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THE CORRELATION BETWEEN BEDROCK GEOLOGY AND INDOOR RADON: WHERE IT WORKS AND WHERE IT DOESN'T-SOME EXAMPLES FROM THE EASTERN UNITED STATES

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ABSTRACT

In the eastern half of the United States, below the limit of glaciation, bedrock geology accounts for a significant amount of the variation seen in indoor radon. Various geologic parameters as well as soil radon and surface gamma radiation have been compared with thousands of indoor radon measurements and regression analyses indicate high positive correlations ($R>.5$ to $.9$). In this part of the U.S., bedrock geologic models for indoor radon can be used successfully for prediction. Across the northern tier of states that have been subject to glaciation, the correlation of bedrock geology to indoor radon is obscured or is positive in only certain situations. In glaciated areas of the country, the type, composition, thickness, and permeability of glacial deposits play major roles in controlling radon sources in the soil. The contribution from water to indoor air and certain types of house architecture are also confounding factors in certain areas of the United States.

INTRODUCTION

The relationship between geology and radon has been documented since the late 1970s, most notably in uranium exploration literature. Among the first to document a correlation between regional geology and indoor radon were Sachs and others (1982). More recent studies have confirmed that this relationship is complicated and dependent on climate, terrain, bedrock composition, soil permeability, and other parameters particular to the region's climate and geology. Geology controls the chemical composition of the rocks and soils from which radon is derived. It also controls the distribution of certain surficial deposits like glacial till and river alluvium. Climate exerts a strong control over the temperature and moisture content of soils, thus affecting radon emanation and physical and chemical weathering of the soils and rocks.

Indoor radon assessments often rely on *a priori* factors such as bedrock geology or soil permeability to predict the potential of an area for radon. A regional-scale indoor radon assessment of the United States was recently completed using indoor radon and several types of geologic data including bedrock geology, soil permeability, and aerial gamma-ray surveys (Gundersen and others, 1992; Schumann, 1993). As a result of these and other studies, some general statements can be made about which rocks and soils are radon sources. Rock types that are most likely to cause indoor radon problems include carbonaceous black shales, glauconite-bearing sandstones, certain kinds of fluvial sandstones and fluvial sediments, phosphorites, chalk, karst-producing carbonate rocks, certain kinds of glacial deposits, bauxite, lignite, certain kinds of coals, uranium-rich granitic rocks, metamorphic rocks of granitic composition, graphitic schist and slate, silica-rich volcanic rocks, many sheared or faulted rocks, and certain kinds of contact-metamorphosed rocks. Rock types least likely to cause radon problems include marine quartz sandstones, non-carbonaceous shales and siltstones, certain kinds of clays, silica-poor metamorphic and igneous rocks, and basalts. Exceptions exist within these general lithologic groups because of the occurrence of localized uranium deposits, commonly of hydrothermal origin, causing veins in crystalline rocks, or "roll-front" deposits in sedimentary rocks. Uranium and radium are most commonly sited within rocks in heavy minerals, iron-oxide coatings on rock and soil grains, organic materials in soils and sediments, uranium with phosphate and carbonate complexes in rocks and soils, and uranium minerals. Some physical features, most notably faults and shear zones, have been identified as sites of localized uranium concentrations and have been associated with some of the highest reported indoor radon levels (Gundersen, 1991).

In this report we examine the utility of bedrock geology, soil radon, and gamma-ray data in predicting indoor radon and some of the regional and climatic limitations on these types of data with examples from the eastern United States.

METHODOLOGY AND DATA USED

Data presented in this paper includes indoor radon measurements, soil radon grab samples, surface gamma-ray spectrometry, and observations of geology and soil.

Indoor radon measurements

Indoor radon values used in this paper are predominantly charcoal canister measurements made in the lowest livable areas of the home over a 2-7 day period of time. Data were collected by the author and others as cited in the text. These data are expressed in units of concentration as picocuries per liter (pCi/L).

Gamma-ray measurements

Equivalent uranium (eU) data from surface gamma-ray measurements are used in this report and are expressed in units of parts per million (ppm). These data provide an estimate of the surficial concentrations of uranium or radium in bedrock, soil, and surficial deposits. Equivalent uranium is calculated from the counts received by a gamma-ray detector in the wavelength corresponding to bismuth-214 (^{214}Bi), with the assumption that uranium and its decay products are in secular equilibrium. Three ppm eU corresponds to approximately 1 picocurie per gram (pCi/g) of radium-226. Surface gamma-ray measurements were made using a multi-channel calibrated gamma spectrometer, gamma radiation was counted for five minute intervals at each ground location.

Radon in Soil

Radon in soil gas was determined using a modified version of the method of Reimer (1992). A steel probe of approximately 8 mm diameter is driven into the ground to a depth of .75 to 1 meter. A grab sample of 20 cm^3 is withdrawn through an air-tight septum in a removable cap fitted on top of the probe. Soil air enters the probe through 10 holes which pierce a recessed zone of the probe 1.3 cm from the end. Radon concentration, expressed in picocuries per liter (pCi/L), was determined using an alpha scintillometer several hours after sampling to eliminate thoron and to alow each sample to equilibrate. Sampling was usually performed during dry stable periods of time in the spring and summer by the author and others as cited in the text.

DISCUSSION

Saprolite Soils of the Northeast and Mid-Atlantic States and Indoor Radon

In the Northeastern and Mid-Atlantic states that are unaffected by glaciation, bedrock geology can be successfully used to predict indoor radon, especially in basement homes. Figure 1 presents frequency distributions of indoor radon and soil radon for several major metamorphic rock types in the Piedmont of Maryland (Gundersen and others, 1988). The soils of the Piedmont are saprolitic, meaning that they are derived directly from the underlying bedrock and still retain some of the original bedrock structure. The indoor radon data in Fig. 1 are predominantly basement charcoal canister data and the soil radon data were sampled at a depth of 0.75 m. The frequency distribution of indoor radon levels in homes varies for each rock type but is generally asymmetrically normal to log normal. Radon in soil gas varies accordingly. Some rock types, like the gneiss and schist, are more heterogeneous than the phyllite and mafic rock, and this is reflected in the distribution of the measurements. Figure 1 also shows that soil radon and indoor radon vary systematically with different rock types. Each rock type has a radioactivity signature that is distinctive for that rock type and applicable to other regions of the country with similar rocks. The composition and origin of the rock control to some extent the amount of uranium that will be in it. Gneiss and schist in this instance are metamorphosed and deformed sediments, possibly sandstones, shales, and conglomerate, whereas the phyllite is derived mostly from carbonaceous shale. Most of the very high readings in both Figs. 1a and 1b are from soils derived from sheared rocks. Shearing of these rocks took place after the sediments had become lithified into rock and metamorphism had begun. Shearing imparts a foliation to the rock causing mineral crystals like quartz and feldspar to become elongated and reduced in size. During shearing, uranium minerals and minerals that contain uranium, like titanite and zircon, break down and the uranium migrates to the foliation with iron oxides in an oxidizing fluid and are then redeposited in the foliations.

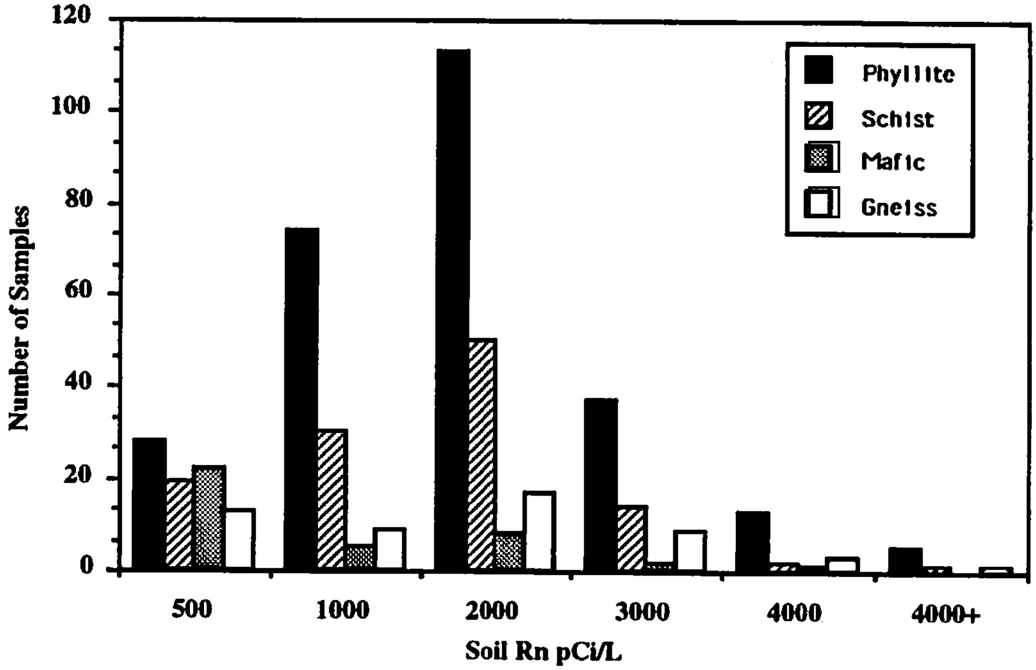


Figure 1A. Soil gas radon for four major rock types in the Piedmont of Maryland.

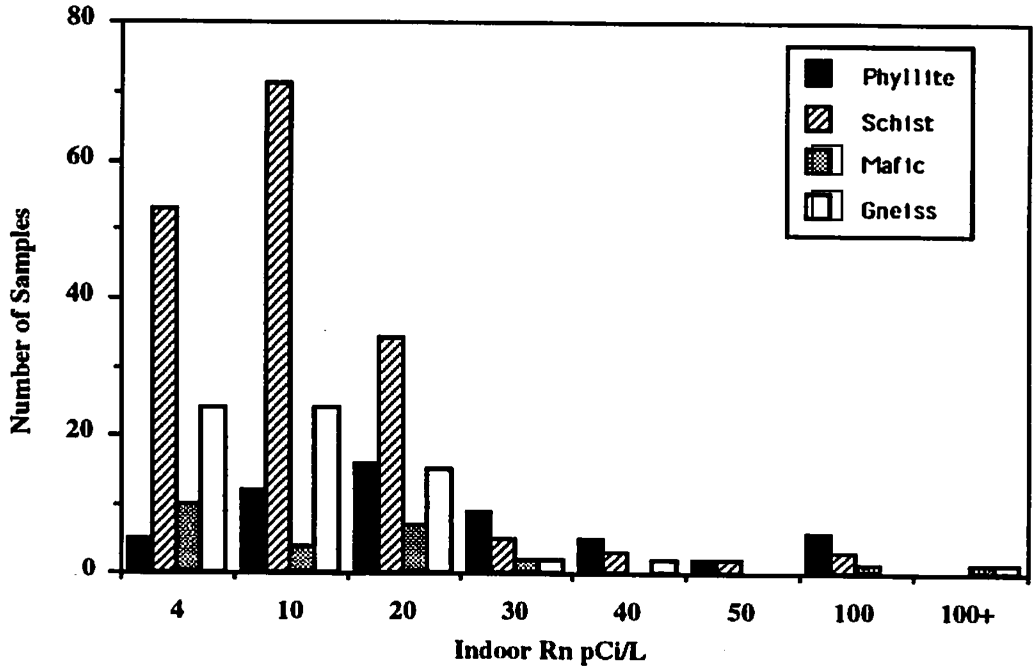


Figure 1B. Indoor radon for four of the major rock types in the Piedmont of Maryland.

If the data from Maryland are compared with similar rock types and saprolitic soil from the Reading Prong (Gundersen, 1991) the pattern of the relationship among indoor radon, soil radon, and rock type emerges (Fig. 2). The data shown in this figure include the averages of over 1000 indoor radon measurements and 1500 soil radon measurements including the data from Figures 1A and 1B. Mafic rocks are characteristically a poor radon source. Rocks such as aluminous and feldspathic gneiss, schist, and phyllite vary but are generally sources of moderate to high radon. Granites and sheared rocks are generally sources of very high radon. Another factor reflected in Fig. 2 is permeability. At lower permeability, radon migration in the soil is impeded and at higher permeability radon migration is favored, or radon may move by flow rather than diffusion. The permeability of saprolitic soils over shear zones is typically very high because of the deformation structure imparted to the rock and mimicked in the soil. Further, the rock weathers along the deformation structure, opening the soil structure and increasing the permeability and radon emanation. Permeability of gneiss and schist is moderate compared to their sheared counterparts and soils may be very clayey because of the break down of mica and feldspar. Mafic rocks usually have low permeability because most of the minerals in mafic rocks (biotite, hornblende, pyroxene, and serpentinite) weather easily and break down into clays.

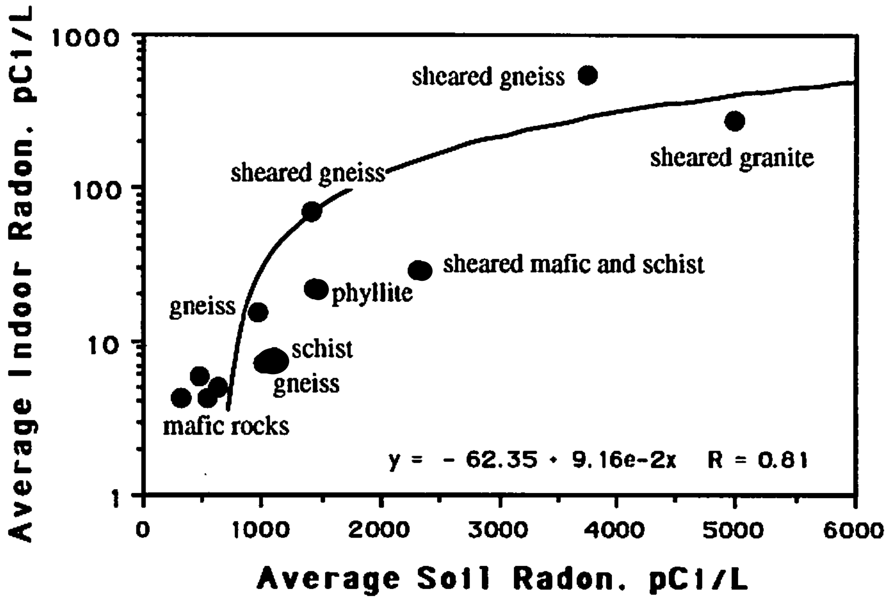


Figure 2. Average indoor radon versus average soil radon for major rock units in the Piedmont of Maryland and in the Reading Prong of New Jersey and Pennsylvania.

Indoor Radon and Soil Radon From a Glaciated Area

Soil radon (485 samples) and indoor radon (126 samples) were examined in rocks from Orange County, New York, where glaciation has occurred. Here, the bedrock is diverse and consists of sedimentary rocks as well as metamorphic rocks that are similar to the metamorphic rocks in the previous examples. The bedrock under Orange County consists predominantly of shale, sandstone, conglomerate, and graywacke with several large areas of limestone, dolomite, mafic and granitic gneiss, and granite. The bedrock in Orange County does not have saprolitic soils developed on it. Various glacial deposits that are derived from local bedrock and rock sources to the north have been deposited over the area. These glacial deposits include kame, lake deposits, outwash, ground moraine, and recessional moraine deposits. Moraines are ridges of till that form at the margin of a glacier and their thickness, permeability, and grain size varies over the area. Generally they are poorly sorted mixtures of gravel, sand, silt, and clay. Kame deposits are composed of gravel and sand left by rivers and streams flowing along margins or on top of the glacial ice. Glacial outwash silt, sand, and gravel is typical of the river valleys in Orange County. The glacial lake deposits are composed of fine sand, silt and clay. As can be seen in Fig. 3, a very high correlation between indoor radon and soil radon is achieved when the measurements are grouped by glacial deposit and the measurements averaged. When the measurements are grouped by bedrock type the regression only yields an R=0.21. Several studies of soil radon and indoor radon in New York (Kunz and others, 1987; Laymon and others, 1990) and in New Jersey (Gates and others, 1990) also demonstrate clearly that glacial deposits are better predictors of indoor radon and radon sources in soil than bedrock geology. In the northern midwestern states, Schumann and others (1991) has shown positive correlations between soil radon and different kinds of glacial deposits and used glacial deposits to characterize the radon potential of this part of the United States (Schumann, 1993).

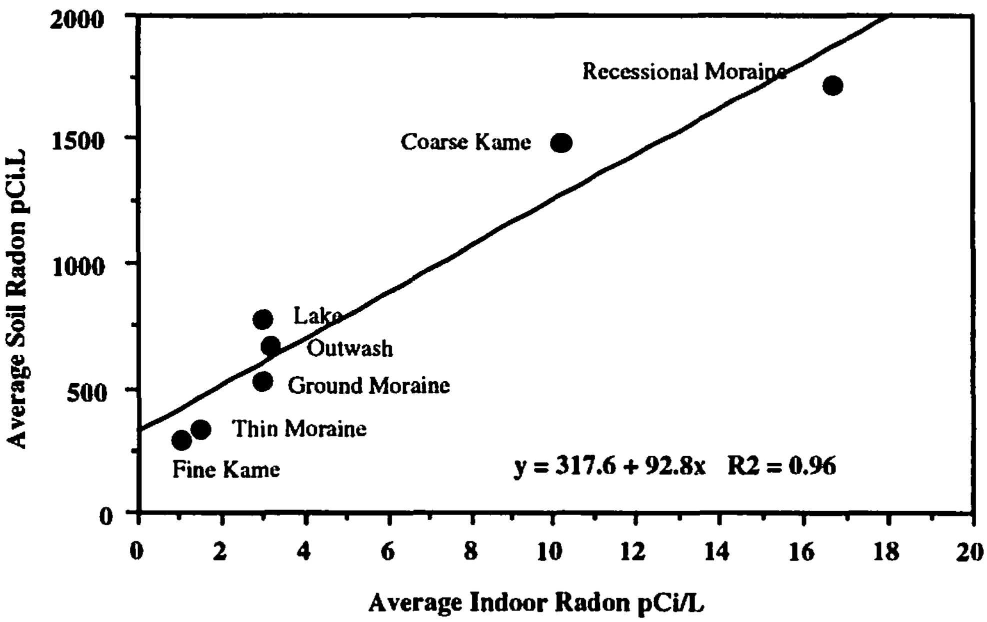


Figure 3. Average indoor radon and average soil radon for glacial deposits in Orange County New York

<u>Affect of Housing and Radon in Water in a Saprolitic Soil Area</u>

South of Maryland, into Virginia and North Carolina, the incidence of basement homes generally decreases and slab-on-grade and homes with crawl spaces increases. The correlation among indoor radon, equivalent uranium, and soil radon decreases partly because of this change in architecture. The soils in this area are saprolitic and are derived directly from the underlying bedrock. Data from the Hylas area just west of Richmond, Virginia shows an excellent correlation between soil radon and equivalent uranium for the major rock types (Gates and Gundersen, 1992). The rocks of this area are also in the Piedmont and consist of metamorphic, igneous, and sedimentary rocks. As can be seen in Figs. 4A and 4B, equivalent uranium derived from surface gamma-ray surveys, when compared with soil radon, yields a very high positive correlation. In 4A, the data are grouped and averaged by underlying bedrock. Figure 4B shows the data individually. Grouping by rock type dramatically increases the correlation. In this example, amphibolite, which is a mafic metamorphic rock, is a very low source of radon whereas schist and gneiss are moderate sources of radon. The granite and sheared gneiss are sources of high radon. This pattern is similar to the one seen in the Piedmont north of this area. The sedimentary rocks of this area are much younger than the metamorphic rocks and are partly derived from them. The sandstone in the Hylas area is known to have local uranium deposits and the conglomerate contains a significant proportion of sheared rocks.

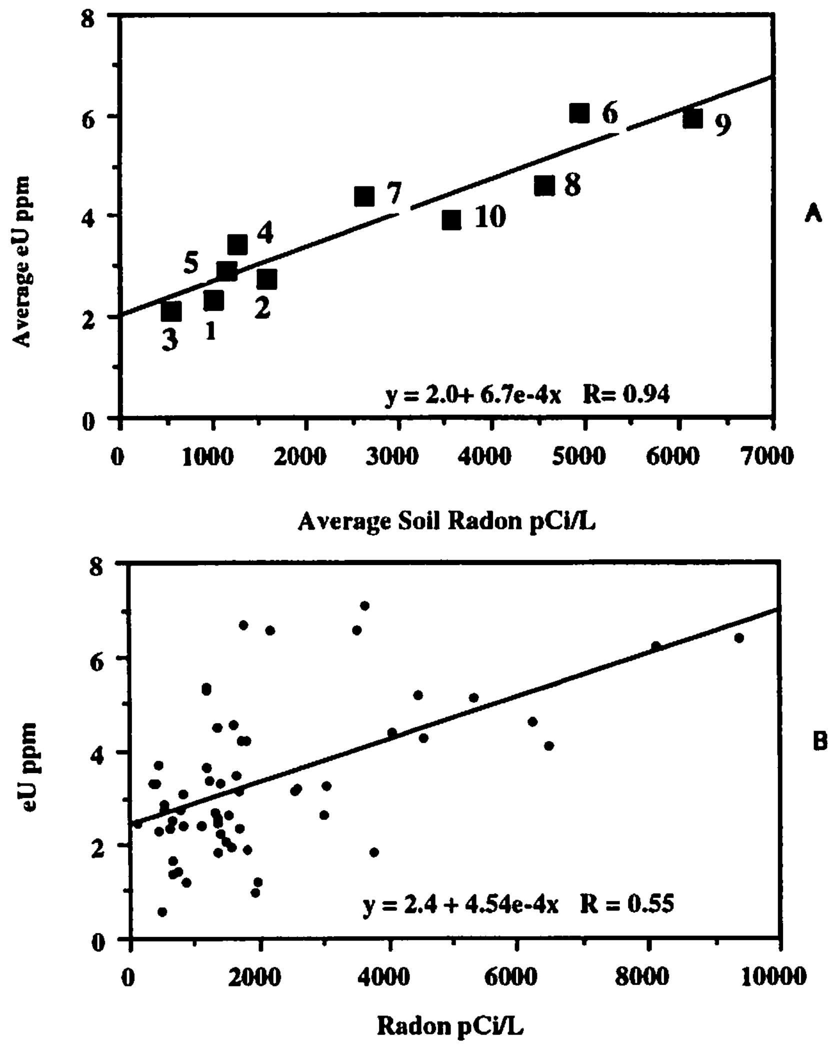
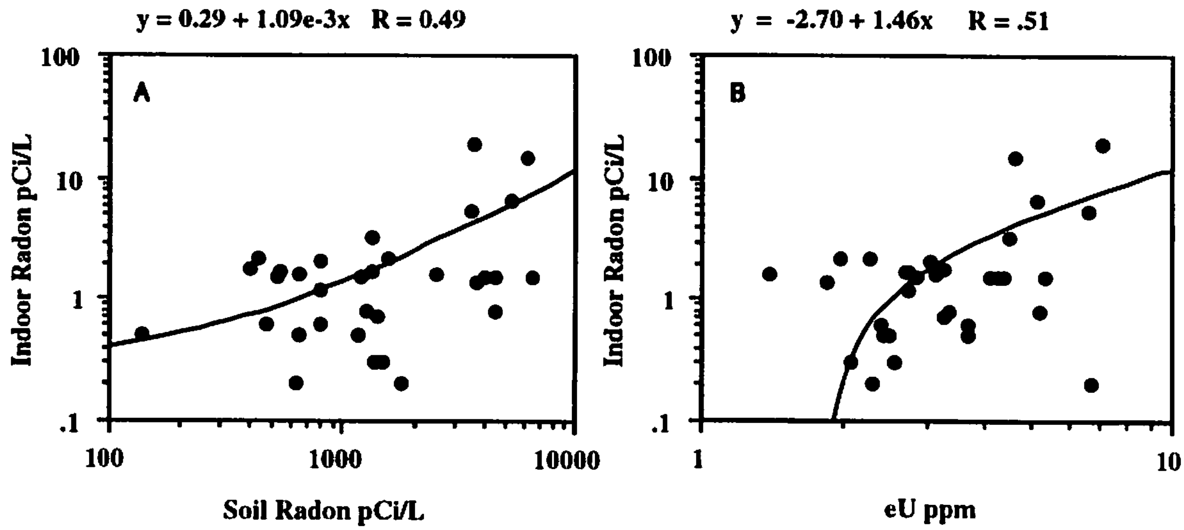


Figure 4A and 4B. Average equivalent uranium and average soil radon for major rock units in the Hylas area, Virginia. Numerals on 4A represent: granitic gneiss (1); granitic gneiss (2); amphibolite (3); schist (4); garnet-biotite gneiss (5); pegmatite (6); granite (7); sheared rocks (8); conglomerate (9); and sandstone (10).

Indoor radon was measured in a limited number of homes in this area from four of the major rock types–schist, granite gneiss, sheared rocks, and granite. Radon in soil and radon in domestic well water were also measured at the same time at each house site. Figures 5A and 5B show these individual indoor radon data plotted against eU and soil radon. Although the correlation is positive and statistically significant there is much scatter. When indoor radon is plotted against radon measured in domestic well water (Fig. 6) a correlation is also found, suggesting input from water. Lawrence and others (1992) have demonstrated with continuous indoor radon measurements in homes and documentation of water use, that radon in water is a significant contributor to indoor radon. Studies by Lanctot and others (1992) in Maine also show significant contribution to indoor radon from water and have tied the radon in water to certain bedrock aquifers. They also found that house architecture and soil permeability accounted for much of the variability seen in their indoor radon data set.



Figures 5A and 5B. Indoor radon versus soil radon (A) and equivalent uranium (B) from the Hylas area, Virginia.

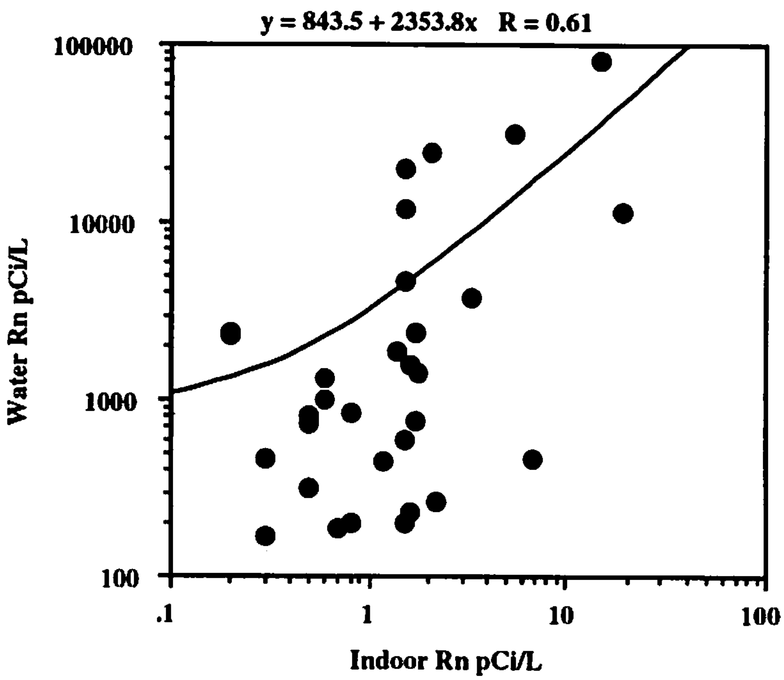


Figure 6. Indoor radon versus radon in domestic well water from the Hylas area, Virginia.

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