by
Richard Lively
Minnesota Geological Survey
2642 University Avenue
St. Paul, MN 55114

Daniel Steck
Department of Physics
St. John's University
Collegeville, MN 56321

Bruce Brasaemle
505 Harriet Avenue S.
Shoreview, MN 55126

A Site Study of Soil Characteristics and Soil Gas Radon in Rochester, Minnesota

A publication of the Center for Urban and Regional Affairs, 330 Hubert H. Humphrey Center, 301 19th Avenue S., Minneapolis, Minnesota 55455.

CURA has supported the work of the authors of this report but has not reviewed it for final publication. Its content is solely the responsibility of the authors and is not necessarily endorsed by CURA.

1991

Publication No. CURA 91-2

TABLE OF CONTENTS

ACKNOWLEDGEMENTS

We would like to acknowledge the help and cooperation of the Olmsted County Health Department and the USDA Soil Conservation Service in Rochester, Minnesota for their assistance with the indoor radon survey and field operations. We would also like to thank the homeowners for taking part in the survey and allowing us access to their property.

Partial funding for this project was provided by the Center for Urban and Regional Affairs, University of Minnesota, Minneapolis.

ABSTRACT

In regional surveys, indoor radon is usually the parameter of interest, but occasionally soil gas radon at depths of 1 meter or less is also measured. At statewide scales, even limited data sets can be used to infer relationships between geology and soil gas or indoor radon. However, predicting the radon potential of a single house or even an area the size of a neighborhood is more difficult. As the size of a surveyed area decreases, site-specific variables become more significant.

During 1990 we completed a study of two residential neighborhoods within 7 kilometers of each other near Rochester, Minnesota. Eight holes were augered into glacial sediments to maximum depths of 4.5 meters and samples collected for grain-size analysis, measurement of radon parent/daughter nuclides and radon emanation. A total of sixty-five homes in the areas were provided with two alpha-track registration detectors for indoor monitoring between September 1988 and September 1989.

Positive correlations were observed between the average soil radon, the average indoor radon, and the precursor/daughter radionuclides. The study area with the most topographic relief also had the highest radionuclide contents, the most variability with depth, and some variation with time and soil moisture; these results were not observed at the low-relief site. The type of study described would best be applied to site-specific preconstruction screening, rather than to predicting radon in existing structures.

INTRODUCTION

This project was designed to collect data on soil type and soil characteristics, radon and other related nuclides at several depths, and porosity and permeability. At the same time, radon levels in basements and living areas of homes built on the soils were also measured.

Two areas were chosen for the pilot study (Figure 1). St. Mary's Hills on the west side of Rochester consists of modern, single-family homes on ½-acre to 2-acre lots on the west side of a bedrock hill composed of St. Peter sandstone, Decorah shale, and Galena limestone, with a total vertical relief of about 40 meters. The bedrock surface is covered by 2 and 6 meters of glacial sediment and loess. Essex Park, about 6.5 kilometers northeast of St. Mary's Hills, is a mix of modern, single-family and multiple-residence homes on ½-acre lots. The topography is subdued, with about 9 meters of relief. Depth to the bedrock (Prairie du Chien Group) is between 3 and 18 meters. The profiles for each area and locations of the sample holes are shown in Figure 2.

Figure 1. Map Showing Study Areas Near Rochester, Olmstead County, Minnesota

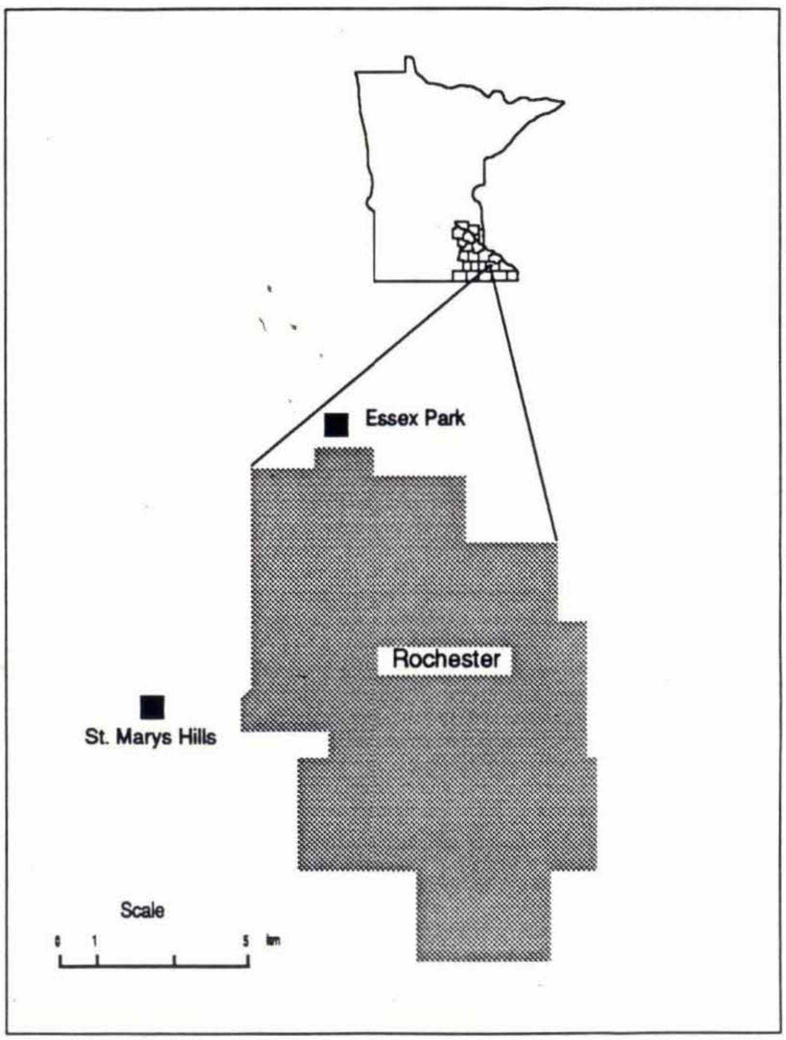
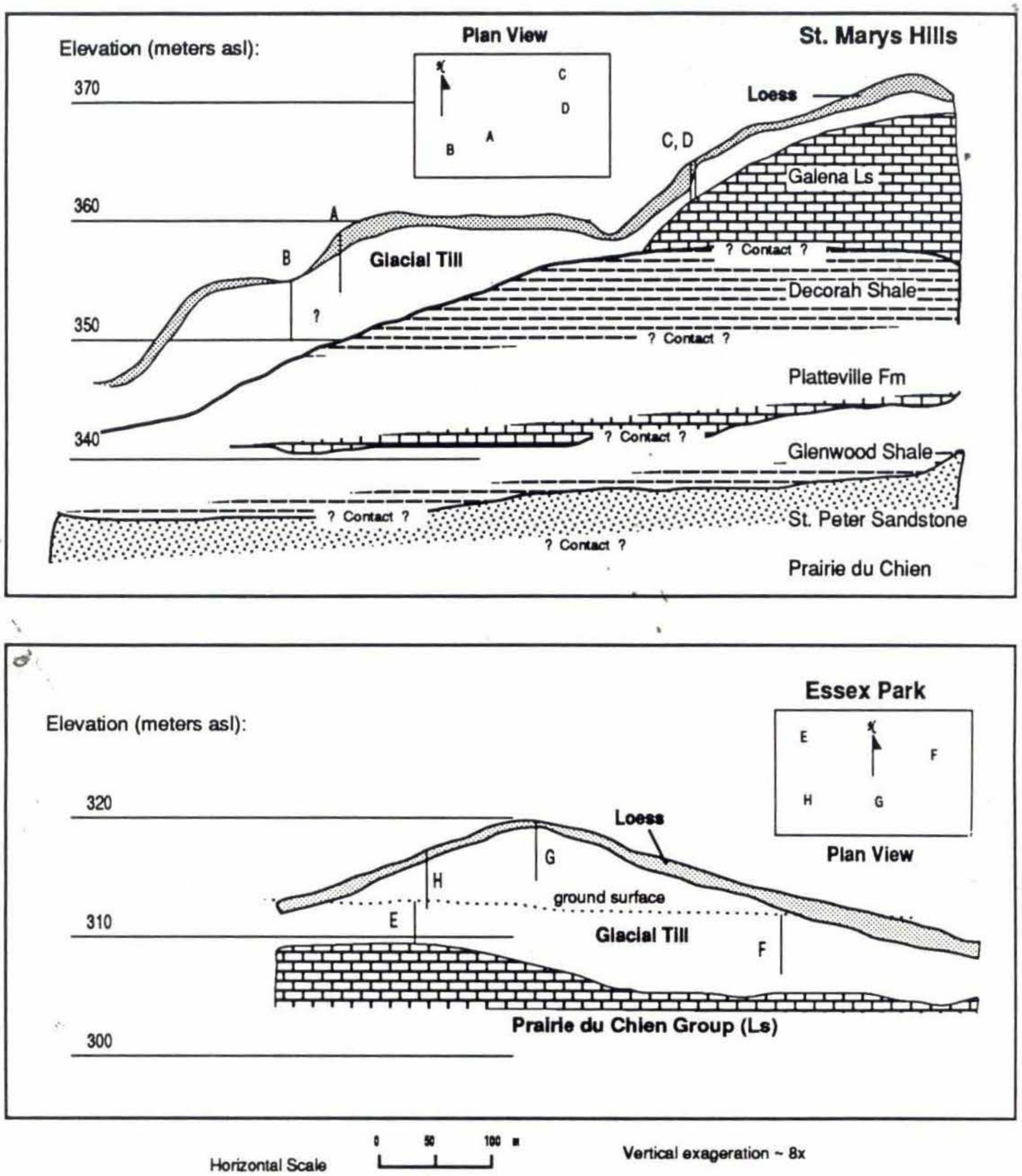


Figure 2. Profiles and Location of Sample Holes*



* Modified from Plates 2 and 3, *Geologic Atlas of Olmsted County* (4, 5).

Sixty-four owners of single-family homes participated in the study, forty-five from Essex Park and nineteen from St. Mary's Hills. Each received two radon detectors, one for the basement and one for a first-floor living area. Exposures lasted from nine to twelve months.

METHODOLOGY

The test holes were drilled in October 1988 using a truck-mounted Giddings soil auger with a 5-cm-diameter bit and core tube. Sediment samples collected during drilling were placed in sealable plastic bags.

The following is a summary of the analyses and methods used to study the sediment samples.

1. Moisture content and bulk density: the wet weights were measured within two days after collection. Soils were dried for a minimum of twenty-four hours at 70°C and reweighed. The results are only approximate, because they do not reflect moisture lost prior to measurement.

2. Solid particle density: these measurements were based on a procedure from Luetzelschwab and others.[1] These results combined with the wet and dry bulk densities can be used to approximate the pore volume in a sample of soil.

3. Grain-size fractions: the soils were screened into fractions consisting of a bulk sample (undifferentiated as to grain size), >149 μ (sand and gravel), 149-63 μ (very fine sand), and <63 μ (silt and clay by wet sieving).

4. Mineralogy: the mineralogy was determined by examining the >149 μ grain-size fraction with a binocular microscope.

5. Radon: radon emanation was measured from the bulk soil samples, the <63 μ, and the 63-149 μ fractions using a charcoal trap system modified from an unpublished report by Dr. J.N. Andrews, University of Bath, England. Scatter in the bulk fraction is thought to result from inhomogeneous radium in the sediment. The reproducibility of the other duplicate analyses was very good, and replicate analyses of radium standards varied by less than 10 percent.

6. ^{210}Po - ^{210}Pb: polonium-210 was extracted from the sediment with a leaching technique modified from Eakins and Morrison,[2] Blake and Norton (unpub.), and D.R. Engstrom (unpub.). The ^{210}Po was assumed to be in radioactive equilibrium with the ^{210}Pb.

7. Radium and thorium: 1-kilogram sediment splits from each depth were analyzed for ^{226}Ra and ^{232}Th by gamma-ray spectroscopy using a high-resolution germanium detector. The measured activities reflect total radium and thorium in the sediments.

8. Radon concentrations in the soil at multiple depths were measured by: 1) pumping air from isolated intervals through a liquid scintillation cocktail (active sampling), and 2) extended monitoring of isolated intervals with alpha-track detectors (passive sampling). Inflatable rubber packers on the outside of hollow PVC pipe were used to isolate each collection point. Each alpha track detector was wrapped in Saran Wrap® to keep out water vapor but still allow diffusion of radon. Initial data from alpha-track detectors are not included in the tables because of

large variance in the calibration constant for the detectors used at that time and our doubts about the integrity of the original packers. In 1989, a redesigned system for both the active and passive sampling was used with more reliable packers and flexible barriers, which prevented vertical air movement if a packer failed.

SOIL CHARACTERISTICS

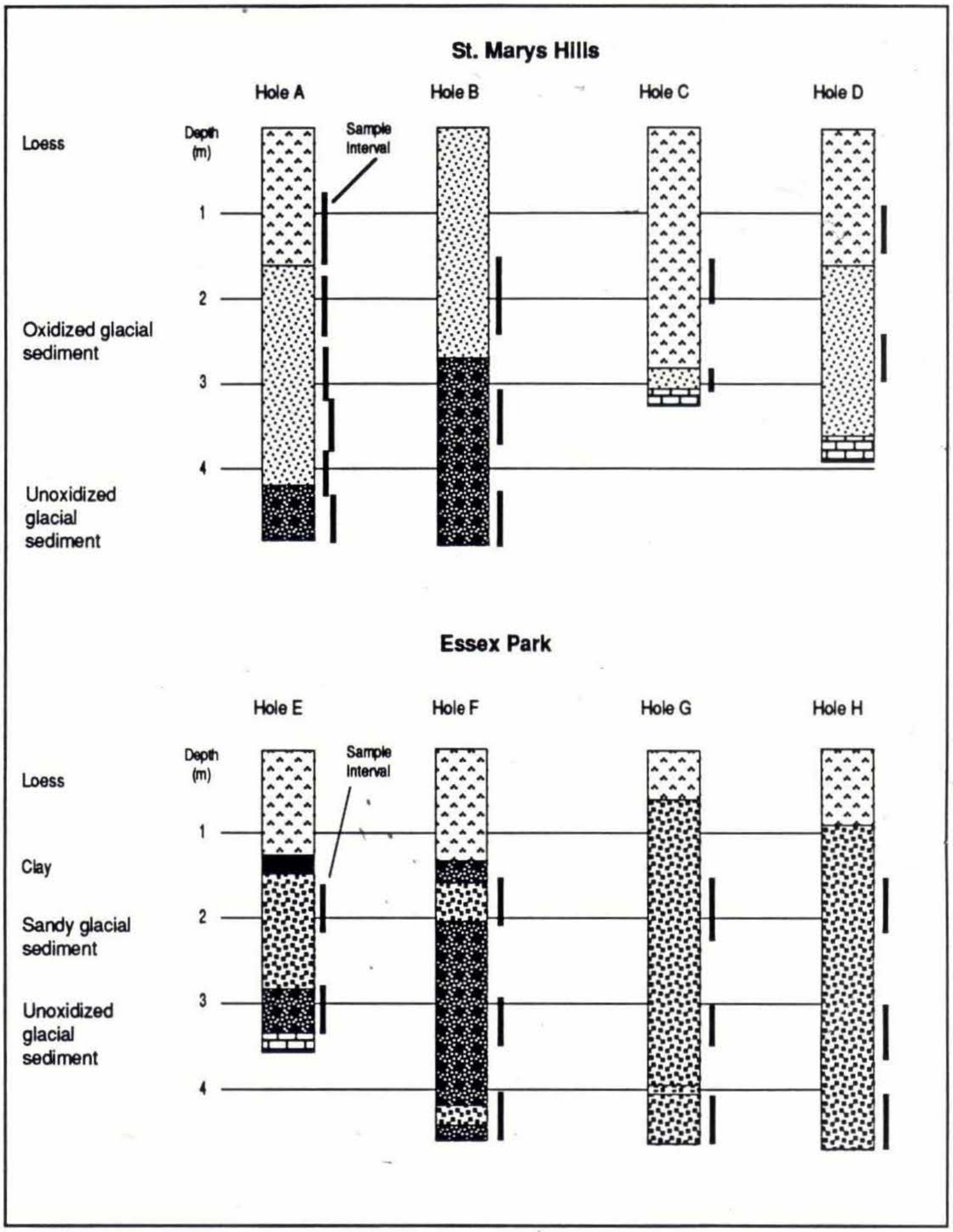
The sediments within the Rochester area are the result of glacial processes and include tills, outwash, colluvium, and loess. Loess, ranging from 0.6 to 2.8 meters thick, covers all of the sample sites except Hole B in St. Mary's Hills. The glacial tills below the loess are oxidized; some show the reddish-brown colors of ferric iron to depths of about 4.3 meters (Figure 3).

Moisture ranged from a low of 6.8 weight percent in the loess to a high of 20 weight percent, also in loess. Soil moisture increased slightly with depth, but not in all holes and not more than a few percent. Between the initial sampling in 1988 and measurement of radon in 1989, Hole B (St. Mary's Hills) collected water in the bottom meter. This could have been due to seepage from the sediment or water infiltrating from the surface.

There is a fairly broad range of grain-size distributions in the sediment samples, but the means within and between the sites were not statistically different. The available data do not allow us to distinguish between the relative effects of deposition and post-depositional soil development on the grain-size distribution.

Mineralogically the sediments are very similar, being predominantly composed of quartz, feldspar, biotite, and muscovite. Rock fragments form up to 50 percent of the >149 μ size fraction and include granite, limestone, quartzite, sandstone, and metamorphic and volcanic rocks. Varying percentages of magnetite, pyrite, hematite, and limonite were also observed.

Figure 3. Borehole Lithology and Sample Locations Based on Field Identifications



RADIOMETRIC RESULTS

Radon concentrations in the soil gas at St. Mary's Hills generally increase with depth and range from 17 to 71 kBq/m^3 (Table 1), with an average of 44 ± 13. In Hole A, both active and passive radon samples were collected. Below 1 meter, the two methods gave concentrations that were, within error, identical. The lower radon value at sample point A1 using the active monitor was probably due to leakage around the original packer. A second group of passive monitors was placed in Hole B during August-November and produced results that were significantly lower than the July-August measurements. Hole B also contrasts with the other St. Mary's Hills data in that radon decreases with depth. These trends appear related to increased water retention in the clayey soil of Hole B as well as collection of water in the lower meter.

Table 1. Downhole Radon Measurements, Active and Passive—St. Mary's Hills

Sample No.- Depth (m)	Date mo/yr	Active (kBq/m^3)	Date mo/yr	Passive (kBq/m^3)	Date mo/yr	Passive (kBq/m^3)
A1-1	10/88	17 ± 2	7-8/89	29 ± 4	—	—
A2-2	10/88	40 ± 3	7-8/89	40 ± 6	—	—
A3-3	10/88	61 ± 4	7-8/89	57 ± 8	—	—
A4-4	10/88	68 ± 6	7-8/89	71 ± 9	—	—
B1-1	—	—	7-8/89	42 ± 6	8-11/89	25 ± 2
B2-2	—	—	7-8/89	41 ± 6	8-11/89	28 ± 2
B3-3	—	—	7-8/89	29 ± 4	8-11/89	20 ± 1
B4-4	—	—	7-8/89	water	8-11/89	5 ± 0.4
C1-1	—	—	7-8/89	26 ± 3	—	—
C2-2	—	—	7-8/89	44 ± 6	—	—
D1-1	—	—	7-8/89	44 ± 6	—	—
D2-2	—	—	7-8/89	46 ± 6	—	—
D3-3	—	—	7-8/89	53 ± 7	—	—
Average		—		44 ± 13		—

Error values are one standard deviation based on counting statistics.

In Essex Park the radon levels range from 3 to 42 kBq/m^3 with an average of 26 ± 7 kBq/m^3 (Table 2). The level of 3 kBq/m^3 was obtained at a depth of 0.2 meters in Hole G; at a depth of one meter the lowest concentration was 13 kBq/m^3. Some of the holes show an increase in radon with depth; others show relatively uniform levels. Some of the radon concentrations measured by the active sampling are as much as 30 percent lower than concentrations measured with the passive monitors. However, the means are not statistically different.

Table 2. Downhole Radon Measurements, Active and Passive—Essex Park

Sample No.-Depth (m)	Date mo/yr	Active (kBq/m^3)	Date mo/yr	Passive (kBq/m^3)	Date mo/yr	Passive (kBq/m^3)
E1-1	8/89	22 ± 2	7-8/89	15 ± 2	—	—
E2-2	8/89	21 ± 2	7-8/89	22 ± 3	—	—
E3-3	8/89	21 ± 2	7-8/89	18 ± 3	—	—
F1-1	8/89	15 ± 2	7-8/89	21 ± 3	—	—
F2-2	8/89	26 ± 3	7-8/89	32 ± 4	—	—
F3-3	8/89	27 ± 3	7-8/89	24 ± 3	—	—
F4-4	8/89	27 ± 3	7-8/89	36 ± 5	—	—
G1-1 (0.2)*	8/89	3 ± 0.3	7-8/89	18 ± 3	8-11/89	20 ± 1
G2-2 (1.2)*	8/89	23 ± 2	7-8/89	31 ± 4	8-11/89	28 ± 2
G3-3 (2.2)*	8/89	24 ± 2	7-8/89	33 ± 4	8-11/89	23 ± 2
G4-4 (3.2)*	8/89	31 ± 3	7-8/89	42 ± 6	8-11/89	collapsed
H1-1	8/89	13 ± 1	7-8/89	23 ± 3	—	—
H2-2	8/89	21 ± 2	7-8/89	25 ± 4	—	—
H3-3	8/89	19 ± 1	7-8/89	25 ± 4	—	—
H4-4	8/89	17 ± 1	7-8/89	23 ± 3	—	—
Average		22 ± 5†		26 ± 7		

* Depth (meters) of active radon measurements in Hole G. Error values are one standard deviation based on counting statistics.

† Average does not include sample from depth 0.2 meters.

A second set of measurements in Hole G during August-November showed lower radon levels than during July-August and correspond to the decrease observed in Hole B at St. Mary's Hills. Although the decrease can be attributed to higher water retention in the soil during a rainy fall, it is difficult to be sure—as only one hole was measured within each area during the late fall.

Radon emanation was measured on the bulk samples, the 63-149 μ and the <63 μ fractions as described above. Replicate analyses gave reproducible results with standard deviations comparable to the error associated with counting statistics. A number of factors, such as moisture, radium content, and location of radium either on grain interiors or secondary coatings, control the amount of radon emanated[3]; however, on the average, higher radon emanation would be expected to produce higher radon concentrations in the soil gas. In Tables 3 and 4 the emanation results are given relative to the mass of the sample. The <63 μ fraction includes both silt and clay, and the 63-149 μ (very fine sand) represents about a third of the total sand fraction (up to 2 mm in size). In estimating total emanation, the results from the 63-149 μ measurements were considered representative of all the sand-size fractions.

Table 3. Emanation Results—St. Mary's Hills

Sample No.-Depth (m)	Bulk Emanation (Bq/kg)	Sum of Emanation from Sand & (Silt+Clay)* (Bq/kg)	Emanation 63-149 μ (Bq/kg)	Emanation <63 μ (Bq/kg)
A1-1.3	7.6 ± 0.4	14.7 ± 0.7	16.7 ± 0.9	14.6 ± 1.0†
A2-2.1	10.6 ± 0.7†	14.3 ± 0.7	11.0 ± 0.8	16.9 ± 1.0†
A3-2.9	20.1 ± 1.0	18.0 ± 0.9	15.9 ± 0.9	21.3 ± 0.9
A4-3.5	20.2 ± 0.9	22.4 ± 1.1	19.1 ± 1.0	26.8 ± 1.2
A5-4.0	11.0 ± 0.6	12.3 ± 0.6	11.4 ± 0.7	14.5 ± 1.0
A6-4.6	38.2 ± 3.3†	17.5 ± 0.9	13.7 ± 0.8†	20.3 ± 1.3†
B1-1.9	15.6 ± 0.7	9.5 ± 1.2	6.6 ± 0.6	11.2 ± 1.7†
B2-3.4	11.1 ± 0.8	12.2 ± 0.6	20.2 ± 0.9	11.9 ± 0.6
B3-4.6	13.8 ± 0.7	11.1 ± 0.6	15.0 ± 0.8†	10.9 ± 0.6†
C2-1.8	18.8 ± 1.0	11.4 ± 0.6	21.7 ± 1.0	1.2 ± 0.6
C2-2.9	11.0 ± 0.6	12.0 ± 0.6	19.5 ± 0.8	11.2 ± 1.7†
D1-1.2	18.2 ± 0.7	12.1 ± 0.6	32.4 ± 2.0	11.4 ± 0.7
D2-2.7	34.0 ± 2.0	27.1 ± 1.4	21.8 ± 1.0	30.9 ± 1.0
Average	17.7 ± 9.2	—	—	—

* Emanation measured on 63-149 μ size and applied to total sand fraction; emanation from <63 μ size includes both silt and clay. Sum is the measured emanation times the weight percent of each size fraction.

† The number is the mean of replicate measurements; error is the standard deviation.

Table 4. Emanation Results—Essex Park

Sample No.-Depth (m)	Bulk Emanation (Bq/kg)	Sum of Emanation from Sand & (Silt+Clay)* (Bq/kg)	Emanation 63-149 μ (Bq/kg)	Emanation <63 μ (Bq/kg)
E1-1.9	6.3 ± 0.6†	6.8 ± 0.7	NS‡	16.5 ± 1.0
E2-3.1	8.2 ± 0.5	12.3 ± 1.2	11.4 ± 0.7	14.9 ± 0.8
F1-1.8	9.8 ± 0.7	12.7 ± 1.2	35.5 ± 1.4	10.1 ± 0.6
F2-3.1	11.8 ± 0.6	9.3 ± 0.6	5.0 ± 1.0	9.4 ± 1.0
F3-4.3	8.8 ± 0.6	8.0 ± 0.8	2.2 ± 0.6†	10.0 ± 0.7
G1-1.9	7.4 ± 0.6	5.6 ± 0.8	3.1 ± 0.4	10.6 ± 0.6
G2-3.3	7.2 ± 0.5	6.3 ± 0.8	2.7 ± 0.4	9.5 ± 0.7
G3-4.4	10.5 ± 0.7†	6.7 ± 0.8	1.2 ± 0.5†	10.7 ± 0.8†
H1-1.8	5.6 ± 0.7	5.6 ± 0.8	2.8 ± 0.4	9.4 ± 0.6
H2-3.3	4.7 ± 0.8	5.2 ± 0.8	2.3 ± 0.4	9.7 ± 0.7
H3-4.3	5.2 ± 0.5	4.8 ± 0.7	2.0 ± 0.4	10.0 ± 0.7
Average	7.8 ± 2.3	—	—	—

* Emanation measured on 63-149 μ size and applied to total sand fraction; emanation from <63 μ size includes both silt and clay. Sum is the measured emanation times the weight percent of each size fraction.

† The number is mean of replicate measurements; error is the standard deviation.

‡ NS indicates insufficient sample for measurement.

Differences between the radon emanation rates of the two sites were comparable with those of the radon concentrations. The average radon emanating from the soils in St. Mary's Hills is just over twice that emanating from the Essex Park soils. The difference in means is statistically significant at the 0.025 confidence level. Although emanation rates in St. Mary's Hills were divided fairly evenly between the 63-149 μ and <63 μ size fractions, in Essex Park the emanation rates for nine out of ten samples was highest in the <63 μ fraction. The variation of emanation rates in Essex Park was much smaller than in St. Mary's Hills, in accordance with the more uniform radon concentrations in Essex Park.

The sum of the emanation rates from the grain-size fractions should be comparable with the emanation rate measured from each of the bulk samples. In Essex Park this was the case, but in St. Mary's Hills, although most were comparable, some soils, such as A6, had a bulk emanation rate that was larger than either the individual or the sum of the fractional emanations. The overall agreement between the bulk and weighted fractional emanations indicates that the assumption that the 63-149 μ size represents the total sand fraction is reasonable for these samples.

Other radionuclides measured included ^{232}Th, ^{226}Ra, and ^{210}Po (Tables 5 and 6). Both the mean and standard deviation of ^{232}Th are equivalent for both sites. Radium and ^{210}Pb values were higher in St. Mary's Hills than in Essex Park and were also more variable both within and between sites than was thorium. If post-depositional migration altered the radionuclide distributions, it did not affect thorium, which is not mobile under near-surface geochemical conditions. Uranium isotopes, however, respond to weathering and changing oxidation/reduction environments, leading to separation from daughter radionuclides and altered distribution patterns. The relatively uniform distributions of radionuclides in Essex Park sediments are consistent with little post-depositional migration, whereas the uneven distributions in St. Mary's Hills indicate significant migration, possibly related to enhanced weathering of the sediments on the hill slope.

Table 5. Radium-226, Lead-210 and Thorium-232 in St. Mary's Hills

Sample No.- Depth (m)	Ra-226 (Bq/kg)	Pb-210 (Bq/kg)	Th-232 (Bq/kg)	$^{210}Pb/^{226}Ra$ $\pm \approx 10\%$
A1-1.3	82 ± 10	24.9 ± 0.7†	32 ± 14	0.30
A2-2.1	77 ± 10	18.8 ± 2.6†	48 ± 18	0.24
A3-2.9	74 ± 9	37.8 ± 0.6	29 ± 15	0.51
A4-3.5	64 ± 9	37.2 ± 0.5	55 ± 19	0.58
A5-4.0	45 ± 7	26.4 ± 0.5	23 ± 17	0.59
A6-4.6	117 ± 12	146 ± 46 †	38 ± 18	1.25
B1-1.9	30 ± 6	23.7 ± 0.6	33 ± 16	0.79
B2-3.4	47 ± 8	26.4 ± 0.5	55 ± 15	0.56
B3-4.6	42 ± 7	27.0 ± 0.7	55 ± 14	0.64
C1-1.8	60 ± 9	39.9 ± 0.8	45 ± 19	0.67
C2-2.9	39 ± 7	25.8 ± 0.6	34 ± 16	0.66
D1-1.2	39 ± 7	32.3 ± 0.7	42 ± 17	0.83
D2-2.7	79 ± 9	54.9 ± 7 †	44 ± 13	0.69
Average	61 ± 25	40 ± 33	41 ± 11	0.64 ± 0.25

† The number is the mean of replicate measurements; error is the standard deviation.

Table 6. Radium-226, Lead-210 and Thorium-232 in Essex Park

Sample No.- Depth (m)	Ra-226 (Bq/kg)	Pb-210 (Bq/kg)	Th-232 (Bq/kg)	$^{210}Pb/^{226}Ra$ $\pm \approx 10\%$
E1-1.9	27 ± 6	16.1 ± 0.4	29 ± 10	0.60
E2-3.1	21 ± 5	10.9 ± 0.4	32 ± 11	0.52
F1-1.8	39 ± 7	19.4 ± 0.5	49 ± 17	0.50
F2-3.1	36 ± 7	18.4 ± 0.8	64 ± 20	0.51
F3-4.3	33 ± 7	16.1 ± 0.7	50 ± 17	0.49
G1-1.9	26 ± 5	13.3 ± 0.3	30 ± 14	0.51
G2-3.3	25 ± 7	14.4 ± 0.4	37 ± 12	0.58
G3-4.4	28 ± 6	11.9 ± 0.2†	29 ± 13	0.42
H1-1.8	30 ± 5	12.8 ± 0.4	33 ± 15	0.43
H2-3.3	23 ± 5	6.5 ± 0.3	32 ± 14	0.28
H3-4.3	25 ± 6	9.2 ± 0.4	31 ± 10	0.37
Average	28 ± 6	14 ± 4	38 ± 12	0.47± 0.09

† The number is the mean of replicate measurements; error is the standard deviation.

The activity ratio $^{210}Pb/^{226}Ra$ in the sediment can be a useful indicator of relative radon loss. A ratio smaller than one implies that radon has moved away from the radium source, resulting in less ^{210}Pb activity relative to ^{226}Ra. All but one of the samples (A6) have activity ratios less than unity; in fact, the overall activity ratio is about 0.5, with St. Mary's Hills having a somewhat higher mean value (significant at the 0.05 confidence level). Lower activity ratios could also result from only partial recovery of polonium from the sediment, with the apparent effect of reducing the Pb/Ra activity ratio. Sample A6, with an activity ratio of 1.25, is at present an anomaly because the individual activities of ^{210}Pb and ^{226}Ra, as well as the activity ratio, are much greater than those of the other samples.

Contrary to expectations, the lowest activity ratios were not always near the surface where radon could easily escape into the atmosphere. The sandy soils in Essex Park with the lowest activity ratios imply that radon has moved away from its source even at depths of 3 meters. Disequilibrium between ^{226}Ra and ^{210}Pb could also result from downward migration of radium during weathering of the sediments or could, as noted above, be partially related to inefficient extraction of polonium from the sediment. We were not able to compare the radon directly with either ^{226}Ra or ^{210}Pb because the units were different (volume vs. mass), and the samples did not always correspond in depth.

We also used a one-inch NaI detector to measure the total gamma activity at two-foot intervals in several of the holes. In general, the activity versus depth relationship followed the pattern of radium and polonium in the sediment except near the surface, where there may have been accumulations of potassium. Total gamma activity in the sediment appeared higher in St. Mary's Hills, in accordance with the other measurements, but not all holes were measured. The results do indicate that subsurface gamma activity is a potentially useful and simple screening technique, which could be improved by using a spectroscopy system that determines the energy of the radiation and identifies the isotopes present.

INDOOR RADON

The summary of the indoor radon information is given in Table 7. Of the sixty-four homeowners who were given the two detectors, forty-eight returned them. Of those, seventeen were from the St. Mary's Hills area and thirty-one from the Essex Park area. The mean indoor radon levels of St. Mary's Hills and Essex Park are different and significant at the 0.025 level for a two-sided t-test. The higher average indoor radon in St. Mary's Hills corresponds to the higher average radionuclide contents in the sediments of St. Mary's Hills and to the higher radon emanation rates. The range of indoor radon concentrations is similar for both areas; each has levels that exceed 370 Bq/m^3 and levels that are less than 37 Bq/m^3. Although this reduces the probability of predicting radon levels for individual homes, there is a good correlation between the average soil radon concentrations, parent/daughter radionuclides, and indoor radon levels.

Table 7. Summary of Radon Levels (Bq/m^3) in Homes Within the Study Area

	Geometric Mean	Arithmetic Mean	Minimum	Maximum
St. Mary's Hills				
Radon index no.†	180 * ÷ 1.8	220	70	610
Radon basement	250 * ÷ 2.1	270	40	1,100
Radon 1st floor	130 * ÷ 3.0	160	30	400
Essex Park				
Radon index no.	60 * ÷ 2.5	90	10	390
Radon basement	80 * ÷ 2.4	130	15	650
Radon 1st floor	40 * ÷ 2.7	70	10	280

† The radon index number is a weighted average of the two radon measurements in the house. The weighting factor for each floor was an estimate of the amount of time an occupant spends on each floor.

CONCLUSIONS

Our primary objective in this study was to measure, in two different areas, radionuclides related to and including radon at several depths within unconsolidated sediments, and to see what, if any, correlation existed between the characteristics of the sediment and indoor radon levels. All of the measurements were made in glacially derived or related material. None were obtained from the limestone bedrock, which was encountered in only three holes. We think that within the study areas the glacial sediments are the primary source of indoor radon and that bedrock probably is not a significant source. A more extensive study is needed to determine which homes were built on or near bedrock and collect additional data on the radon and other radionuclide levels.

Radium-226, ^{210}Pb, radon emanation, and downhole radon levels all have statistically higher averages in St. Mary's Hills sediments than those in Essex Park. Indoor radon levels also were statistically higher in St. Mary's Hills, and had a positive correlation with the radionuclides in the soil. The mineralogy, moisture levels, and bulk densities were similar in both areas and did not correlate with the radionuclide distribution. Texturally, the sediments were variable but showed similar average contents of gravel, sand, and silt/clay; however, more work is needed before firm conclusions can be made about the effect of grain-size distribution on the radionuclide content and distribution within the sediments.

All of the techniques used to assess the radon potential were consistent with each other and could be applied individually or collectively to other areas. We believe that at these sites near Rochester, mineralogical characteristics of the sediments and the location of samples within the stratigraphic column were only partially responsible for the observed distribution of radionuclides. We suggest that post-depositional transport of uranium and radium related to weathering processes contributed to the observed distributions. The redistribution of radionuclides was more extensive in the St. Mary's Hills area, probably owing to the greater vertical relief. In both areas ^{226}Ra/^{210}Pb activity ratios indicate migration of radon independent of the parent/daughter movement.

Predicting radon source areas in regions where sediments are more than a couple of meters thick should not be based solely on identification of geological materials or on near-surface radon measurements. Evidence for the secondary transport and redistribution of radionuclides is not shown on geologic maps, and near-surface radionuclide characteristics may differ from those at basement depth. The data from this study, although limited in area, indicate that measurement of radon or related radioactive nuclides in soils can be a useful preconstruction indicator of potential indoor radon problems. Survey methods could involve active measurements at depths greater than 1 meter of soil gas radon, subsurface gamma spectroscopy and ^{226}Ra in the sediment.

REFERENCES

1. Luetzelschwab, J.W., Helweick, K.L., and Hurst, K.A. "Radon concentrations in five Pennsylvania soils." *Health Physics* 56: 181, 1989.

2. Eakins, J.D., and Morrison, R.T. "A new procedure for the determination of Lead-210 in lake and marine sediments." *International Journal of Applied Radiation and Isotopes* 29: 531, 1989.

3. Nazaroff, W.W., and Nero, A.V., Jr. *Radon and its Decay Products in Indoor Air*. J. Wiley & Sons, 1988. 518 pp.

4. Olsen, B.M. "Bedrock geology," Plate 2 of 9. Balaban, N.H., editor. *Geologic Atlas of Olmsted County,* Minnesota Geological Survey County Atlas Series, Atlas C-3, Scale 1:100,000.

5. Hobbs, H.C. "Surficial geology," Plate 3 of 9. Balaban, N.H., editor. *Geologic Atlas of Olmsted County*, Minnesota Geological Survey County Atlas Series, Atlas C-3, Scale 1:100,000.