UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

Relationships between geology, equivalent uranium concentration, and radon in soil gas, Fairfax County, Virginia

by

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This report is preliminary and has not been reviewed for conformity with U.S. Geological Survey editorial standards and stratigraphic nomenclature. Any use of trade names is for descriptive purposes only and does not imply endorsement by the U.S. Geological Survey.

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ABSTRACT

Sampling was conducted in May, 1987 to determine the soil-gas radon concentrations of rocks and soils in Fairfax County, Virginia. Radon concentration, eU, eTh, and percent K in soils were determined for 129 sites along 15 traverses in the county. These data were grouped according to underlying rock type and analyzed to determine correlations between soil-gas radon concentrations and geologic characteristics of the soils and underlying rocks.

Sedimentary and metasedimentary rocks in the Triassic Lowland physiographic province, and the Peter's Creek Schist and Occoquan Granite in the Piedmont Province had high levels of radon in soil gas that could produce elevated indoor radon levels. Most other soils that were sampled generate moderately high soil-gas radon levels.

An attempt was made to consider the data collected in this study in light of factors that cause variations in radon concentrations in soils. The most important factors appear to be rainfall and barometric pressure variations. While these factors cause day-to-day variations in the measured soil radon concentrations, variations between sites are more likely to be caused by differences in soil weathering or in parent-rock composition. A direct correlation was found between soil gas radon concentrations and equivalent uranium (eU) values, but only if the data are averaged by rock type to minimize the effects of soil moisture, atmospheric, and soil composition and structure factors at individual sites.

INTRODUCTION

Elevated concentrations of radon-222 in indoor air occur in a significant number of homes in the U.S. The Environmental Protection Agency estimates that between 5,000 and 20,000 lung cancer deaths per year in the U.S. may be attributed to radon (U.S. EPA and CDC, 1986). Although it was originally believed that elevated indoor radon levels were only found in homes underlain by uraniferous mill waste or in homes constructed with uraniferous building materials, it is now known that many naturally occurring soils can produce elevated indoor radon levels.

Radon is produced by the radioactive decay of radium, a product of uranium and thorium decay in rocks and soils. Theoretically, radon-222 concentrations in soil gases should be directly related to the uranium content of the mineral matter in the soil. In actuality, however, the amount of radon produced by and contained in a soil is influenced by a number of additional factors, including porosity and permeability, soil moisture and temperature conditions, and atmospheric conditions. While these factors may affect the amount of radon available for entry into a building's foundation at a given time, it is clear that the geochemical characteristics (concentrations of radon parent materials) are of greater importance in determining the radon emanation characteristics of a site or area.

The purpose of this study was to characterize the radon concentrations of gases in rocks and soils in Fairfax County, Virginia. The intent of this paper is to discuss some generalizations concerning radon in rocks and soils underlying the county, and how these radon concentrations are related to the physical and chemical characteristics of their associated near-surface materials.

METHODS

Samples were collected at quarter- to half-mile (0.4 - 0.8 km) intervals along 13 traverses (fig. 1). Sample spacing was variable and partially dependent on changes in the underlying geology. Two additional sites, the Hiddenbrook School site (traverse 1, fig. 1) and a single home site (traverse 6, fig. 1), were sampled in detail. Traverse lines were selected to provide a representative sample of most of the major rock types in the county. A total-count aeroradiometric map (USGS, 1980) was used to pinpoint areas with anomalously high or low radiometric signatures, and many of these areas were crossed by the traverses. In addition, the traverses were selected such that undisturbed natural soils were sampled wherever possible. Because of its higher urban density, much of the eastern part of the county did not meet the sampling criteria, so this part of the county was not extensively sampled.

At each site, measurements of radon in soil gas and equivalent uranium, thorium, and potassium concentrations in surface materials were made using an EDA RDA-200 radon detector and Scintrex GAD-6 gamma spectrometer. The detector unit of the GAD-6 was placed on the ground near the soil gas probe. The number of counts registered during the 300-second counting period were recorded and converted to percent K, ppm eU, and ppm eTh using calibration equations.

Radon measurements were made using a 75 cm-long soil gas probe (fig. 2). The probe was pounded into the soil using a slide hammer and fitted with a device containing a silicone and rubber septum through which a hypodermic

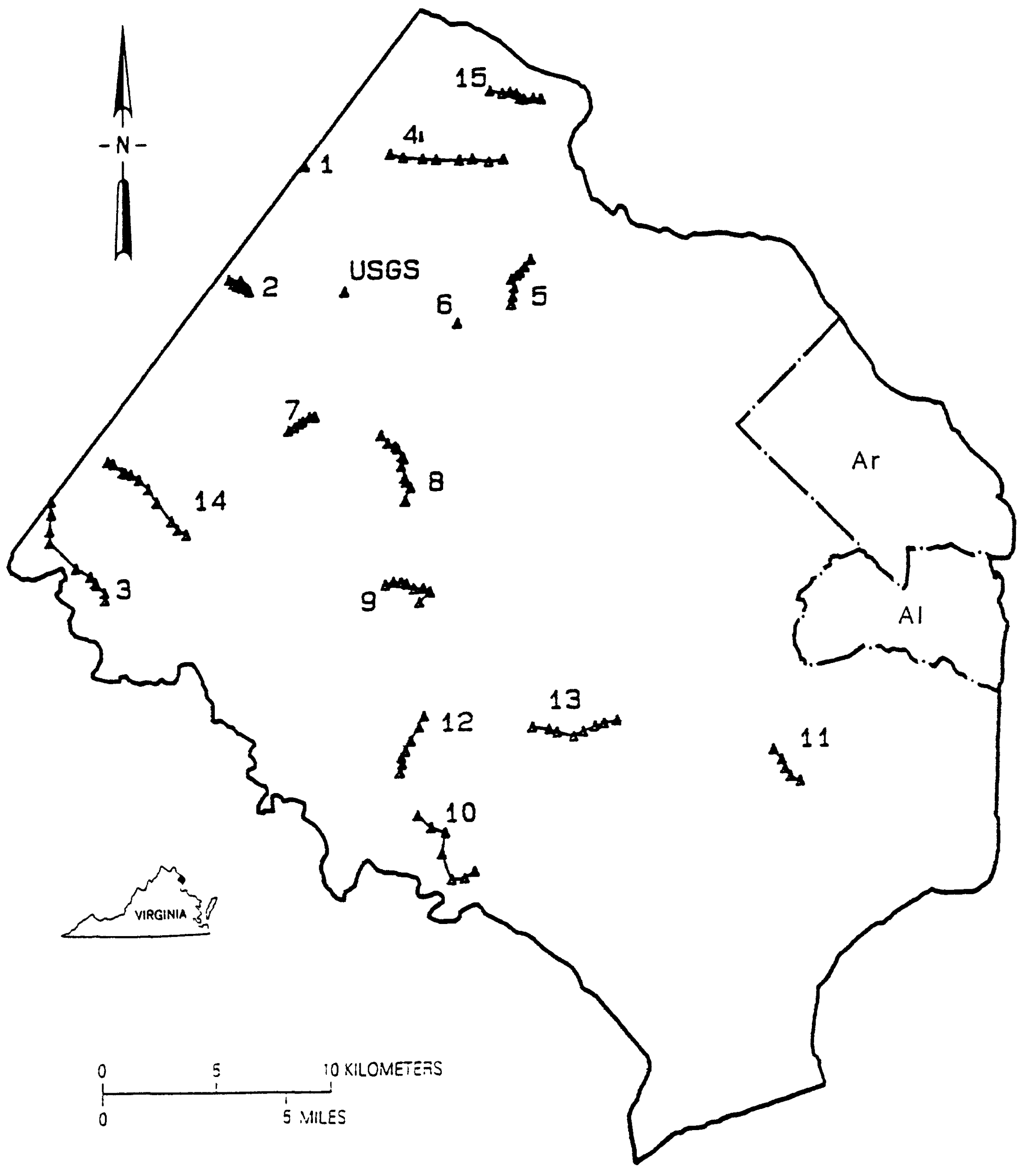


Figure 1. Index map of Fairfax County and vicinity, Virginia, showing locations of sampling traverses. "USGS" indicates location of USGS National Center in Reston. Ar- city and county of Arlington; Al- city of Alexandria.

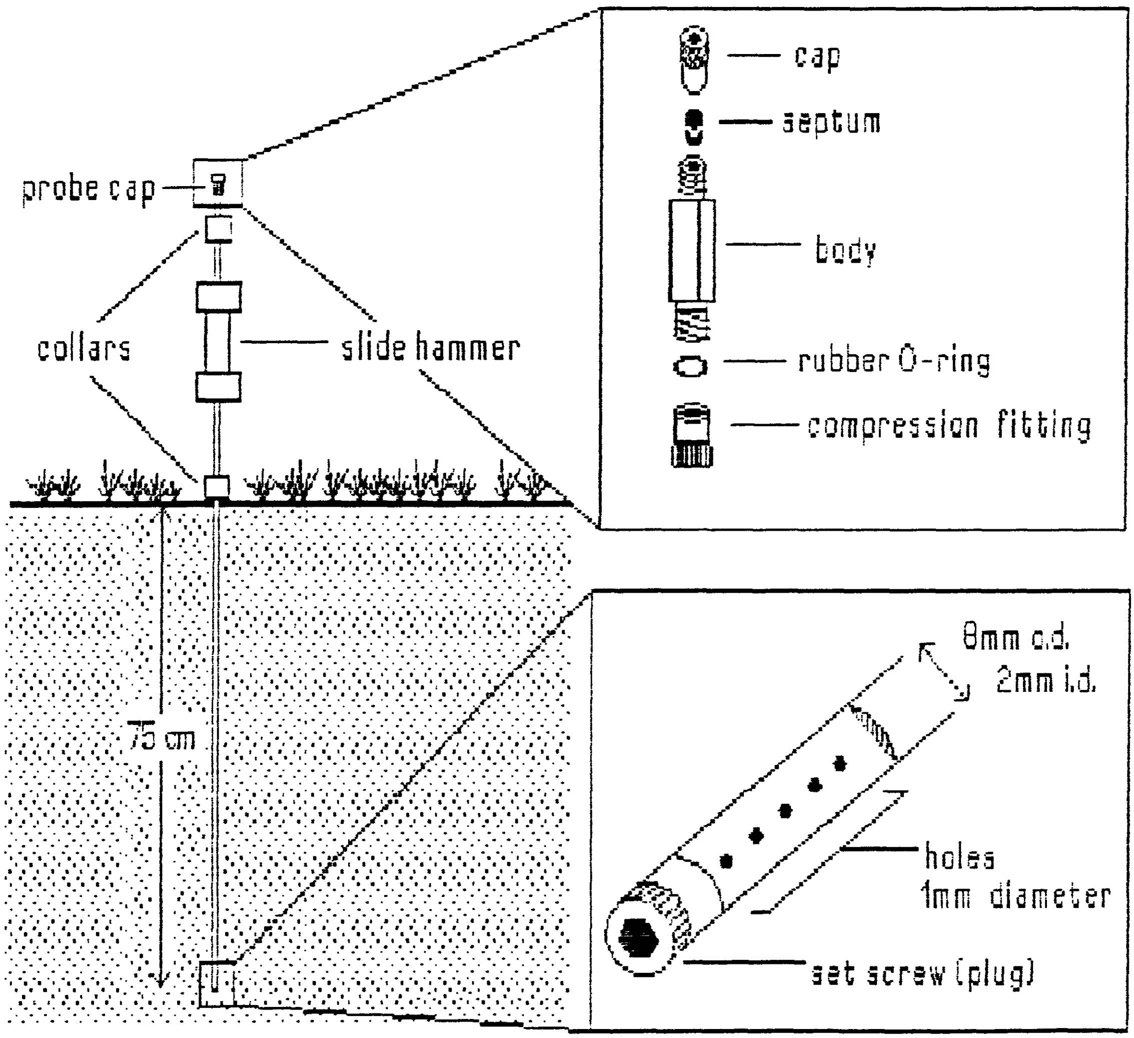


Figure 2. Sketch diagram showing 75-cm-long soil gas probe, with insets showing details of construction for the probe cap (top right) and the probe tip (bottom right).

needle was inserted to withdraw a sample of soil gas. The probe was purged of atmospheric air by withdrawing and discarding at least 10cc of gas; then a 20cc sample of soil gas was withdrawn with the hypodermic syringe and allowed to remain in the syringe for at least one minute to allow thoron (radon-220) to decay. The sample was then injected into the sample chamber of the radon detector and counted for one minute. To achieve greater accuracy when low radon values were detected or expected, 50cc samples were used (an alternate method is to use longer count times, but this was not done during this study).

Not all of the soil gas samples were taken at a depth of 75 cm. Fieldwork for this study was done between April 30 and May 12, 1987, following a period of heavy rainfall. In many parts of the study area, soils were saturated at depths less than 75 cm, so sampling at those locations was conducted at the maximum possible depth above the saturated zone. Sample depths for each location are listed in the appendix.

The rock units underlying each sample locality were determined by field inspection and comparison with a geologic map of Fairfax County (Drake and others, 1979). The data were grouped into 13 categories based on bedrock type. The rock classes were chosen so that similar rocks were grouped together (such as rocks of the same formation or member), but rocks with distinct physical or chemical differences, such as siltstones and contact-metamorphosed siltstones (hornfels), were placed in separate groups. Summary statistics (mean, standard deviation, and median) for the geophysical and radon data were calculated for each rock category.

GEOLOGY

The discussion in this section is based in part on Obermeier and Langer (1986) and Drake and others (1979).

The geology of Fairfax County is closely related to the three physiographic provinces of the area (fig. 3). The topographic relief in the study area is moderate and shows no abrupt changes across province boundaries. The Coastal Plain Province is underlain by flat-lying to gently eastward-dipping unconsolidated sediments of Cretaceous, Tertiary, and Quaternary age that unconformably overlie the folded and faulted igneous and metamorphic rocks that are exposed in the gently rolling Piedmont Province. The Triassic Lowland Province, located in the western part of Fairfax County, is an area of modest relief underlain by Triassic- to Jurassic-aged sedimentary and intrusive igneous rocks.

Much of the bedrock in the Triassic Lowland and Piedmont Provinces has been deeply weathered, and deep soil development has occurred in all three provinces. The geochemical and engineering properties of the soils are highly dependent on source rock composition. Soils formed from sedimentary rocks are commonly derived from the disaggregation of cemented or lithified strata, whereas soils formed from crystalline rocks are derived almost exclusively from in-place chemical weathering and leaching of bedrock (Obermeier and Langer, 1986). Mineralogy of the parent rock is an important control on the rate and extent of soil development and can produce large variations in soil properties over short distances.

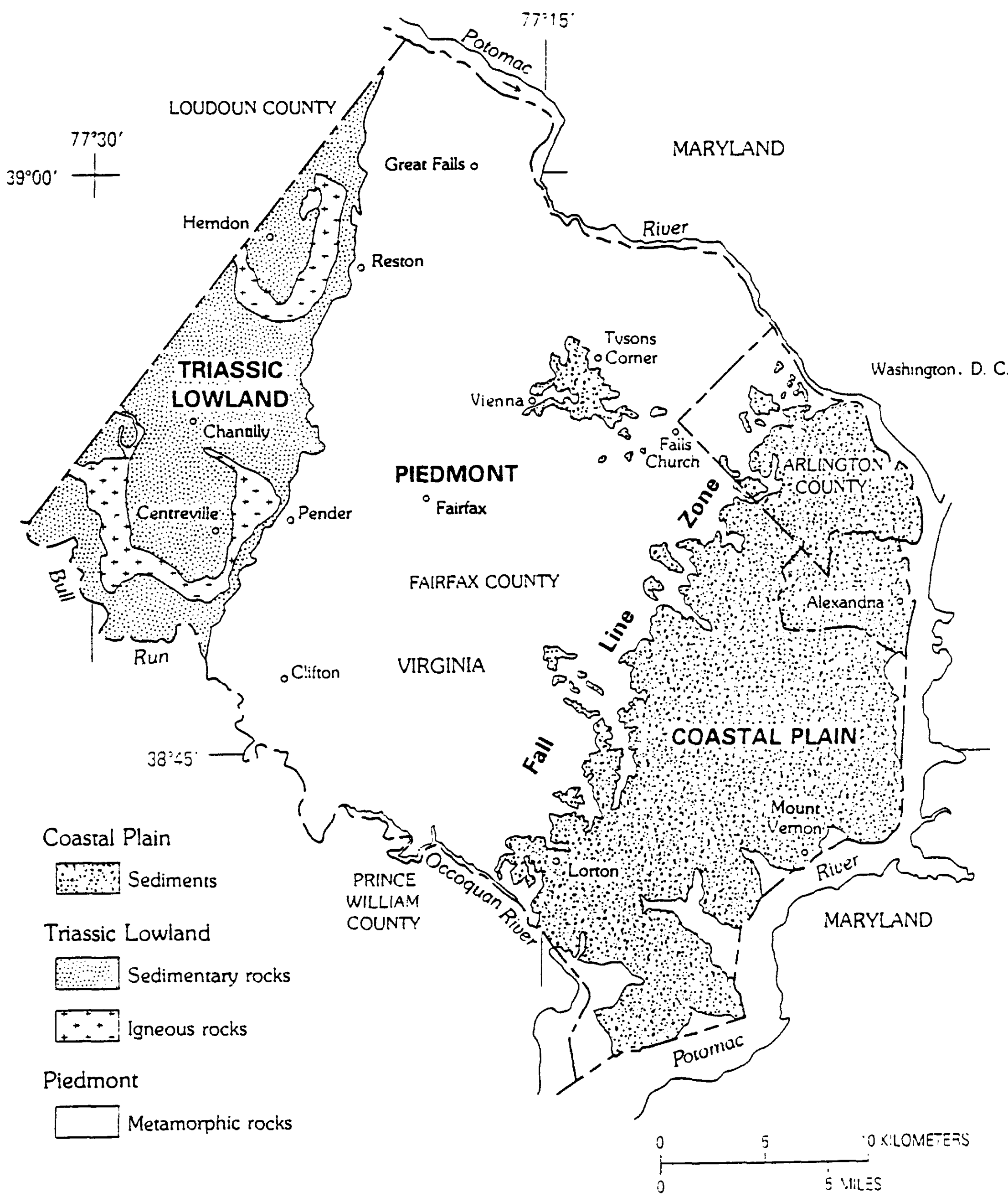


Figure 3. Generalized geologic map of Fairfax County and vicinity showing phisiographic provinces (from Froelich and Langer, 1983).

The descriptions of bedrock units sampled in this study are condensed from Drake and others (1979); the reader is referred to this map or more localized maps such as those of Drake (1986) or Drake and Froelich (1986) for more complete geologic information. Two- or three-letter abbreviations were assigned by the authors, and the descriptions are listed in alphabetical order by abbreviation and grouped by province.

Triassic Lowland Province rocks:

BBS - Balls Bluff Siltstone (Triassic). A micaceous, calcareous, sandy siltstone interbedded with sandstone and shale. The unit is believed to be of fluvio-lacustrine origin and interfingers laterally and vertically with the underlying Manassas Sandstone and the overlying Bull Run Formation.

DIA - Diabase (probably Lower Jurassic). Fine to coarse- crystalline intrusive igneous rock occurring as dikes, sills, and stocks.

HOR - Hornfels (Upper Triassic-Lower Jurassic). Thermally altered Triassic sedimentary rocks in contact with intrusive diabase. Thermal effects diminish away from diabase; halo of baked rocks may be as much as 1000 ft (300 m) wide.

MSS - Manassas Sandstone (Triassic). A very fine- to coarse-grained, thick bedded, locally crossbedded arkose, predominantly fluvial in origin. The unit interfingers laterally and vertically with the Balls Bluff Siltstone.

RCG - Reston Conglomeratic Member of the Manassas Sandstone (Triassic). A predominantly pebble-to-boulder conglomerate with subangular clasts of schist, quartz, and quartzite in an arkosic sand or clayey silt matrix. The unit is apparently a fluvial fan deposit. It rests unconformably on saprolites formed on metamorphic rocks and grades laterally and vertically into the Manassas Sandstone.

Piedmont Province rocks:

MG - Metagraywacke (Upper Precambrian? and/or Lower Paleozoic?). The unit is graded in most places, but some beds are laminated.

MS - Metasiltstone (Lower Paleozoic). Medium- to very fine-grained, with graded bedding that suggests a distal turbidite origin. The unit interfingers with a phyllite.

PCS - Peter's Creek Schist (Upper Precambrian? and/or Lower Paleozoic?). A fine to coarse-grained, quartz-rich phyllite, schist, and mica gneiss. Although several authors (Johnston, 1962, 1964; Stose, 1928) have mapped this metamorphic sequence as the Wissahickon Formation, Drake and others (1979) and Drake and Morgan (1981) believe the Peter's Creek Schist to be allochthonous and tectono-stratigraphically higher than the Wissahickon Formation as mapped elsewhere. The Peter's Creek is, however, geochemically similar to the Wissahickon Schist.

SYK - Sykesville Formation (Lower Paleozoic). Primarily a medium-grained granofels, containing quartz and allochthonous Peter's Creek Schist, pelitic schist, metagraywacke, and other metamorphic rocks.

UM - Ultramafics of the Piney Branch Complex (Upper Precambrian? and/or Lower Cambrian?). Serpentinite, soapstone, actinolite schist, and amphibolite; contains small dikes and sheets of plagiogranite.

Coastal Plain Province rocks:

ALV - Alluvium, colluvium, and terrace deposits. In the Coastal Plain Province, terrace deposits (Miocene to Pleistocene) consisting of sheetlike gravel and sand are included in this classification. Alluvium and colluvium (Quaternary) are found in all three provinces.

POT - Potomac Formation (Lower Cretaceous). Clay and silt interbedded with sand, pebbly sand, and gravel; of fluvial origin. Only the clay facies of the Potomac Formation was sampled in this study.

FACTORS AFFECTING RADON CONCENTRATIONS IN SOILS

Summary statistics for radon in soil gas and equivalent uranium values for rocks in Fairfax County are listed in Table 1. Arithmetic means and medians were calculated for each rock class. Plots of mean versus median values for radon and eU (fig. 4) show that while mean and median eU values are nearly perfectly correlated (fig 4A), some of the mean radon values are slightly higher than their corresponding median values (fig. 4B). This is due to the presence of one or more anomalously high radon values in approximately half of the sampled rock classes that serve to bias the means toward higher values. Because median values are not affected in this way, they were used rather than mean values for most of the statistical analyses presented here. The fact that the mean and median values for both radon and eU are closely correlated suggests that the data generally follow or approach a normal distribution; however, many of the rock classes contain too few samples to adequately determine the distribution of their populations.

The large standard deviations for some mean radon values reflect a wide variation in the sampled radon values within each rock type. The radon concentration in a soil at a given time is influenced by a number of factors that can increase or decrease the measured values relative to an "average" or "normal" value. Common causes of variation include diurnal variations, soil moisture conditions, atmospheric effects, and depth-related variations.

The existence of diurnal variations in radon exhalation from soils is commonly known. Radon exhalation typically peaks during the early morning hours and is at its lowest approximately 12 hours later. This variation is associated with the normal daily variations in air temperature and atmospheric pressure caused by differences in insolation throughout the day (Baver, 1956; Schery and others, 1984; Wilkening and Hand, 1960), and the variation is generally small compared to those caused by weather-related atmospheric effects. Sampling for this study was generally conducted between 7 a.m. and 6 p.m. each day, so a general decline in soil-gas radon values would be expected through the course of the day. However, because most of the rock types were sampled at various times during the day on different transects, the diurnal effect is minimized by averaging the values, and the mean and/or median values should reflect "typical" radon concentrations for those rocks and soils.

Larger scale atmospheric effects are responsible for most significant variations in measured soil-gas radon concentrations. The most important factors are rainfall (which directly affects soil moisture), barometric pressure variations, soil and atmospheric temperature variations, and wind (Baver, 1956, as summarized by Tanner, 1964). An informative review of this subject was presented by Tanner (1964, 1980). In this study, wet soils were encountered over much of the study area.

Table 1. Summary statistics for soil gas radon and eU values, Fairfax County, Virginia.
Radon values expressed in pCi/L; eU in ppm. See text for explanation of rock type abbreviations.

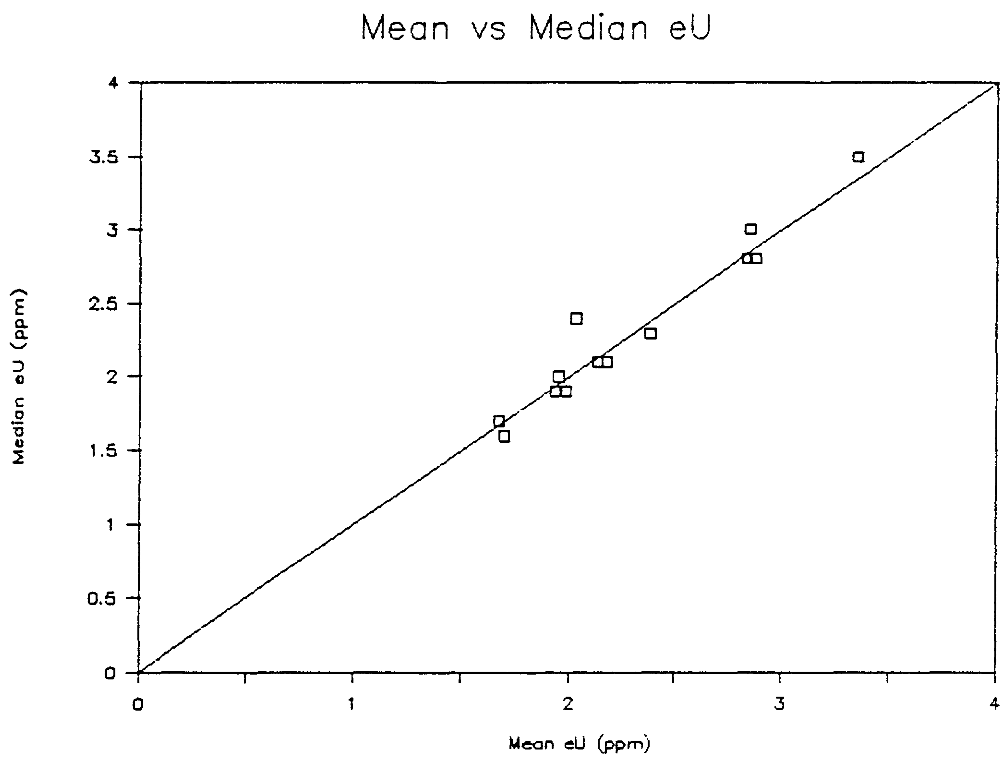
RADON

AVERAGE DEPTH(cm)	MIN	MAX	MEDIAN	MEAN	S.D.	n	ABBR.	DESCRIPTION
51	0	1175	200	388	415	13	ALV	Alluvium, colluvium, terrace deposits
43	250	2575	838	1028	737	8	BBS	Trbb - Balls Bluff Siltstone
52	225	1675	775	761	457	9	DIA	JTrd - diabase
51	150	2250	1650	1625	683	8	HOR	JTrtm - hornfels
58	575	1600	938	1022	375	8	MG	mg - metagraywacke
61	650	1775	950	1081	510	4	MS	phs - metasiltstone
64	0	4300	1300	1582	1200	17	MSS	Trm - Manassas Sandstone
71	350	2150	1300	1425	544	9	OCC	oa - Occoquan Adamellite
62	0	2425	1113	1076	588	34	PCS	mp - Peter's Creek Schist
68	375	625	500	500	177	2	POT	Kpc - Clay facies of Potomac Fm.
50	175	775	425	458	301	3	RCG	Trmr - Reston Mbr. of Manassas Ss.
55	0	1425	213	483	583	6	SYK	d - Sykesville Fm.
65	975	1300	1138	1138	230	2	UM	Czpb - Piney Branch Complex (ultramafics)

eU

MIN	MAX	MEDIAN	MEAN	S.D.	n	ABBR.	DESCRIPTION
1.2	2.9	1.9	2.0	0.5	13	ALV	Alluvium, colluvium, terrace deposits
2.2	3.4	2.8	2.9	0.4	9	BBS	Trbb - Balls Bluff Siltstone
1.8	3.0	2.3	2.4	0.4	12	DIA	JTrd - diabase
2.1	3.9	3.5	3.4	0.6	8	HOR	JTrtm - hornfels
1.5	2.9	2.1	2.2	0.5	8	MG	mg - metagraywacke
1.1	2.2	1.7	1.7	0.5	4	MS	phs - metasiltstone
0.8	4.0	3.0	2.9	0.8	17	MSS	Trm - Manassas Sandstone
1.4	2.7	1.9	1.9	0.5	9	OCC	oa - Occoquan Adamellite
1.4	4.9	2.8	2.8	0.9	34	PCS	mp - Peter's Creek Schist
1.8	2.1	2.0	2.0	0.2	2	POT	Kpc - Clay facies of Potomac Fm.
1.1	2.6	2.4	2.0	0.8	3	RCG	Trmr - Reston Mbr. of Manassas Ss.
1.6	2.8	2.1	2.1	0.5	6	SYK	d - Sykesville Fm.
1.0	2.5	1.6	1.7	0.8	3	UM	Czpb - Piney Branch Complex (ultramafics)

A



B

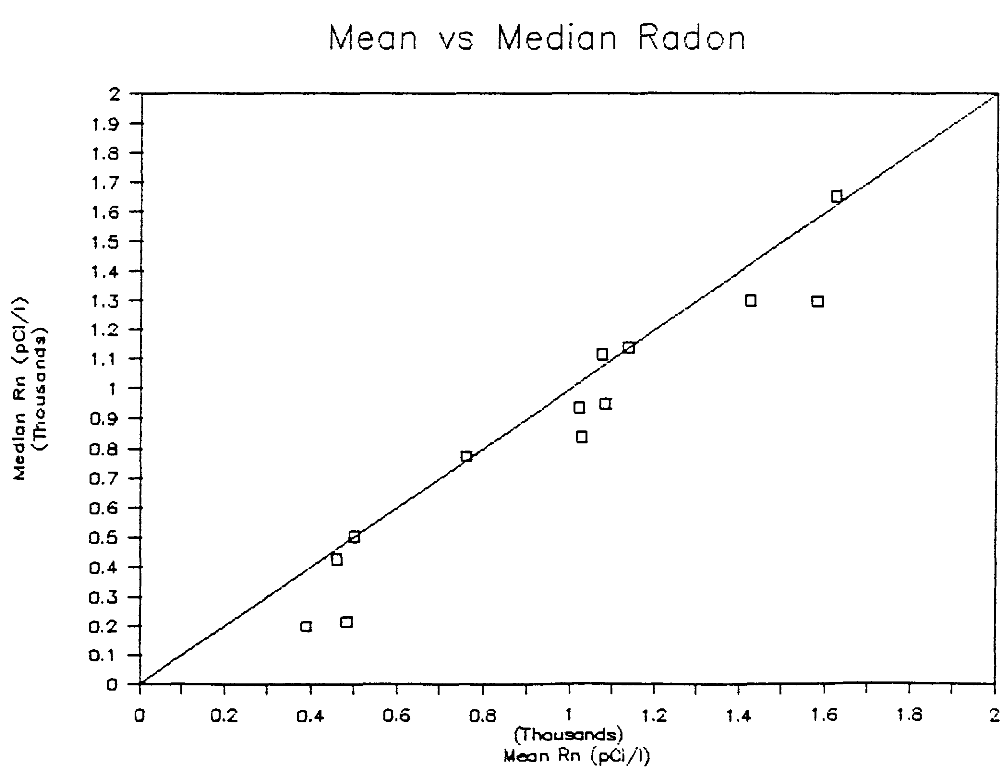


Figure 4. A) Plot of mean versus median eU for each rock class. B) Plot of mean versus median radon in soil gas for each rock class. Lines denote equality, i.e., a point plots exactly on the line if its mean and median are equal.

Although a small amount of soil moisture generally enhances radon emanation (Lindmark and Rosen, 1985; Tanner, 1964, 1980), radon emanation and transport are dramatically reduced when soil moisture increases above approximately 15-20 percent (Lindmark and Rosen, 1985). In saturated soils, the pore spaces between soil grains are completely filled with water, reducing the amount of soil gas present to nearly zero and inhibiting soil gas transport. It was not possible to obtain samples of soil gas from saturated soils because water was drawn into the sampling probe. In clay-rich soils, which absorb water readily and dry much more slowly than coarser-grained soils, water was not drawn into the probe, but because the effective gas permeability was zero, soil gas could not be extracted for sampling.

At each station, the probe was inserted to 75 cm, and if no sample could be taken at that depth, the probe was raised until gas could be extracted. The soil gas probe also served as a crude penetrometer; the difficulty of insertion with depth was qualitatively noted at each site and related to observations of soil structures. At many sites, the sampling probe encountered a water-saturated clay-rich layer (B horizon?) at 75 cm that may have had a more permeable, unsaturated horizon below it. This phenomenon was observed at other sites, where the probe passed through a tight clay-rich layer at less than 75 cm depth into a more permeable zone at greater depth that yielded sufficient soil gas for sampling.

Because the soils were sampled at varying depths and from different soil horizons there was some concern that the data may not be adequate to characterize the sampled rock units. A plot of radon concentration versus depth (fig. 5) shows a poor correlation between radon concentrations and depth of sample, indicating that higher radon values can be measured at shallow depths, and vice versa. Because rocks and soils with higher concentrations of radon parents (uranium and radium) generate higher soil-gas radon levels, these higher levels should be detectable even at shallower depths if the average sampling depths for each rock class are similar, which was the case for this study (table 1). Depth of sampling in this study was limited by soil moisture conditions, but under less restrictive circumstances it should ideally be based on knowledge of soil profiles. Soil gas samples should be taken from similar positions in similar horizons so that the engineering and chemical properties of the soils are comparable. In reconnaissance sampling programs, in which there is rarely time to describe soil profiles at each site, sampling at a consistent depth provides the next best basis for comparison.

A source of systematic error that may be associated with sampling at shallow depths is the possibility of atmospheric dilution of the soil gas. In highly permeable soils, atmospheric air can interchange relatively freely with soil air at shallow depths, lowering the measured soil-gas radon concentrations. This effect may have been responsible for some of the low concentrations measured at shallow depths, and thus may account for the high standard deviations associated with some of the average soil-gas radon concentrations (table 1).

Atmospheric contamination (note that a distinction is made between dilution and contamination) may also have affected a small number of samples (one instance is noted in the next section). In soils of extremely low permeability, it was necessary to draw on the hypodermic syringe for several minutes to collect a sufficient volume of soil gas for testing. Because of the relatively long time period and the high differential pressures involved

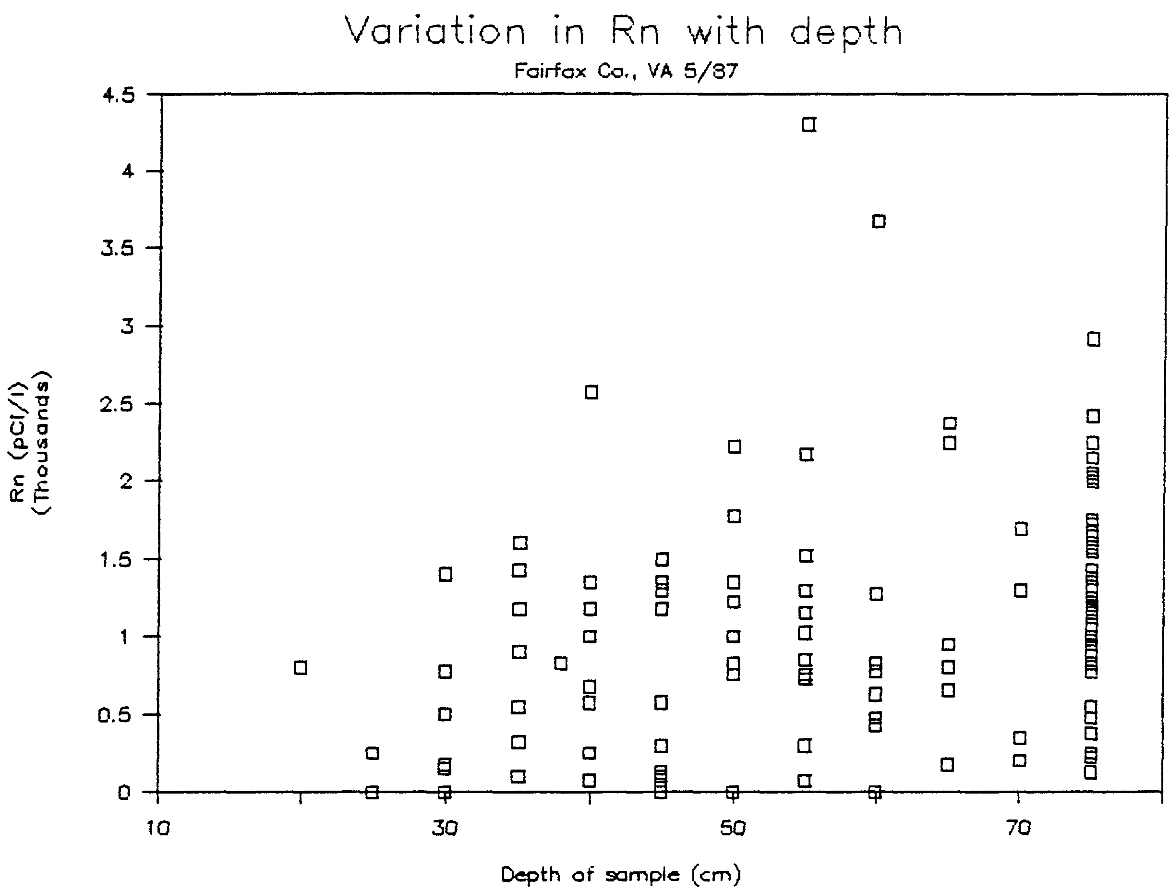


Figure 5. Plot showing radon concentration in soil versus depth at which sample was collected (n=123).

compared to those encountered when sampling from permeable soils, it is possible that atmospheric air leaked into the syringe past O-ring seals, septa, or other connectors during sampling. The seals on the sampling apparatus were checked at regular intervals, and we have complete confidence in data collected under normal conditions. In most cases in which a sufficient soil gas sample could not be extracted in less than 30 seconds, the soil was judged to be "functionally impermeable", and no soil gas sample was collected.

VARIATION IN RADON CONCENTRATION WITH DEPTH

While it is true that radon concentrations in soils generally increase with depth (Fig. 6A; Hesselbom, 1984; Lindmark and Rosen, 1985; Schery and others, 1984), the shape of the radon-depth profile rarely follows an ideal diffusion model (Tanner, 1964), because diffusion is rarely the sole agent responsible for radon movement in soils. Researchers have become increasingly aware that convective transport phenomena play a crucial and often dominant role in moving radon through soils (Tanner, 1980). Radon transport is greatly influenced by differences in soil characteristics, including development of weathering profiles, permeability differences, and soil moisture effects, as well as atmospheric effects. The shape of a radon-depth profile may change from day to day at a site as soil and atmospheric conditions change.

An experiment was conducted to investigate the effects of soil characteristics on the shape of a radon-depth profile under real-world conditions. Four soil-gas monitoring probes of the type shown in figure 2 were installed at depths of 25, 40, 60, and 75 cm at the USGS National Center in Reston, Virginia (see fig. 1 for location). Soil gas samples were extracted from each probe once each morning for six days (May 4-8 and May 11, 1987) following a heavy rain. The soil contains a clay-rich layer at 40 cm and becomes more clay-rich below 60 cm, which made extraction of soil gas from the 40 and 75 cm depths difficult. The probes at 25 and 60 cm were in silty layers that generally offered little difficulty in soil gas sampling.

Immediately following the heavy rainstorm (day 1, fig. 6B), soil gas was difficult to extract at all levels. A sample could not be extracted at the 75 cm depth, and the 40 cm value is in doubt; the reading was below detection limits and may have suffered from atmospheric contamination during sampling. The 60 cm sample was also anomalously low relative to the other days' values, and may also have been contaminated by atmospheric air leakage during sampling. By day 2 (fig. 6B), sufficient drying of the soil had occurred so that samples could be extracted at all depths, but still proved difficult at 40 and 75 cm. By day 4, the soil had dried enough for the depth profile to appear similar to the theoretical profile shown in figure 6A except for the sharp increase in radon concentrations between 25 and 40 cm.

An overnight rainstorm between days 4 and 5 caused the profile to return to a shape similar to that of days 2 and 3 (days 5 and 6, fig. 6B). In all cases, a dramatic increase in radon concentration at 60 cm was probably due to the low permeability and high moisture retention of the clay-rich layer above it, which allowed little gas to pass through it (as evidenced by the consistent difficulty encountered in extracting gas samples at 40 cm) and thus acted as a capping layer that trapped soil gas in the more permeable layer below it. This allowed radon in the 60 cm layer to accumulate to anomalously high levels compared to the layer beneath it (75 cm) while preventing radon from being transported to the surface. Above the

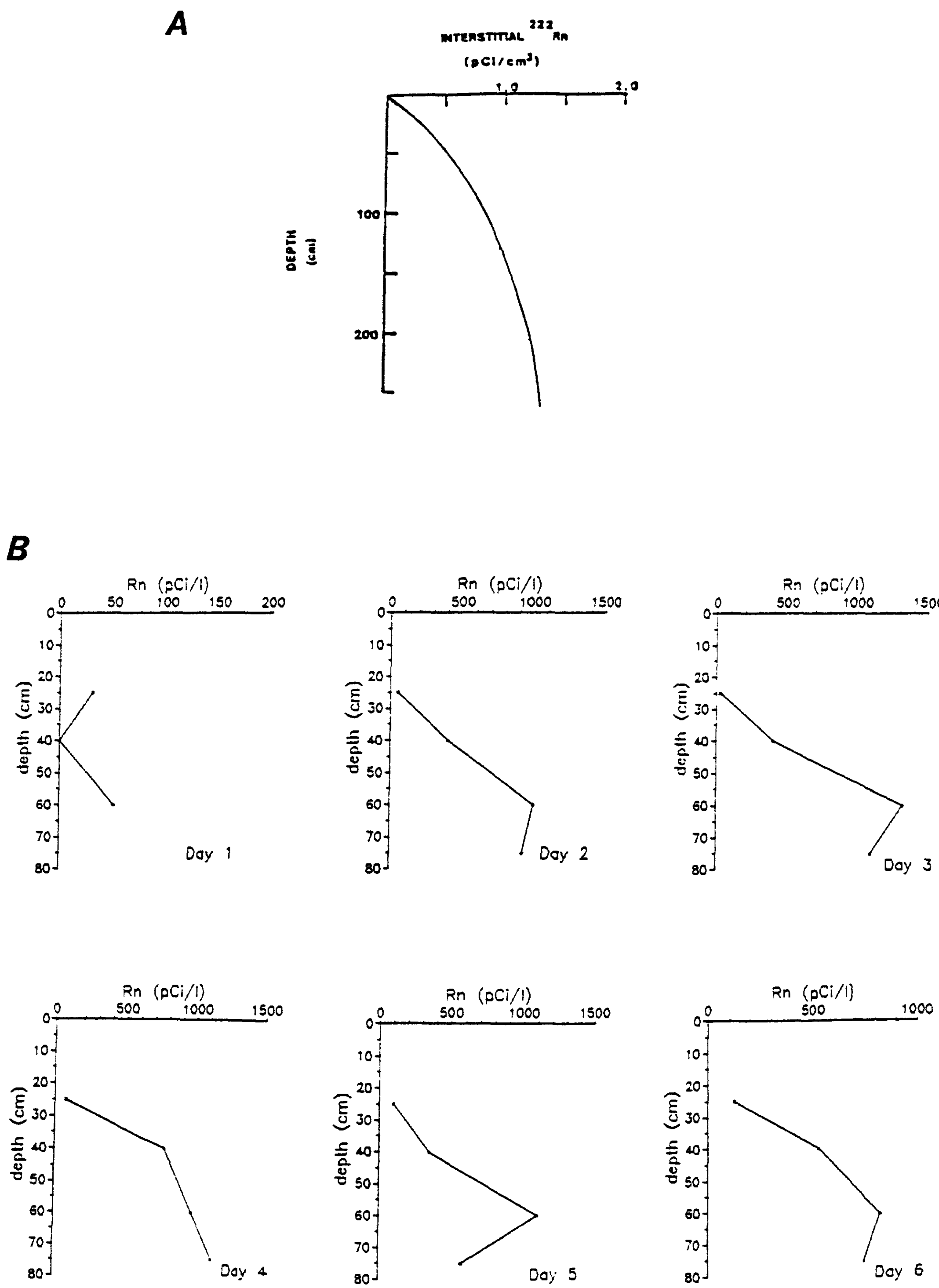


Figure 6. A) Plot showing theoretical profile of radon concentration with depth (modified from Schery and others, 1984). B) Plots showing radon concentration at four sampled depths for six days following a heavy rainstorm. Note scale changes between days 1 and 2, and between days 5 and 6. Probes were located on the grounds of the USGS National Center in Reston, Virginia.

clay-rich layer (i.e., at 25 cm), atmospheric mixing likely caused dilution of the soil gas that partly accounts for the lower levels recorded at 25 cm.

The results of this experiment indicate that the diffusion-based theoretical radon-depth profile (fig. 6A) cannot adequately describe the distribution of radon in most natural soils. This is due primarily to the restrictions imposed by the simplifying assumptions of the diffusion model: 1) that the soil is physically and chemically homogeneous; 2) that ideal soil moisture conditions for diffusion exist in the soil; and 3) that the soil gases are not affected by atmospheric disturbances such as changes in barometric pressure and winds. Obviously, these criteria cannot all be met in natural soils under normal conditions; therefore, soil gas data can best be interpreted when some knowledge of the physical and chemical properties of the soils in question has been obtained. Likewise, data from any short-term soil gas sampling technique can only provide an estimate of the average radon concentrations in soils because of the previously mentioned sources of variation, many of which are not considered or cannot be adequately measured in a reconnaisance sampling program.

RELATIONSHIPS BETWEEN RADON AND eU IN SOILS

Because radon-222 is a daughter product of uranium-238, it is reasonable to suggest that there should be a close correlation between equivalent uranium (eU), which was measured by portable gamma spectrometer, and soil-gas radon concentrations. A plot of radon concentration versus eU (fig. 7) shows that, at first glance, there appears to be a poor correlation. This apparent disparity suggests that one cannot have much faith in radon hazard assessments that are based primarily on radiometric (gamma-ray) data. Determining the reliability of gamma-ray data for preliminary radon hazard evaluation is important because aeroradiometric data, particularly data generated by the National Uranium Resource Evaluation (NURE) program, are often the only relevant data available for use in preliminary regional radon hazard assessments.

An aeroradiometric map of Fairfax County (USGS, 1980) was used during the initial selection of sampling transects for this study, and ground-based spectral gamma-ray measurements were taken at each sampling location. Several inconsistencies between the gamma-ray data (both aerial and ground-based) and soil gas radon measurements highlighted some major limitations of both types of data that should be considered when studies of this type are conducted. Although the data presented here are for ground-based gamma-ray measurements, the discussion is generally applicable to aeroradiometric data as well.

Gamma-ray measurements provide a sample of earth surface materials to a depth of approximately 20 cm (Durrance, 1986) over an area with a radius of approximately twice the height of the detector above the ground surface (Duval and others, 1971). The relatively shallow depth of investigation provided by both aerial and ground-based gamma-ray measurements has important consequences when an attempt is made to correlate eU with radon levels on a site-by-site basis.

The variability of radon concentrations in the soil caused by differences in soil moisture, permeability, and atmospheric effects also makes a direct comparison of radon concentrations with eU difficult. Grab samples of soil gas are probably not representative of average soil radon levels if radon concentrations have been temporarily reduced by excessive soil moisture or temporarily enhanced by an abrupt drop in barometric

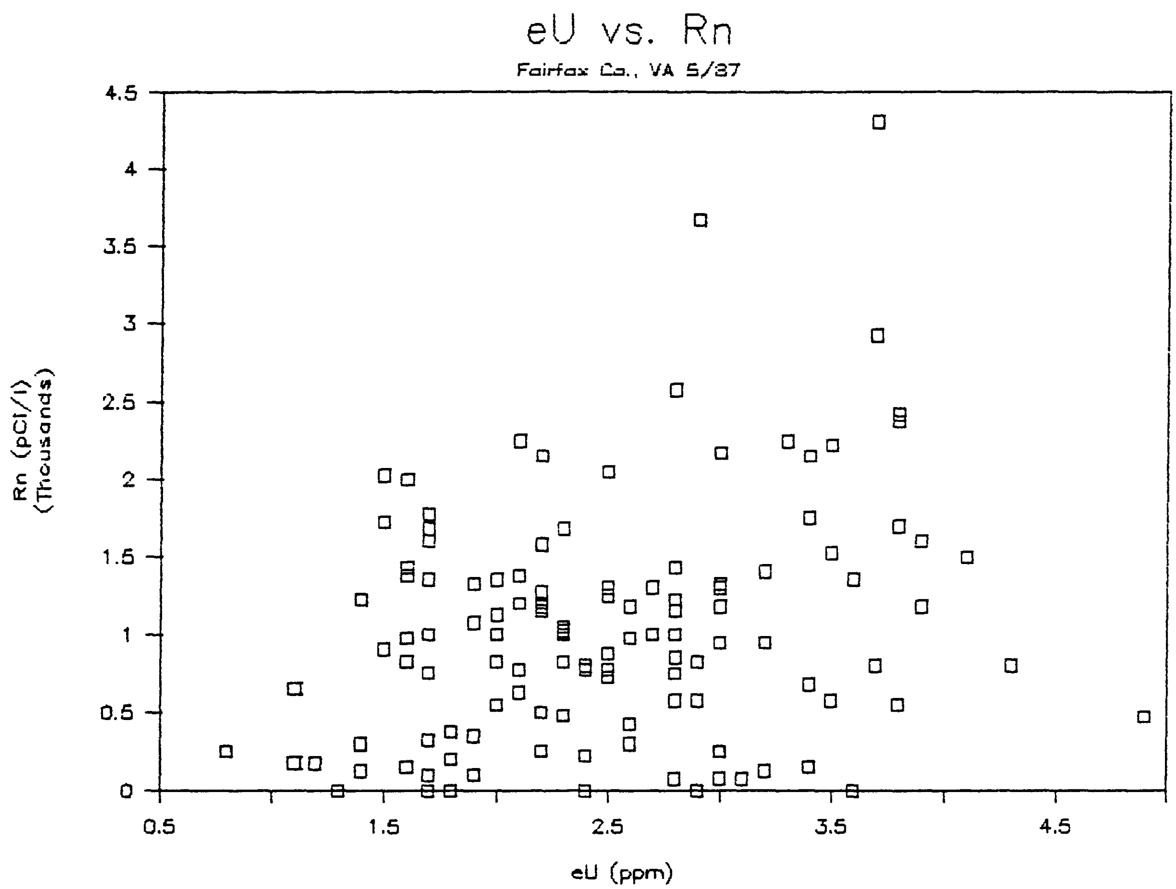


Figure 7. Plot showing radon concentration in soil gas versus eU for individual samples (n=122).

pressure. The magnitudes of the variations that can occur in soil-gas radon measurements are likely to be far greater than those of the expected variations in eU at a given site because radon, as a gas, is highly mobile and thus it is readily affected by short-term perturbations such as weather-related disturbances. This variability may account for much of the scatter seen in the graph of figure 5.

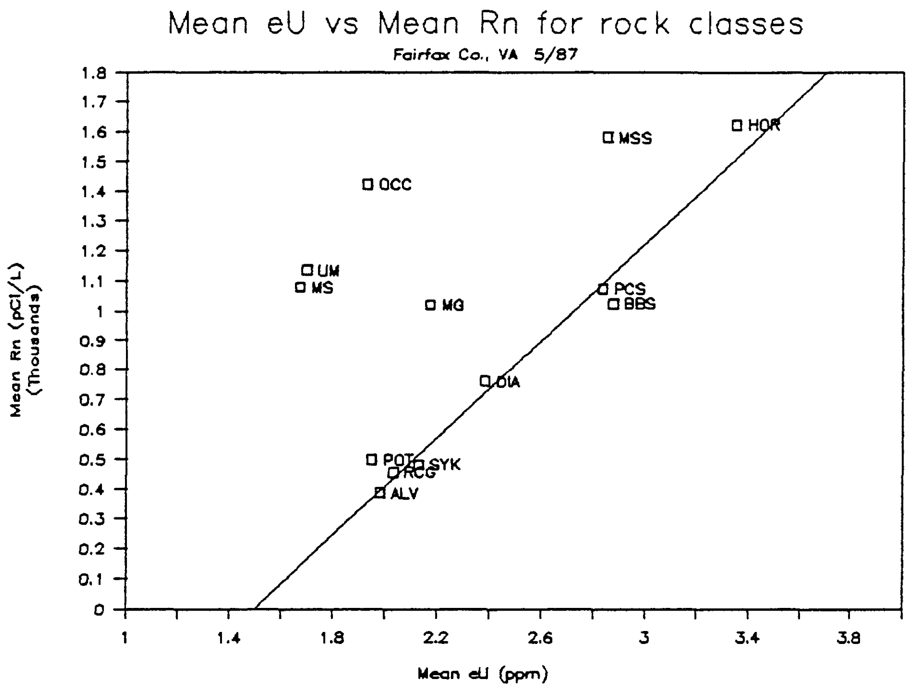
A statistical approach to this problem provides several important insights. In a statistically representative sample of a given lithologic unit, variations greater than and less than the average should effectively cancel each other if the data are normally distributed about the mean. Thus, a plot of mean or median eU versus mean or median radon concentrations should show a recognizable correlation, and this is indeed the case (fig. 8). Regardless of whether means or medians are used, the plots show a linear correlation between radon and eU, with four or five points above the line indicating radon values that are higher than expected according to their corresponding eU values. In the case of the Manassas Sandstone samples (MSS) on the plot of mean radon versus mean eU (fig. 8A), the mean radon concentration is biased toward a higher value by several anomalous readings taken at a radon "hot spot" (the Hiddenbrook School site, traverse 1, fig. 1, and appendix). Because the median is less affected by this bias, the value for MSS falls nearer the line on the plot of medians (fig. 8B).

The other four "outlier" points (OCC, UM, MS, and MG samples) are common to both plots and appear to be true anomalies. However, the possibility exists that the means and medians of those rock classes represented by small sample numbers (see table 1) may not reflect a true average for those rock types, and thus may not plot in their proper positions on the graph. It is possible that some or all of the outliers would plot closer to the line if a larger sample was averaged. However, all of the outliers plot in a loose cluster representing higher than expected soil-gas radon values for their eU values, suggesting that their positions on the graphs are due to the workings of some non-random process rather than to random variations. The following proposed explanations are based on this assumption.

Three of the four anomalous radon-eU relationships (OCC, MS, and MG) appear to represent eU values that are low relative to their corresponding radon values, suggesting that although the upper soil layers contain lower than expected uranium concentrations relative to the amount of radon detected, relatively higher concentrations of uranium occur deeper in the soil than could be detected with the gamma spectrometer. Most soils in Fairfax County are very well developed and intensely weathered. The depth of weathering of most soils in the Piedmont Province, for example, exceeds 20 m and in some places exceeds 50 m (Obermeier and Langer, 1986). Soils that have been subjected to intense chemical weathering have had a large portion of their uranium-bearing minerals leached from their top few meters, but still contain significant concentrations of uranium at greater depths that provide a source for radon. If the soils are relatively permeable, the radon can migrate upward and thus be available for entry into a building's foundation; by the same token, the radon is also available to the soil-gas sampler. An alternate explanation for the metamorphic rocks (MS and MG) is that the uranium in these rocks was remobilized during metamorphic alteration.

The fourth anomaly, that of the ultramafics (UM), cannot be as easily explained. Ultramafic rocks typically contain less uranium than most rocks,

A



B

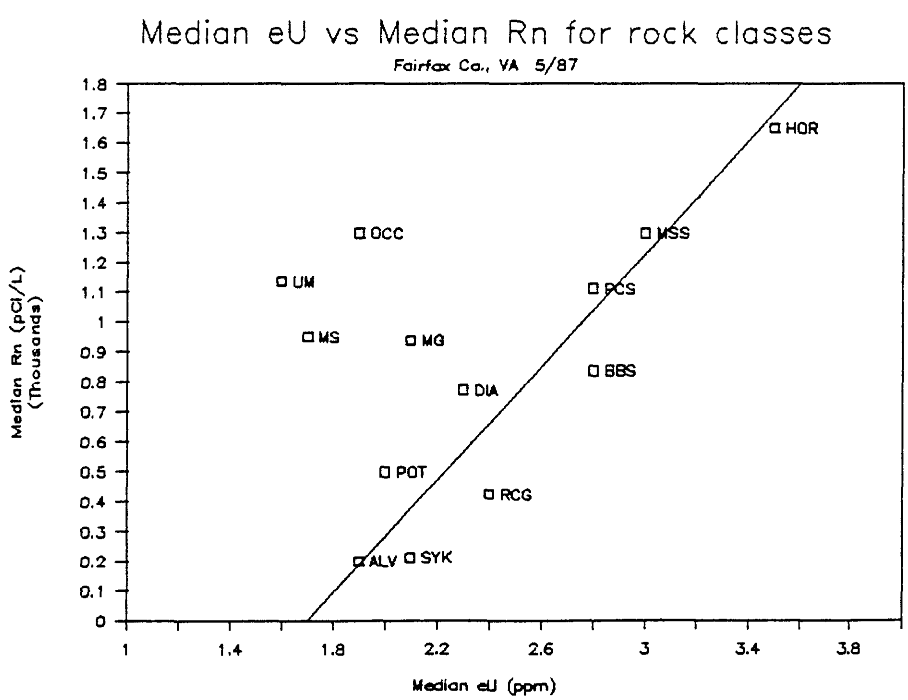


Figure 8. A) Plot of mean radon concentration versus mean eU for each rock class. B) Plot of median radon concentration versus median eU for each rock class. Lines fitted by eye; outlier points were not included in regressions.

so the lower eU values may be accurate. Three samples comprise this group, and all of these samples were collected on a single traverse (traverse 9, fig. 1 and appendix) crossing an outcrop of the Piney Branch Complex where it is exposed in the Jermantown synform (Drake, 1986). The Piney Branch Complex is bounded to the east and west by Peter's Creek Schist, and the rocks are highly sheared and faulted. Uranium may have migrated into these rocks during shearing. Intermixed fragments of Peter's Creek Schist or small granitic dikes in the Piney Branch Complex are other possible localized radon sources.

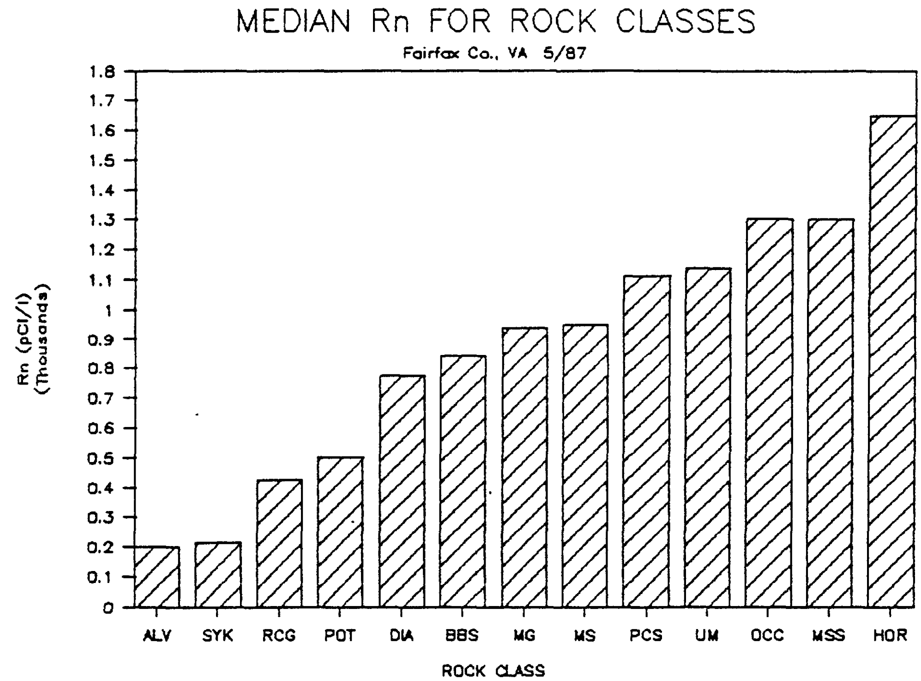
Because of its shallow depth of investigation, the reliability of aerial or ground-based gamma-ray data as an estimate of soil-gas radon concentrations may be doubtful in areas with deep soil weathering profiles or complex geology, as was demonstrated by the anomalous radon-eU relationships discussed above. We recommend that gamma-ray data always be supplemented with geologic and soils data, and with ground-based soil gas sampling whenever possible, to avoid overestimating or underestimating the radon concentrations of rocks and soils in an area.

COMPARISON OF SOIL-GAS RADON CONCENTRATIONS BY ROCK CLASS

To provide a comparison of radon concentrations in rocks underlying Fairfax County, the soil-gas radon data were plotted in order of increasing median radon concentration (fig. 9A). Although median values of soil-gas radon should reflect "average" or "typical" expected radon values, much of the preceeding discussion has shown that the physical and chemical characteristics of soils, which directly influence soil-gas radon values, are spatially and temporally variable. Because we are not yet fully able to quantify all of these physical and chemical factors, individually or in combination, to accurately determine the expected range of soil-gas radon values, a comparison of maximum measured soil-gas radon concentrations should also be made (fig. 9B).

In general, rocks with the highest soil-gas radon concentrations are sedimentary and contact metamorphic rocks of the Triassic Basin, and the Peter's Creek Schist and Occoquan Granite in the Piedmont Province. Most other rocks of the Piedmont Province yield soils with moderate soil-gas radon levels. Rocks of the Coastal Plain Province appear to have generally low radon concentrations, but this is based on only five samples from rocks in the Coastal Plain Province, so the accuracy of such a generalization is unknown.

A



B

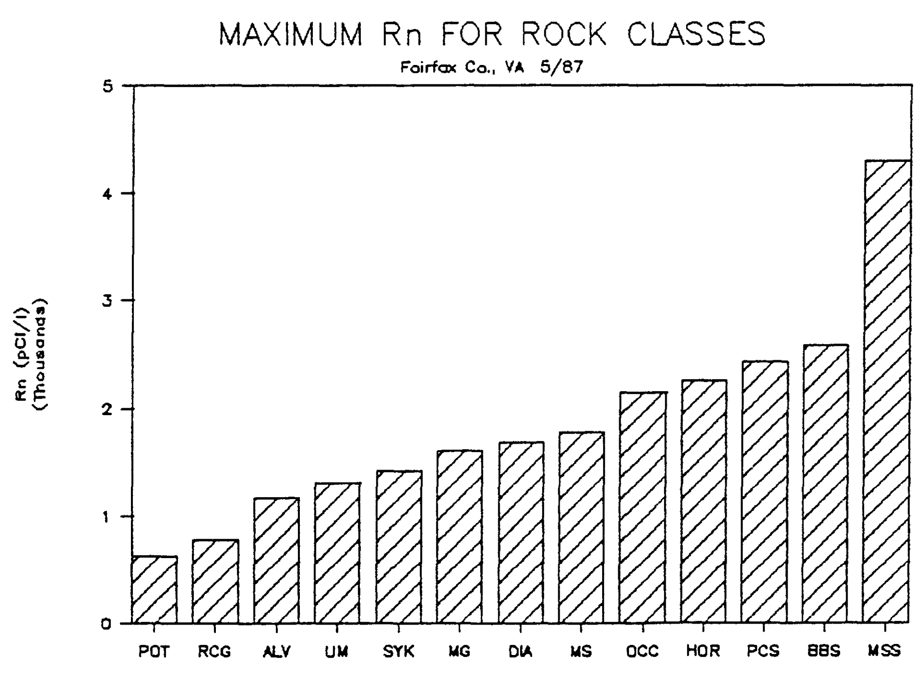


Figure 9. A) Graph showing median soil-gas radon concentrations for each rock class plotted in increasing order. B) Graph showing maximum soil-gas radon concentrations for each rock class plotted in increasing order. Note vertical scale change.

SUMMARY AND CONCLUSIONS

Radon concentrations in soil gas are highly variable, and the variability is caused by a number of independent and interrelated factors. An effort was made to identify and determine the effects of some of these factors during the course of this study. Although much of this discussion has focused on physical processes affecting radon generation and migration in soils on a day-to-day basis, the results of this study indicate that the primary factor that determines the gross concentration of radon in a soil is the geology of its parent rock. Climatic and weather-related factors affect the measured concentration of radon in soil gas at any point in time, but are of secondary importance overall, as these factors can only modify existing radon emanation and transport characteristics, whereas these characteristics are determined by geologic factors. The mineralogy of the parent rock determines uranium concentration; other geologic processes, such as tectonism and pore-fluid interactions, may then redistribute the uranium. The physical and chemical properties of soils, determined by source-rock composition and weathering processes, control their radon emanation and transport characteristics. A basic understanding of these processes is necessary to effectively perform field investigations relating to radon. In addition, one cannot effectively interpret soil-gas radon data without an awareness of the factors that can affect the measured values. Thus is it essential that geologic and soil characteristics always be noted and considered, especially for site evaluation purposes.

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APPENDIX: DATA TABLES

FOR EACH TRAVERSE, SAMPLES ARE LISTED IN THE FOLLOWING ORDER: If the trend of the traverse is primarily N-S, samples are listed in order from north to south. If the traverse trends dominantly E-W, samples are listed from west to east. Refer to index map (fig. 1) for general location of traverses. Column headings: Station-sample site within traverse. Depth-depth at which radon sample was collected, in cm. Rn-soil gas radon, in pCi/l. K-potassium, in percent. eU-equivalent uranium, in ppm. eTh-equivalent thorium, in ppm. Rock Code-assigned by authors according to underlying bedrock type. Description-more detailed description of underlying bedrock at each site, including map abbreviation from Drake and others (1979). Blank indicates no sample taken.

Traverse 1: Hiddenbrook School site. See index map (fig. 1) for approximate location.

STATION	DEPTH	Rn,pCi/l	K,%	eU,ppm	eTh,ppm	ROCK CODE	DESCRIPTION
A	75	2925	1.1	3.7	6.5	MSS	Trm-Manassas Sandstone
B			2.5	4.0	14.8	MSS	Trm-Manassas Sandstone
C	75	1550				MSS	Trm-Manassas Sandstone
D	75	2050	1.6	2.5	4.6	MSS	Trm-Manassas Sandstone
E	75	2250	1.9	3.3	5.1	MSS	Trm-Manassas Sandstone
F	70	1300	1.6	3.0	4.8	MSS	Trm-Manassas Sandstone
G	60	3675	1.7	2.9	5.1	MSS	Trm-Manassas Sandstone
H	55	1150	1.4	2.8	6.1	MSS	Trm-Manassas Sandstone
I	55	4300	1.3	3.7	6.9	MSS	Trm-Manassas Sandstone
J	65	950	1.3	3.0	5.5	MSS	Trm-Manassas Sandstone
K	60	1275	1.4	2.2	7.4	MSS	Trm-Manassas Sandstone
L	55	850	1.0	2.8	5.3	MSS	Trm-Manassas Sandstone
M	50	750	1.3	2.8	5.6	MSS	Trm-Manassas Sandstone
N	55	2175	1.6	3.0	6.4	MSS	Trm-Manassas Sandstone

Traverse 2: County Road 665 (Coppermine Road), between County Rds. 605 (Horse Pen Rd.) and 657 (Centreville Rd.)

STATION	DEPTH	Rn,pCi/l	K,%	eU,ppm	eTh,ppm	ROCK CODE	DESCRIPTION
G	65	2250	2.2	2.1	7.8	HOR	JTrtm-hornfels
F	75	2150	2.5	3.4	8.8	HOR	JTrtm-hornfels
E	55	1525	1.6	3.5	7.5	HOR	JTrtm-hornfels
D			0.9	3.0	7.5	DIA	JTrd-diabase
C			0.9	2.9	7.2	DIA	JTrd-diabase
H	75	1675	0.7	2.3	6.6	DIA	JTrd-diabase
B	35	550	0.5	2.0	5.5	DIA	JTrd-diabase
A	75	1075	1.0	1.9	6.2	DIA	JTrd-diabase

Traverse 3: County Road 621 (Bull Run Post Office Road), between the Loudon-Fairfax County Line and State Highway 29 (Lee Highway).

STATION	DEPTH	Rn,pCi/l	K,%	eU,ppm	eTh,ppm	ROCK CODE	DESCRIPTION
H	75	225	0.8	2.4	7.8	DIA	JTrd-diabase
I	75	1325	2.3	3.0	11.5	MSS	Trm-Manassas Sandstone
G			1.5	3.4	9.7	BBS	Trbb-Balls Bluff Siltstone
J	25	250	3.2	3.0	11.4	BBS	Trbb-Balls Bluff Siltstone
F	75	1000	1.8	2.7	10.1	BBS	Trbb-Balls Bluff Siltstone
E	35	1425	1.3	2.8	9.7	BBS	Trbb-Balls Bluff Siltstone
D	50	2225	2.2	3.5	9.7	HOR	JTrtm-hornfels
K			0.9	1.8	4.6	DIA	JTrd-diabase
C	38	825	1.3	2.9	8.7	DIA	JTrd-diabase
B	40	1000	0.9	2.8	6.8	DIA	JTrd-diabase
A	40	250	0.8	2.2	7.6	DIA	JTrd-diabase

Appendix (continued)

Traverse 4: County Road 193 (Georgetown Pike), between County Rd. 7 (Leesburg Pike) and County Rd. 681 (Walker rd.)

STATION	DEPTH	Rn,pCi/l	K,%	eU,ppm	eTh,ppm	ROCK CODE	DESCRIPTION
A	75	2425	2.5	3.8	11.0	PCS	mp-Peter's Creek Schist
B	75	2000	1.1	1.6	5.4	PCS	mp-Peter's Creek Schist
C	75	1175	2.0	2.6	8.6	PCS	mp-Peter's Creek Schist
D	75	1200	1.8	2.2	10.2	PCS	mp-Peter's Creek Schist
E	75	1750	1.7	3.4	6.9	PCS	mp-Peter's Creek Schist
F	75	1200	1.8	2.1	8.5	PCS	mp-Peter's Creek Schist
G	75	950	1.7	3.2	6.5	PCS	mp-Peter's Creek Schist
H	75	1375	1.7	2.1	9.0	PCS	mp-Peter's Creek Schist

Traverse 5: County Road 702 (Beulah Road), between County Rd. 7 (Leesburg Pike) and County Rd. 267 (Dulles Access Rd.)

STATION	DEPTH	Rn,pCi/l	K,%	eU,ppm	eTh,ppm	ROCK CODE	DESCRIPTION
H	75	475	2.8	4.9	11.7	PCS	mp-Peter's Creek Schist
G	75	1000	1.3	1.7	6.0	PCS	mp-Peter's Creek Schist
F	75	1375	0.9	1.6	3.5	PCS	mp-Peter's Creek Schist
E	65	800	2.1	3.7	8.5	PCS	mp-Peter's Creek Schist
D	75	1000	1.6	2.3	5.9	ALV	Qal-alluvium
C	65	2375	1.9	3.8	7.7	PCS	mp-Peter's Creek Schist
B	75	550	1.0	3.8	6.2	PCS	mp-Peter's Creek Schist
A	75	1050	1.6	2.3	7.5	PCS	mp-Peter's Creek Schist

Traverse 6: Site of home in Reston. See index map (fig. 1) for approximate location.

STATION	DEPTH	Rn,pCi/l	K,%	eU,ppm	eTh,ppm	ROCK CODE	DESCRIPTION
A	45	1175	2.7	3.9	13.4	PCS	mp-Peter's Creek Schist
B	40	1350	2.2	3.6	11.4	PCS	mp-Peter's Creek Schist
C	35	1175	2.2	3.0	12.6	PCS	mp-Peter's Creek Schist
D	20	800	2.3	4.3	12.6	PCS	mp-Peter's Creek Schist
E	40	75	2.1	3.0	10.5	PCS	mp-Peter's Creek Schist
F	75	1750	2.1	3.4	12.0	PCS	mp-Peter's Creek Schist
G	40	575	2.1	3.5	11.3	PCS	mp-Peter's Creek Schist
H	50	0	2.1	3.6	9.9	PCS	mp-Peter's Creek Schist
I	45	75	1.8	3.1	9.6	PCS	mp-Peter's Creek Schist

Traverse 7: County Road 764 (Oxon Road), between County Rd. 669 (Thompson Rd.) and County Rd. 608 (West Ox Rd.)

STATION	DEPTH	Rn,pCi/l	K,%	eU,ppm	eTh,ppm	ROCK CODE	DESCRIPTION
A	60	0	1.6	1.8	6.1	MSS	Trm-Manassas Sandstone
B	75	250	1.2	0.8	2.7	MSS	Trm-Manassas Sandstone
C	45	125	1.2	3.2	3.3	MSS	Trm-Manassas Sandstone
E	30	175	1.0	1.1	4.4	RCG	Trmr-Reston cgl.
D	60	775	0.9	2.4	5.7	RCG	Trmr-Reston cgl.
F	60	425	1.0	2.6	7.4	RCG	Trmr-Reston cgl.

Appendix (continued)

Traverse 8: County Road 665 (Fox Mill-Waples Mill Rds.), between County Rd. 672 (Vale Rd.) and Interstate 66.

STATION	DEPTH	Rn,pCi/l	K,%	eU,ppm	eTh,ppm	ROCK CODE	DESCRIPTION
K	60	825	1.7	2.3	8.6	PCS	mp-Peter's Creek Schist
I	50	1000	1.3	2.0	4.1	MG	mg-metagraywacke
J	50	825	1.3	2.0	5.5	MG	mg-metagraywacke
H	30	0	1.7	2.9	6.9	ALV	Qal-alluvium
G	45	1500	3.7	4.1	13.7	PCS	mp-Peter's Creek Schist
F	75	775	1.8	2.5	7.3	PCS	mp-Peter's Creek Schist
E	75	1575	1.9	2.2	7.7	MG	mg-metagraywacke
D	35	900	0.9	1.5	6.0	MG	mg-metagraywacke
C	45	300	1.9	2.6	7.1	ALV	Qal-alluvium
B	75	775	1.8	2.4	6.0	ALV	Qal-alluvium
A	75	125	0.7	1.4	3.4	PCS	mp-Peter's Creek Schist

Traverse 9: County Road 620 (Braddock Road), between County Rd. 655 (Shirley Gate Rd.) and County Rd. 123 (Ox Rd.).

STATION	DEPTH	Rn,pCi/l	K,%	eU,ppm	eTh,ppm	ROCK CODE	DESCRIPTION
A	75	975	0.6	1.6	5.4	UM	CZpb-ultramafics
B	55	1300	0.6	2.5	4.5	UM	CZpb-ultramafics
C			0.5	1.0	4.1	UM	CZpb-ultramafics
D	75	825	1.6	1.6	8.7	PCS	mp-Peter's Creek Schist
E	75	1325	1.7	1.9	8.8	PCS	mp-Peter's Creek Schist
F	55	750	1.7	1.7	7.0	MS	phs-metasiltstone
G	65	650	1.3	1.1	6.1	MS	phs-metasiltstone
H	75	1150	1.0	2.2	6.3	MS	phs-metasiltstone

Traverse 10: County Road 647 (Hampton Rd.), between County Rd. 643 (Henderson Rd.) and Sandy Run.

STATION	DEPTH	Rn,pCi/l	K,%	eU,ppm	eTh,ppm	ROCK CODE	DESCRIPTION
A	75	1225	0.9	1.4	8.8	OCC	oa-Occoquan granite
B	75	1125	1.1	2.0	7.7	OCC	oa-Occoquan granite
C	75	1725	0.8	1.5	4.9	OCC	oa-Occoquan granite
D	30	150	0.5	1.6	3.7	ALV	Qc-colluvium
E	75	2150	1.1	2.2	5.8	OCC	oa-Occoquan granite
G	45	1300	1.0	2.7	6.4	OCC	oa-Occoquan granite
F	75	1675	1.5	1.7	6.6	OCC	oa-Occoquan granite

Traverse 11: County Road 635 (Hayfield Road), between County Rd. 613 (Beulah St.) and County Rd. 611 (Telegraph Rd.).

STATION	DEPTH	Rn,pCi/l	K,%	eU,ppm	eTh,ppm	ROCK CODE	DESCRIPTION
A	40	1175	0.5	2.2	5.2	ALV	Ct3-terrace dep.
B	65	175	0.4	1.2	3.9	ALV	Ct3-terrace dep.
C	75	375	1.2	1.8	4.1	POT	Kpc-Potomac Fm. (clay)
D	60	625	1.5	2.1	4.5	POT	Kpc-Potomac Fm. (clay)
E	70	200	2.3	1.8	4.9	ALV	Qc-colluvium

Appendix (continued)

Traverse 12: County Road 610 (Wolf Run Shoals Road), between Butts Corner and Makleys Corner.

STATION	DEPTH	Rn,pCi/l	K,%	eU,ppm	eTh,ppm	ROCK CODE	DESCRIPTION
G	50	1775	1.2	1.7	8.0	MS	phs-metasiltstone
F	45	100	1.5	1.7	8.0	SYK	d-Sykesville Fm.
E	45	0	1.0	2.4	6.2	SYK	d-Sykesville Fm.
D	55	75	0.9	2.8	5.4	SYK	d-Sykesville Fm.
C	35	100	0.9	1.9	4.1	ALV	Qal-alluvium
B	35	325	0.8	1.7	4.7	SYK	d-Sykesville Fm.
A	75	1425	1.0	1.6	4.0	SYK	d-Sykesville Fm.

Traverse 13: County Road 644 (Keene Mill Road), between County Rd. 643 (Burke Center Parkway) and County Rd. 638 (Rolling Rd.).

STATION	DEPTH	Rn,pCi/l	K,%	eU,ppm	eTh,ppm	ROCK CODE	DESCRIPTION
A	75	875	0.8	2.5	5.7	ALV	Qc-colluvium
B	75	1250	1.1	2.5	7.0	OCC	oa-Occoquan granite
C	55	300	0.7	1.4	6.8	ALV	Qc-colluvium
D	75	2025	1.2	1.5	7.1	OCC	oa-Occoquan granite
E	70	350	0.7	1.9	5.9	OCC	oa-Occoquan granite
F	45	0	0.7	1.7	4.0	ALV	Qal-alluvium
G	75	975	1.4	2.6	8.6	SYK	bg-Lake Barcroft metagraywacke
H	25	0	0.5	1.3	3.0	ALV	Ct2-terrace dep.

Traverse 14: County Road 620 (Braddock Road), between County Rd. 609 (Pleasant Valley Rd.) and County Rd. 28 (Sully Rd.).

STATION	DEPTH	Rn,pCi/l	K,%	eU,ppm	eTh,ppm	ROCK CODE	DESCRIPTION
K	35	1600	2.0	3.9	10.6	HOR	JTrtm-hornfels
J	70	1700	1.8	3.8	8.7	HOR	JTrtm-hornfels
I	30	775	0.8	2.1	6.6	DIA	JTrd-diabase
H	60	475	0.8	2.3	4.5	DIA	JTrd-diabase
G	30	150	1.4	3.4	7.2	HOR	JTrtm-hornfels
F	30	1400	3.6	3.2	13.2	HOR	JTrtm-hornfels
E	40	675	1.6	3.4	7.5	BBS	Trbb-Balls Bluff siltstone
D	50	1225	1.4	2.8	10.5	BBS	Trbb-Balls Bluff siltstone
C	40	2575	1.2	2.8	6.8	BBS	Trbb-Balls Bluff siltstone
B	30	500	1.7	2.2	7.8	BBS	Trbb-Balls Bluff siltstone
A	45	575	1.4	2.8	7.9	BBS	Trbb-Balls Bluff siltstone

Traverse 15: County Road 603 (Beach Mill Road), between County Rd. 681 (Walker Rd.) and County Rd. 603 (River Bend Rd.)

STATION	DEPTH	Rn,pCi/l	K,%	eU,ppm	eTh,ppm	ROCK CODE	DESCRIPTION
H	45	575	3.2	2.9	10.3	MG	mg-metagraywacke
G	55	1025	1.6	2.3	8.4	PCS	mp-Peter's Creek Schist
F	65	800	1.7	2.4	7.3	PCS	mp-Peter's Creek Schist
E	55	725	2.8	2.5	9.0	MG	mg-metagraywacke
D	75	975	2.2	2.6	8.8	MG	mg-metagraywacke
C	50	1350	0.7	1.7	5.6	PCS	um-ultramafics
B	75	1600	1.2	1.7	6.4	MG	mg-metagraywacke
A	45	1350	1.3	2.0	6.8	PCS	mp-Peter's Creek Schist