eroded, transported through Little Cottonwood Canyon, and deposited as sediments in the Little Cottonwood lobe of a compound delta on the margin of Lake Bonneville during the late Pleistocene. Sedimentary rocks of the Big Cottonwood Formation with a relatively low uranium content were eroded, mixed with high-uranium sediments, transported through Big Cottonwood Canyon, and deposited on the Big Cottonwood lobe. Shallow ground water inhibits the migration of radon in soil gas within regressive lake sediments. The combination of deep ground water and high levels of uranium result in high levels of radon in soil gas and a higher hazard potential in transgressive and younger sediments along the range front in the area of the Little Cottonwood delta.

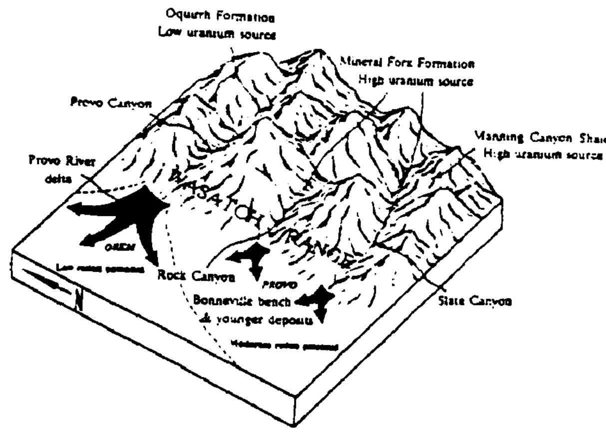

Figure 10. Sketch of regional geology showing relationship between source and depositional areas, east Provo. Material from black shale of the Manning Canyon Shale and diamictite of the Mineral Fork Formation, with relatively high uranium content, was eroded, transported through Rock, Slate, and similar small canyons, and deposited as sediments on the margin of Lake Bonneville during the late Pleistocene, and in alluvial fans during the Holocene. Sedimentary rocks of the Oquirrh Formation with a relatively low uranium content were eroded, transported through Provo Canyon, and deposited on a delta during the Late Pleistocene. Uranium-enriched sediments occur on an elevated bench along the range front where ground-water levels are deep, resulting in high levels of radon in soil gas and a higher hazard potential in transgressive and younger deposits.

CONCLUSIONS

Airborne radiometric measurements, in conjunction with regional geologic maps, are effective tools that can be used for identifying regional uranium anomalies along the Wasatch Front. Ground surveys can rapidly determine the distribution of uranium among various geologic units, and can identify other relevant geologic criteria. This combination of airborne and ground studies was used to identify areas with a higher potential for elevated indoor radon levels in well-drained sediments along the range front in east Sandy, and a similar radon-hazard area was identified along the range front of east Provo with ground studies only.

Field work and interpretation were completed in several weeks. Relevant factors of soil uranium content, radon in soil gas, and depth to ground water were synthesized into a ratings scheme which identified the relative potential for an indoor radon hazard in buildings within various geologic units. The relative hazard potential can be used to prioritize indoor testing, to indicate the urgency with which homeowners should mitigate existing buildings, and to evaluate the need for radon-resistant new construction. Public apathy is difficult to overcome when blanket statements are made to test everywhere. With the use of a selective rating scheme which identifies the potential for high indoor radon levels in areas underlain by relatively homogenous geologic units, a powerful tool is made available to achieve a more efficient allocation of resources devoted to testing and mitigation in existing construction, and to hazard prevention in new construction.

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