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INVESTIGATIONS OF RADON AND RADON DAUGHTERS IN SURFICIAL AQUIFERS OF FLORIDA

Prepared By

Department of Oceanography
Florida State University
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Florida Institute of Phosphate Research
Bartow, Florida

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INVESTIGATIONS OF RADON AND RADON DAUGHTERS IN SURFICIAL AQUIFERS OF FLORIDA

FINAL REPORT

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April, 1991

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PERSPECTIVE

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Florida Institute of Phosphate Research

One of the great natural resources available to the citizens of the State of Florida, but one perhaps too often taken for granted, is a source of plentiful and clean water for domestic consumption and other uses. For a majority of the people living in Florida, this source is groundwater, often obtained from shallow, private wells, but more often obtained from public, community wells tapping the Floridian aquifer. The supply is not infinite, however, and continued growth and development of the state depend in part on proper management of this resource, including especially conservation measures and avoidance of pollution. It has long been known that elevated levels of uranium and many of its associated radioactive decay products occur naturally associated with phosphate deposits found in some soils and waters of central and north Florida. Because of its low solubility, uranium itself generally is not considered to be a major environmental hazard, but several of the members within its decay series are more of a cause for concern. These would include radium-226, a radioactive element chemically similar to calcium radon-222, a water-soluble gas that is chemically inert but still radioactive; and a long-lived "daughter" product, polonium-210, that is the subject of a portion of this report. All the above are naturally occurring radioactive materials that are ubiquitous in the environment, including groundwater, but which tend to be elevated in areas of phosphate deposits.

Since its inception, the Florida Institute of Phosphate Research has been interested in the environmental aspects of the phosphate industry. It is believed that all phases of ore mining, minerals processing, and land reclamation can be accomplished in an environmentally acceptable manner. Because of the array of radionuclides found in phosphate ores and related materials, much of the Institute's concern for the environment has been focused on the issue of radiation. Well over a dozen projects have been conducted or sponsored that directly address the topic of radiation, and numerous additional projects have had radiological components as secondary issues. The Institute has tried not only to characterize natural radionuclides as to their nature, extent, and magnitude, but also to determine their effects on the population that lives and works in the phosphate regions. Assessing the quality of water has been a goal of several sponsored studies. As early as 1981 the Institute sponsored a study by the state Department of Health and Rehabilitative Services to investigate radiochemical contamination in shallow drinking water wells in central and southwest Florida. Later the department expanded the study to be state-wide in scope. Further water quality studies, done mainly at the University of South Florida and Florida State University, have looked in detail at the radiological components of groundwater. Most recently, USF has provided confirmation that polonium, not radium, indeed accounts for most total alpha radiation in groundwater from surficial aquifers. In addition to water quality, other topics of interest over the past few years have included radon gas and how to prevent its entry into homes, radionuclides in foods grown in the phosphate region, and the radiological aspects of phosphogypsum storage and use.

One largely unmet need for the protection of the public against elevated levels of radon gas is some means of estimating from site soil conditions the potential for excessive indoor radon in a structure that might be built on that site. Soil radium content, radon in soil gas, and radon flux from the soil to the atmosphere have all been used as "predictors," but all display very high spatial and temporal variations. This study suggests that radon in shallow or surficial aquifer water could be a useful indicator of the radon potential of an undeveloped site, and one subject to much less variation than is true for the soil parameters. A second finding of this study is further confirmation that polonium can be present in shallow waters in quite high concentrations, unsupported by "parent" radionuclides, but related to low pH and to type and content of sulfur present in the water. A last finding is that common activated carbon seems to be an excellent material for the near-complete removal of both radon and polonium from local waters.

A central theme that continues to run through much of the Institute's work is the evaluation of human exposure to radiation as contributed by some phase of the natural environment. This type of research seems consistent with the societal goal of keeping radiation exposure to "as low as reasonably achievable."

ACKNOWLEDGEMENTS

The Principal Investigators wish to sincerely thank the owners of the undeveloped property tracts that were used as test sites for this study. In Hillsborough County, Mr. and Mrs. C. B. “Bud” Hiscock, together with Mr. and Mrs. John Hardy, Mr. and Mrs. Randy Hiscock, and other family members, have allowed our research group access to their property on numerous occasions during this investigation as well as during a previous study. Mr. Earl Hill and his son Jimmy were very cooperative in allowing the installation of several monitor wells on their property in Alachua County. The officials of Florida State University provided permission and access to the FSU Reservation in Leon County.

Laboratory and field assistance was provided by many individuals during the course of our study. Two former students, David Clark and Renata van der Weijden, played important roles during the initial part of the study. Dr. Koh Harada and Mr. Hisashi Narita, both on research visits from Hokkaido University (Hakodate, Japan) provided very skilled analytical assistance and valuable intellectual contributions to this project.

Assistance in managing the fiscal aspects, purchasing, report preparation, and an assortment of other tasks relating to this study was provided by our Grants Administrator, Alison Watkins. Editorial aspects involved in the preparation of this final report was provided by Susan Kyler and Sara Newton.

We thank the Florida Institute of Phosphate Research for the financial support that made this study possible. Additional funding for a portion of this research was provided by the Florida Department of Environmental Regulation.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Table A-5. Results of radon flux and concentrations in soil gas and shallow groundwater from the Leon County test site. Po-210 concentrations and water quality parameters are also shown.

Table A-6. Radiochemical analyses of soil from cores and surface samples collected from each of the three study sites. Cores were recovered during establishment of monitor wells at stations A-C, H-B, and L-D. Surface soil samples were collected from the same stations where soil radon and flux measurements were made.

Table A-7. Results for ^{210}Po, ^{222}Rn, temperature, pH and conductivity for untreated well water from station 18, Hillsborough County test site, before and after treatment by four different water purification systems.

INVESTIGATIONS OF RADON AND RADON DAUGHTERS
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EXECUTIVE SUMMARY

The principal purpose of this investigation, initiated in January, 1988, was to test the hypothesis that radon soil flux, considered the principal source of indoor radon contamination, has an underlying relationship to the radon content of associated shallow groundwaters. Our working hypothesis was that radon build-up in both soil and shallow groundwater is basically a consequence of the same factor, radon emanation from soil grains and the solid surfaces of the aquifers. Furthermore, since soils are usually very heterogeneous while groundwaters are not, groundwater may be advantageous as an indicator of radon potential. In other words, groundwater may act as a better "integrator" of the radon source term than surface soils which may provide inconsistent results. Another objective of our research project was to investigate temporal and spatial trends of radon daughter products in shallow aquifers. Priority was given to investigation of the cycling of ^{210}Po, a radioisotope previously identified as occurring at very high concentrations in some shallow aquifers of Florida. A final objective was to evaluate several water purification techniques for removal of radionuclides from domestic waters.

Our approach to this study consisted of developing three test sites on undeveloped property in an area of high indoor radon (northern Alachua County), moderate indoor radon but high polonium in groundwater (southeast Hillsborough County), and low radon (southern Leon County). Based on a preliminary survey of these areas, test sites were selected and well fields were developed using a combination of existing shallow wells as well as monitor wells installed for our investigation. We worked with a total of 15 wells at the Alachua site, 14 in Hillsborough County, and 6 in Leon County. At each of these stations, we made approximately bimonthly measurements of radon concentration in the soil, radon flux from the soil to the atmosphere, and radon concentration measurements in the shallow groundwater. Radiochemical measurements and some physical properties were also measured on surface soil samples, and on sediment samples taken at 2-foot intervals throughout three cores up to 30-feet in length, one from each study area.

A modified, charcoal canister based technique was developed as part of this investigation for measurement of radon fluxes. This method, calibrated *via* radium-spiked barium palmitate

filters, compared very well to classical chamber techniques. We also developed a new electrochemical separation method for processing the radon daughters ^{210}Pb, ^{210}Bi, and ^{210}Po from groundwater samples. The technique produced reliable results with only about 6 hours of processing time, compared to approximately two days for standard ion exchange procedures.

During the course of this investigation, we obtained parallel charcoal canister and track etch measurements of soil radon concentrations at 16 stations over a two-year period. These results, as well as an experiment which monitored the radon concentration inside a shallow hole as a function of time, showed that short-term (~18 hours) canister deployments tend to underestimate the true “equilibrium” radon concentration in the soil. A surprising finding was that the long-term (1-3 months) track etch data appeared to consist of distinctly higher radon “events” superimposed on a lower concentration baseline just slightly higher than the corresponding charcoal canister results. Since track etch detectors provide an integrated, average concentration over long time periods, the actual radon concentration obtained during these transient events must have been extremely high. Although we are uncertain what process causes these phenomena, it is reasonably certain that the radon events are real since neighboring stations display similar records.

Analysis of surface soil and core samples for ^{226}Ra and “available” or “extractable” radon shows that the amount of radon free to migrate from soil particles closely follows the total amount of radium present in the soil. The distribution of these radionuclides in the core samples showed that available radon was highest at those levels in the core where the associated groundwater was highest in dissolved ^{222}Rn. These stratigraphic layers were closer to the surface at the Alachua County test site which is apparently the prevalent reason for the greater radon potential measured at this site compared to the others investigated.

After analyzing all of the radon soil, flux, and groundwater measurements made at all 35 stations over the two-year study period, it is clear that while there is no direct relationship between either radon soil concentration or flux and groundwater radon, there are reasons to consider radon in shallow groundwater as a viable indicator of the radon potential of an undeveloped area. When averaged over the study duration by study site, all three indicators provide the same result in terms of potential, i.e., the Alachua site has the greatest radon potential with the Leon site displaying the least. However, both soil radon concentration and flux measurements display considerably more spatial and temporal variation than do the corresponding radon in groundwater records. Our soil measurement results ranged over 1000-fold at any one study site while maximum variations in the groundwater data were limited to no more than a factor of about eight between stations and only about ±10% variation at any single station investigated during this study. Therefore, for radon assessment purposes, when only a single or a limited number of measurements are practical, it is recommended that radon concentration measurements be made in shallow, water table aquifers of the undeveloped site. This approach is more likely to produce an accurate, yet timely, representation of an integrated radon potential over the area to be evaluated.

Measurements of radon daughter activities and related parameters in several of the same wells developed for the radon assessment portion of our study has provided valuable information concerning the cycling and possible origin of excess polonium which has become a health concern in parts of Florida. Our measurements in wells where polonium is present at very high concentrations have shown that: (i) ^{210}Po is largely unsupported by its radioactive predecessor, ^{210}Bi; (ii) the greatest disequilibrium in the ^{210}Po/^{210}Bi activity ratio occurs in aquifers with low pH which contain reduced forms of sulfur; (iii) polonium is considerably more variable, in both space and time, than other parameters measured in the same wells, including radon; and (iv) both experimental and field evidence suggest a link between polonium and the sulfur cycle. These observations lead us to suspect that polonium is being "processed' by sulfur bacteria present in some aquifers and that these bacteria are capable of mobilizing polonium from aquifer surfaces by conversion to a more soluble form. Further research will be necessary to identify the speciation of polonium -- we suspect that the more soluble form may be a type of sulfide or organically-bound complex.

Four standard water purification tanks containing different types of purification products (granular activated carbon or "GAC", a standard water softening agent, manganese greensand, and a mixed resin bed) were installed early in our project adjacent to a well in Hillsborough County which contains high radon (~20,000 pCi/L) and very high polonium (~500 pCi/L). Each type of material was evaluated by analysis of water independently treated by each system as well as an analysis of the unprocessed "feed" water. Our results showed that, of the agents tested, GAC was superior overall with >99% removal efficiencies for both radon and polonium from the well water. In view of its known capacity for removal of other impurities and its relatively low cost, activated carbon appears to be an excellent choice for this type of application.

INTRODUCTION AND BACKGROUND

PURPOSE OF STUDY

Naturally-occurring radon originating within the earth and transported into indoor atmospheres in amounts large enough to constitute a considerable health hazard has been a matter of growing concern throughout the United States. The State of Florida has been one of the leaders in investigating the occurrence of radon within its borders -- a statewide survey of indoor and soil gas radon was funded by the Florida Institute of Phosphate Research and conducted during 1986-87 by Geomet Technologies, Inc. The Geomet survey measured indoor radon in 6158 homes in addition to soil gas measurements at 2896 homes with ground-level total gamma readings taken indoors and outside the 2896 homes. Because of the statewide nature of the survey and because of time constraints, it was not possible to address the various aspects of the behavior and distribution of radon and radon progeny in a detailed manner.

It has been demonstrated that groundwater can be an important reservoir of radon. Our study was intended to evaluate whether a relationship between a shallow aquifer reservoir and the soil gas radon flux is pertinent to understanding radon pathways. In addition, we previously showed that polonium, a highly radioactive descendent of radon, is present in some shallow aquifers at high enough activities to be of health concern. It is the investigation of these two aspects, namely the relationship between radon in shallow groundwater and radon migrating into the atmosphere and the mechanisms of release and transport of polonium, that were the main aspects of this study.

Each of these investigations dovetail nicely with the other. In the following pages, we will discuss the project results both in terms of development of new techniques to measure these nuclides as well as the findings which have enhanced our understanding of these elements.

The **research goals** of this investigation may be summarized as follows:

(1) To discern the processes responsible for release and transport of radon and radon daughters (Fig. 1) in the shallow terrestrial environment;
(2) To investigate the natural pathways of radon in soil and shallow groundwater to discern if there is a predictive relationship between radon flux into the atmosphere and radon concentration in water table aquifers; and
(3) To evaluate the controls on the concentration of radon daughter isotopes, particularly polonium, in shallow groundwaters.

PRELIMINARY STUDY

A preliminary survey of radon in shallow aquifers in various parts of Florida was conducted in order to locate sites for establishment of our detailed study areas which would be satisfactory in terms of several criteria. First, we wanted to have at least two areas in which the groundwater radon was known to be elevated, at least one of which would also contain polonium-enriched waters. We also wanted to have one area of similar geology with relatively low radon to serve as a comparison in terms of temporal variations. Secondly, the land where the well fields would be located must be owned by persons amenable to the drilling of wells on their land and to our sampling of the wells for an extended period. Thirdly, the well fields needed to be located such that the frequent sampling trips would not consume excessive amounts of travel time.

To this end, we utilized the Geomet Technologies survey in order to determine the general areas to reconnoiter. Of the areas chosen on the first pass, the Phosphate Mining District of west central Florida and the north central area of Marion and Alachua Counties were deemed most likely to have high radon. A third site, to be located in Wakulla or Leon Counties, was thought to be a likely location for low radon sampling and would be within easy

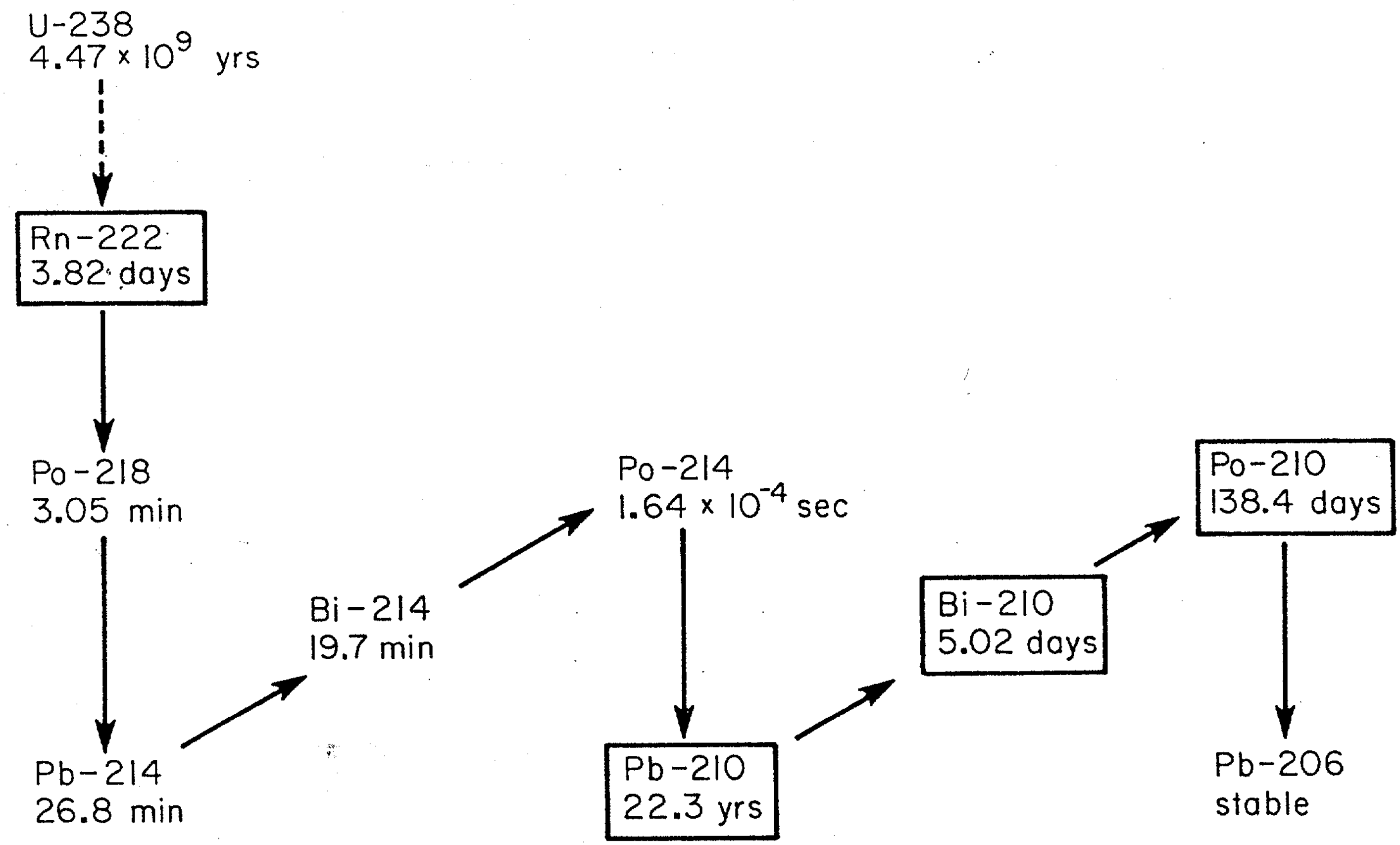


Fig. 1. Natural ^{238}U decay chain with nuclides of interest to this study enclosed in boxes. Downward arrows indicate alpha particle decay and diagonal arrows represent beta decay.

reach of our laboratory. Our previous investigation of the west central Florida area indicated that property owned by C.B. Hiscock in southeastern Hillsborough County not only met the criterion of elevated radon but also had several well locations where high polonium was present in the groundwater. Mr. Hiscock was agreeable to the establishment of a monitor well field on his property.

We had not previously sampled in the north central area of Florida so several collecting trips were necessary to determine the best location for a well field. Collecting trips were undertaken during the early stages of this investigation on February 11-12, Feb. 25-26, March 10-11, and April 13, 1988 to this area to locate and define areas which would best suit the purposes of the investigation. In southwestern Marion County, the area of highest radon in the county as determined by the Geomet survey, there was difficulty in locating shallow wells which were productive. After considerable sampling in the two counties, the area of most promise was located in extreme northern Alachua County. The site chosen is owned by Earl Hill who has been very cooperative in allowing development of a well field as well as allowing us to sample several shallow existing wells on his property.

The third site was to contain relatively low radon at a site geologically similar to the other sites. Our initial area of interest was in the area in the vicinity of Newport springs in southern Wakulla County, an area which we knew from previous sampling to be low in radon but with a site having at least episodically elevated polonium. However, several factors negated this location: (1) the land is low and drill rigs would have a difficult time getting to the possible drills sites and (2) at some times of the year we would have a difficult time getting to the sites. After sampling several locations in Wakulla and Leon Counties, a site was chosen on land owned by Florida State University. The geology is reasonably similar to that of the Hillsborough and Alachua County sites and the logistics of sampling were greatly simplified.

APPROACH AND STRATEGY

We have established 3 monitor well fields in areas of interest which have been defined on the basis of the reconnaissance sampling referred to above (Fig. 2). The monitor wells provide samples from known depths and lithologies. Each area over which the wells are distributed is relatively small, at most a quarter section (about 2500' x 2500'). We feel that this is an area large enough to have some diversity, while at the same time being logistically manageable. Because the general lithology should not change significantly over an area of this size, a reasonable idea of the integrated radon reservoir and flux should be obtainable.

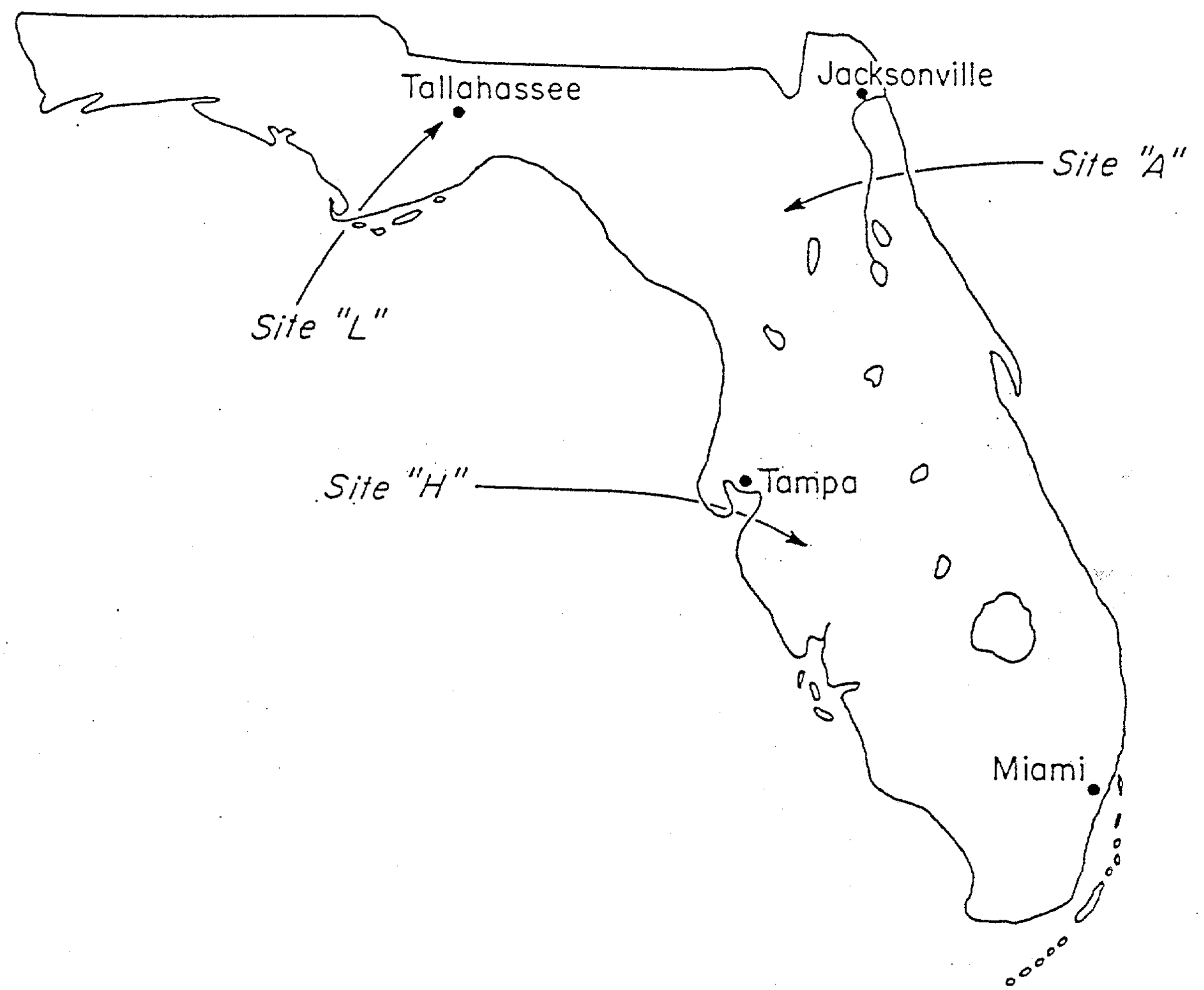


Fig. 2. Index map of Florida with locations of 3 well fields established for this project. Site “L” (low radon) is located in southern Leon county, site “A” in northern Alachua County (high radon), and site “H” in southeastern Hillsborough County (high polonium, moderate radon).

Along with the areal distribution of radon flux and radon concentration both in soil and associated groundwater, the temporal variation of these parameters over about two years was determined. At each monitor well location, a surface soil sample has been obtained for radioelement analysis. In addition, up to 42-ft long cores have been taken at each test site for analysis of vertical variations. Thus, at each monitor well location, we have determined radon in the groundwater, the radon content of the soil gas, the flux of radon into the atmosphere, and the radon generating capacity of the soil. Many of these parameters have been determined several times over the duration of the study, in order to assess temporal trends. A schematic diagram showing the various elements of our sampling approach at each station is shown in Fig. 3.

For the radon daughter aspect of our study, the monitor well field in Hillsborough County, site “H”, provided control and a spatial distribution not previously available. This control allowed closely-spaced measurements of polonium, sulfide, and other parameters which we felt may be related to mobilization.

ESTABLISHMENT OF TEST SITES

Wells at the three monitor well fields were installed by Ardaman and Associates, the Alachua (“A”) and Leon (“L”) fields through their Tallahassee office, and the Hillsborough (“H”) field through their Bartow office. The first field to be developed was the Alachua County site which was drilled on June 14-15, 1988 (Fig. 4). A total of 15 wells were drilled at nine locations. Five locations had a paired set of 15 and 25 ft. deep wells installed; three locations had only 15 ft. wells and one location had a single 25 ft. well. In addition to the regular monitor wells installed, an experimental well having four screened intervals (12.5'-15', 17.5'-20', 22.5'-25', and 27.5'-30') was installed. There are also 4 existing shallow wells at this site for sampling. A continuous split spoon sampling of the lithology was obtained to a depth of 30 ft.

The Hillsborough County site was developed June 20-24, 1988 (Fig. 5). A total of 20 wells were drilled at 11 different locations. Eight of the locations had a paired set of 15 and 30 ft. deep wells installed, the other locations had 15 ft wells. An experimental well having four screened intervals was also installed at this site. Three existing shallow wells are available for

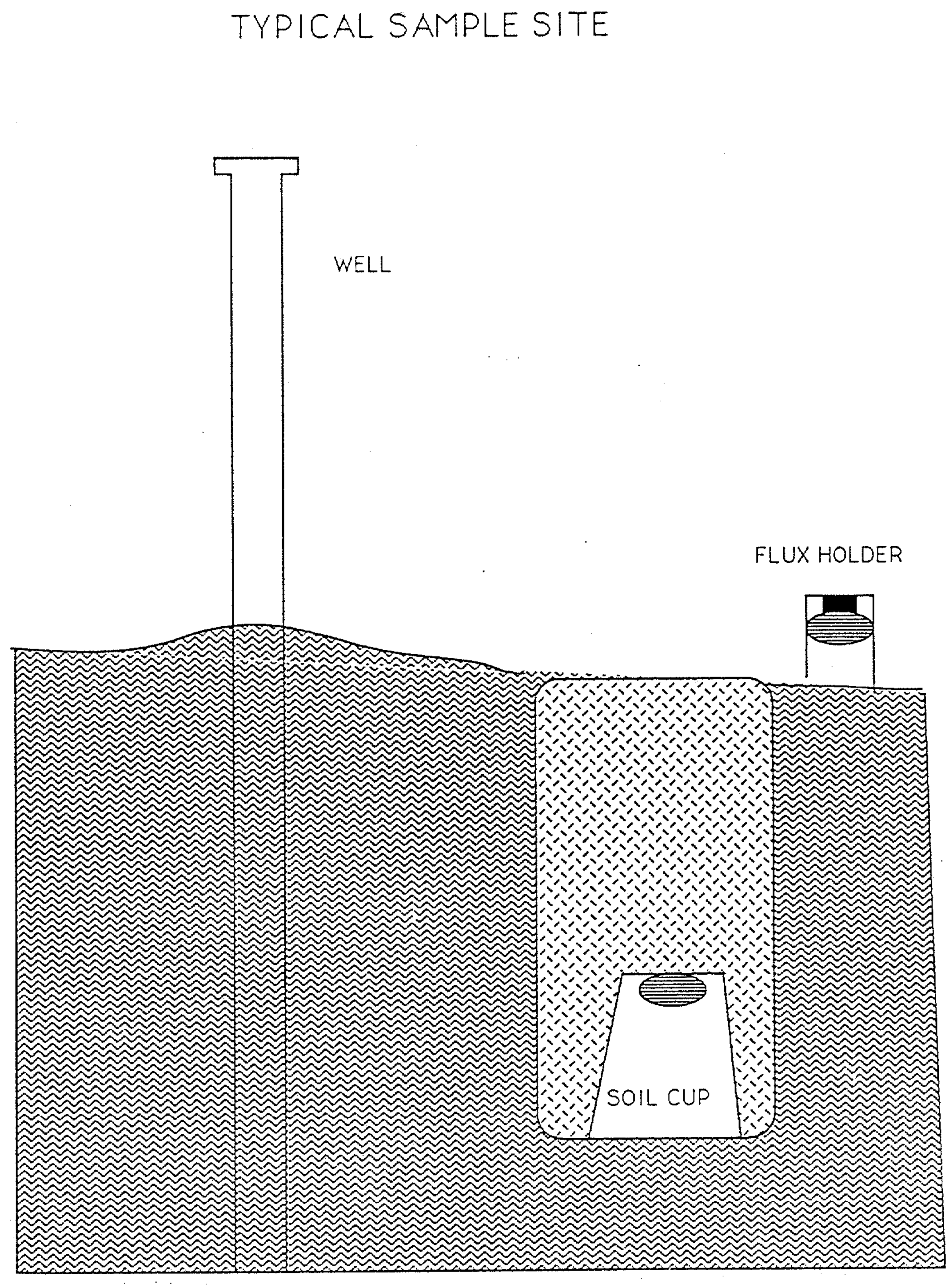


Fig. 3. Diagrammatic representation of one of our typical stations with a monitor well for water sample collection from the shallow aquifer, a charcoal canister and/or track etch detector buried in the ground for measurement of soil gas radon, and a charcoal canister deployed inside a PVC pipe for measurement of radon flux.

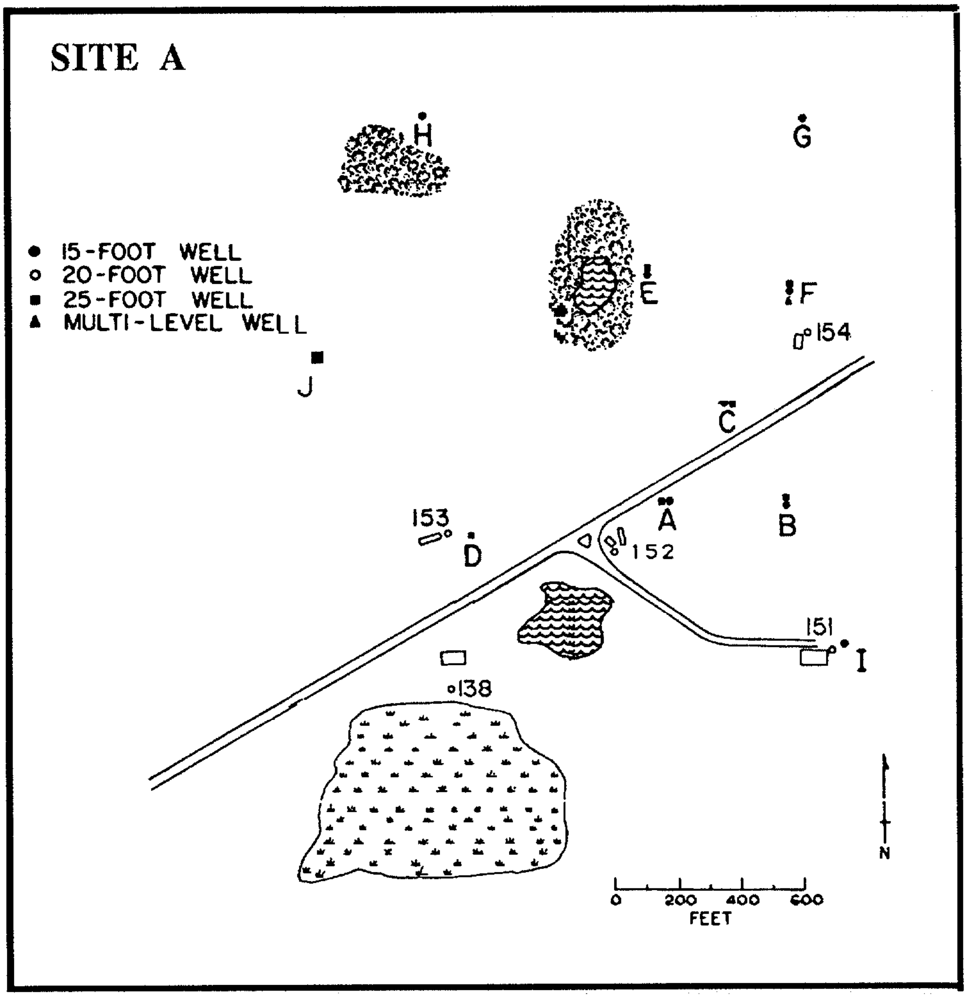


Fig. 4. Index map of test site "A" located in northern Alachua County. Letters refer to monitor wells, numbers represent existing wells.

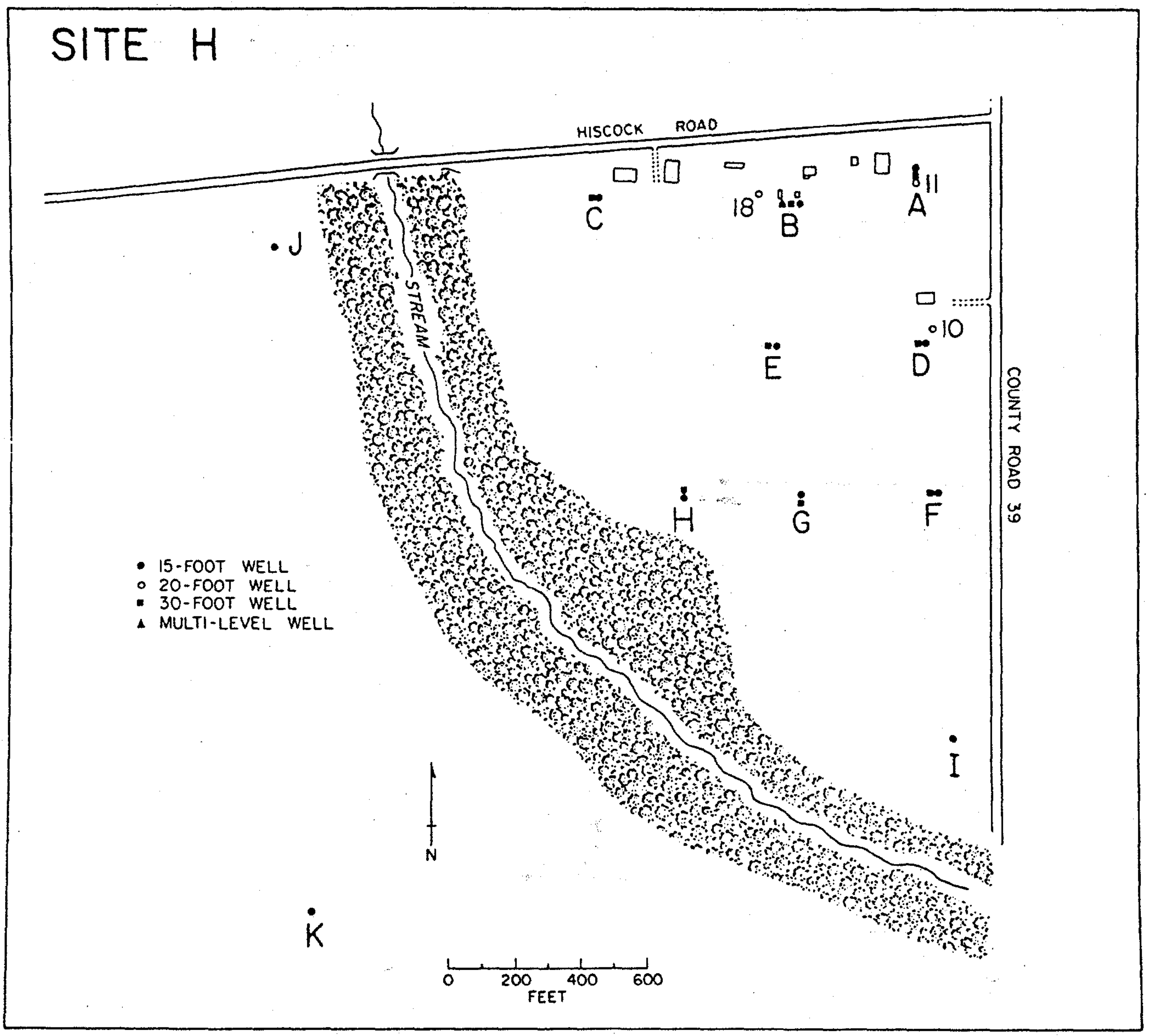


Fig. 5. Index map of test site "H" located in southeastern Hillsborough County, across from the Fort Lonesome Phosphate Mine. Letters refer to monitor wells, numbers represent existing wells.

sampling at site “H”. A continuous split spoon sampling of the lithology was obtained to a depth of 30 ft.

The Leon County monitor well site was developed August 24, 1988 at the Florida State University Reservation in southern Leon County (Fig. 6). A total of 5 wells were drilled, 2 to a depth of 15 ft. and 3 to 30 ft. depths. One USGS monitor well approximately 200 ft. below land surface was also available for sampling at this site. We also obtained a 42 ft, continuous split spoon sample at this location. A summary of the characteristics of each of the three test sites is given below in Table 1.

Table 1. Summary of test site characteristics where well fields were established for this study.

County:	Alachua	Hillsborough	Leon
Location:	~4 mi north of LaCross	southeast part of county, across from Fort Lonesome Mine	FSU Reservation on Lake Bradford
Approx size (ft):	1700 x 1100 {~43 acres}	2000 x 2000 {~92 acres}	500 x 200 {~2.3 acres}
Existing wells:	5	3	1
Monitor wells:	8 @ 15' 6 @ 25' 1 multi-level	11 @ 15' 8 @ 30' 1 multi-level	2 @ 15' 3 @ 25'

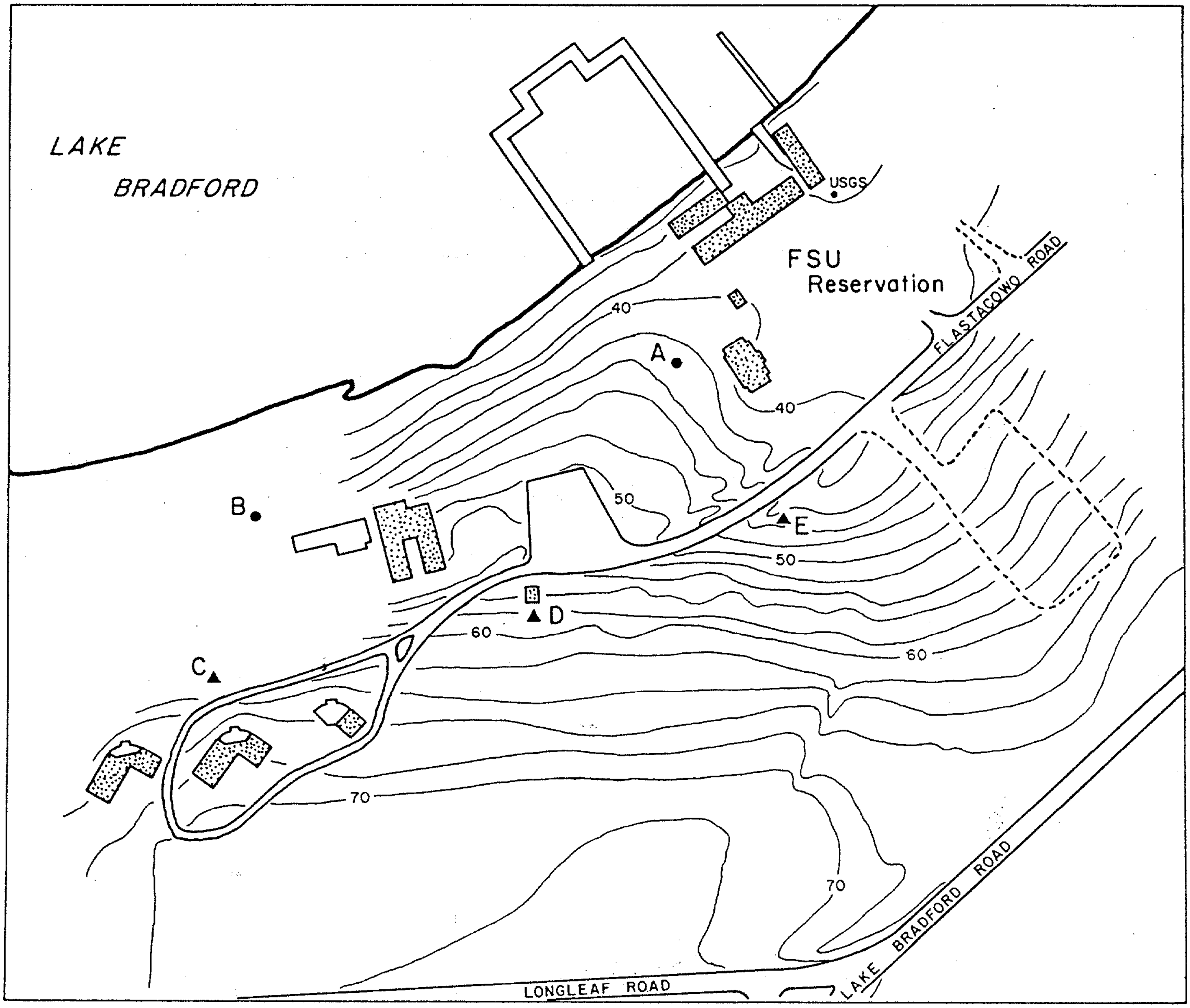


Fig. 6. Index map of test site "L" located in southern Leon County, at the Florida State University Reservation on Lake Bradford. In addition to the five monitor wells (stations A through E established for this study), we also sampled an existing USGS monitor well.

ANALYTICAL METHODS AND DEVELOPMENTS

RADON CONCENTRATIONS IN SOIL AND WATER

All radon in water concentration measurements have been made by standard scintillation counting techniques (Prichard and Gesell, 1977) using sample volumes of 10 milliliters. All analyses have been performed in triplicate and results more than 10 % below the mean of the 3 analyses were rejected. Standards were prepared in triplicate from NBS standard reference material 4958 (radium solution) in a series ranging from 100 to 100,000 pCi/L. In most cases, results of our standard triplicate analyses agreed to better that ±1% while field samples, subject to occasional loss of ^{222}Rn during sample collection and handling, had higher variations but generally agreed to better than ±10%.

Our measurements of soil gas radon concentration have been made with 3" diameter, diffusion-barrier (Pittsburgh style) charcoal canisters (Cohen and Nason, 1986). These charcoal canisters contain 25 grams of charcoal and have diffusion barriers (Sorbet bags) to absorb moisture. After overnight deployment inside a plastic drinking cup under 15" of soil, the canisters were returned to the laboratory and counted on one of two NaI detectors for measurement of the activities due to ^{214}Pb and ^{214}Bi daughters of ^{222}Rn. We corrected for moisture effects by measuring the weight gain during the deployment period and relating this to our calibration factor measured in radon chambers (Fig. 7). Our analytical system (2 NaI detectors and 1 computer-controlled, 16k MCA) is fully calibrated and has been checked

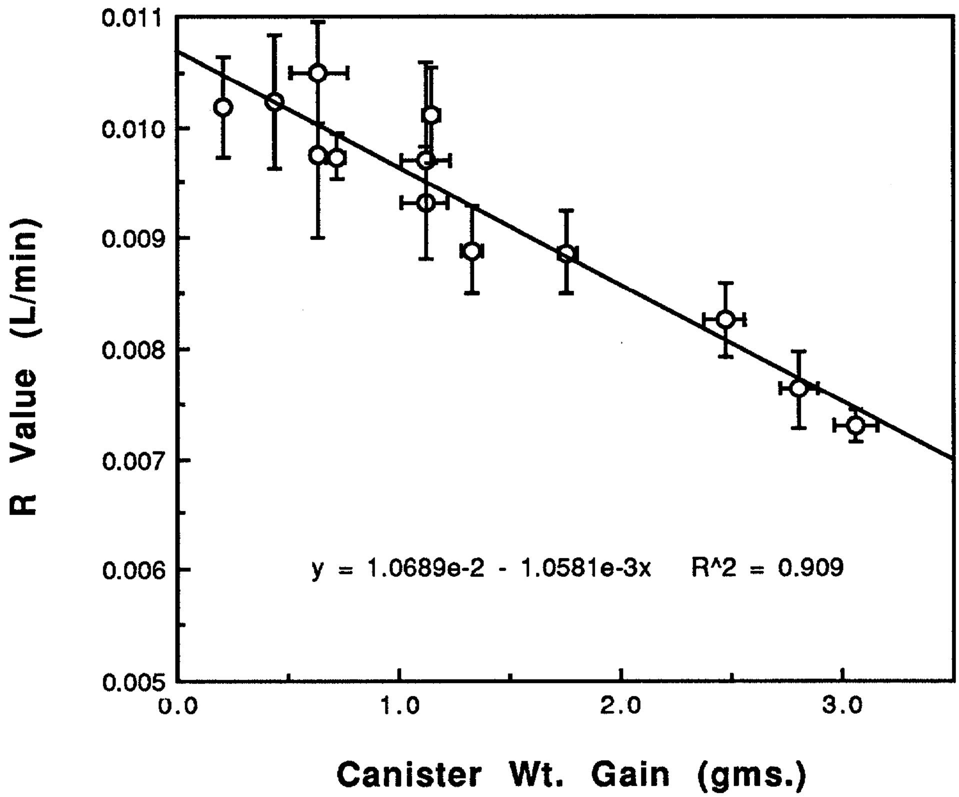


Fig. 7. Calibration factor "R" for our charcoal canisters versus weight gain. Each data point represents a mean and standard deviation of 4-5 measurements taken in calibrated radon chambers.

against the radon chambers at the EPA Radioactivity Laboratory in Montgomery, Alabama and the Mound Laboratory Division of Monsanto, Inc. Deployments were run in these chambers at near constant radon concentrations and humidities for varying lengths of time to produce varying amounts of moisture buildup. We also deployed a number of Terradex track etch detectors at some of the same sites for longer periods (1-3 months) for comparison to our short-term measurements (Alter and Price, 1972). A detailed comparison between these two techniques is presented in the following section.

In order to test the true precision of our radon in soil measurements using charcoal canisters, we designed an experiment to test the precision both within a hole dug into the soil (three canisters deployed inside plastic cups at the bottom of the same 15"-deep hole) as well as between holes dug at nearly the same site. For these experiments, we placed 3 canisters into each of 4 holes dug at spacings of approximately 5 feet around a selected group of our regular stations. Each experiment, therefore, consisted of a total of 12 canisters placed 3 each in 4 holes oriented in compass directions around several of our sites. A total of 9 precision experiments were performed at 7 different sites in Hillsborough and Alachua counties in late 1988 and early 1989. The tabulated results from all these experiments are given in the Appendix of this report.

Virtually all of our precision experiments show the same general result, i.e., relatively good precision within the same holes with significantly higher variations between holes. Our results at site A-B are typical (Fig. 8). None of the four deployments had coefficients of variation greater than 10% but because one hole, “A-B West”, had a significantly higher ^{222}Rn concentration than the other 3, the overall variation was 48%! Out of the 9 experiments performed in this manner, only 1 (station A-H in January, 1989) produced an overall precision less than 10% while only 3 replicate measurements within the same hole, out of a total of 36, had coefficients of variation greater than 10%. These results illustrate an important point regarding soil measurements of this kind, i.e., soil is inherently very heterogeneous. Radon concentration results in soil for deployments only a few feet apart can be very different--far beyond the analytical uncertainty of the measurement. This type of natural variability in the system must be considered, therefore, when using this type of approach for radon assessment.

It is intrinsically more difficult to test accuracy of these types of measurements then precision. Our calibration runs at both the EPA facility in Montgomery, Alabama and at Mound Laboratories were internally consistent implying that our results should be of high quality. In order to test this further, we developed an intercalibration exercise with a colleague

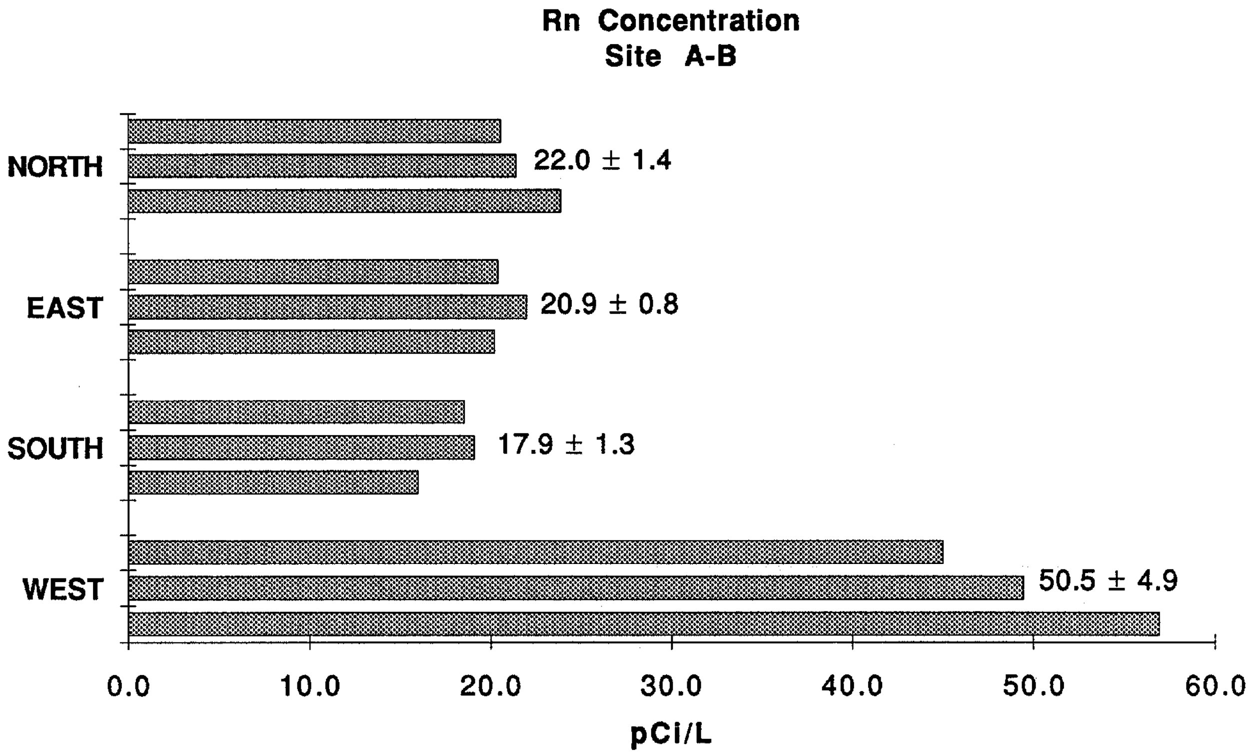


Fig. 8. Results of a precision test showing variations of soil gas radon both within single holes and between holes placed within an approximate 25 square foot area centered at station B in Alachua County. Most canisters deployed within the same hole produced concentration measurements within about ±10% -- variations between holes were substantially greater.

at Florida State University, Dr. Jeffrey Chanton, who is equipped for making radon concentration measurements using a Pylon AB-5 meter coupled with a Trace Environmental Level (TEL) radon detector. We deployed pairs of canisters in the same room (an inside laboratory on the third floor of the Oceanography Department Building) and made repeated 3-day measurements over a period of approximately three weeks in March, 1989. During this interval Dr. Chanton made "grab sample" measurements using an electric pump to completely replace the air in the 17-liter Pylon chamber. The results of both groups of measurements (Fig. 9) show that agreement between the two methods was excellent. These results are especially impressive if one considers that (i) the two techniques were calibrated completely independently (the Pylon detectors were calibrated using a radium standard solution); (ii) the integration times of the two techniques were very different (3 days for the canisters and about 45 minutes for the Pylon chamber); and (iii) the concentrations measured were all extremely low, mostly in the range of only 0.1-0.4 pCi/L.

COMPARISON TO TRACK ETCH MEASUREMENTS

We selected five stations at the Alachua County test site (138, A-B, A-F, A-H, and A-I; Fig. 10, a-e), six sites at the Hillsborough County site (H-A, H-B, H-C, H-D, H-F, and H-G; Fig. 11, a-f), and five sites at the Leon County test site (L-A, L-B, L-C, L-D, and L-E; Fig. 12, a-e) for a long term intercomparison of the charcoal canister and track etch detector methods of measuring soil radon. All canister measurements reported here follow our standard procedure as outlined above with deployment periods for these canisters ranging from 14-18 hours. The track etch detectors (Terradex® DSM detectors in plastic cups) were all deployed at the same depth (15") but in an adjacent hole to the charcoal canisters. This was necessary since the canisters were deployed and retrieved within relatively short time periods while the track etch detectors were left in place for periods ranging from 1-3 months. In view of our observations concerning the heterogeneity of soils (see above), this may account for some of the differences observed. We made every effort to maintain the spacing between the holes for the track etch detectors and the charcoal canisters at a minimum. In no case was this distance greater than approximately three feet.

Because this data set covers virtually the entire period of our study, it is very complete. We are not aware of any other such detailed and long-term intercomparison of these measurement techniques being available, therefore we have reproduced all of our results for this report. The data plots show the track etch concentrations as an unbroken (except in the rare occasions when detectors were lost) curve of straight-line segments. Canister

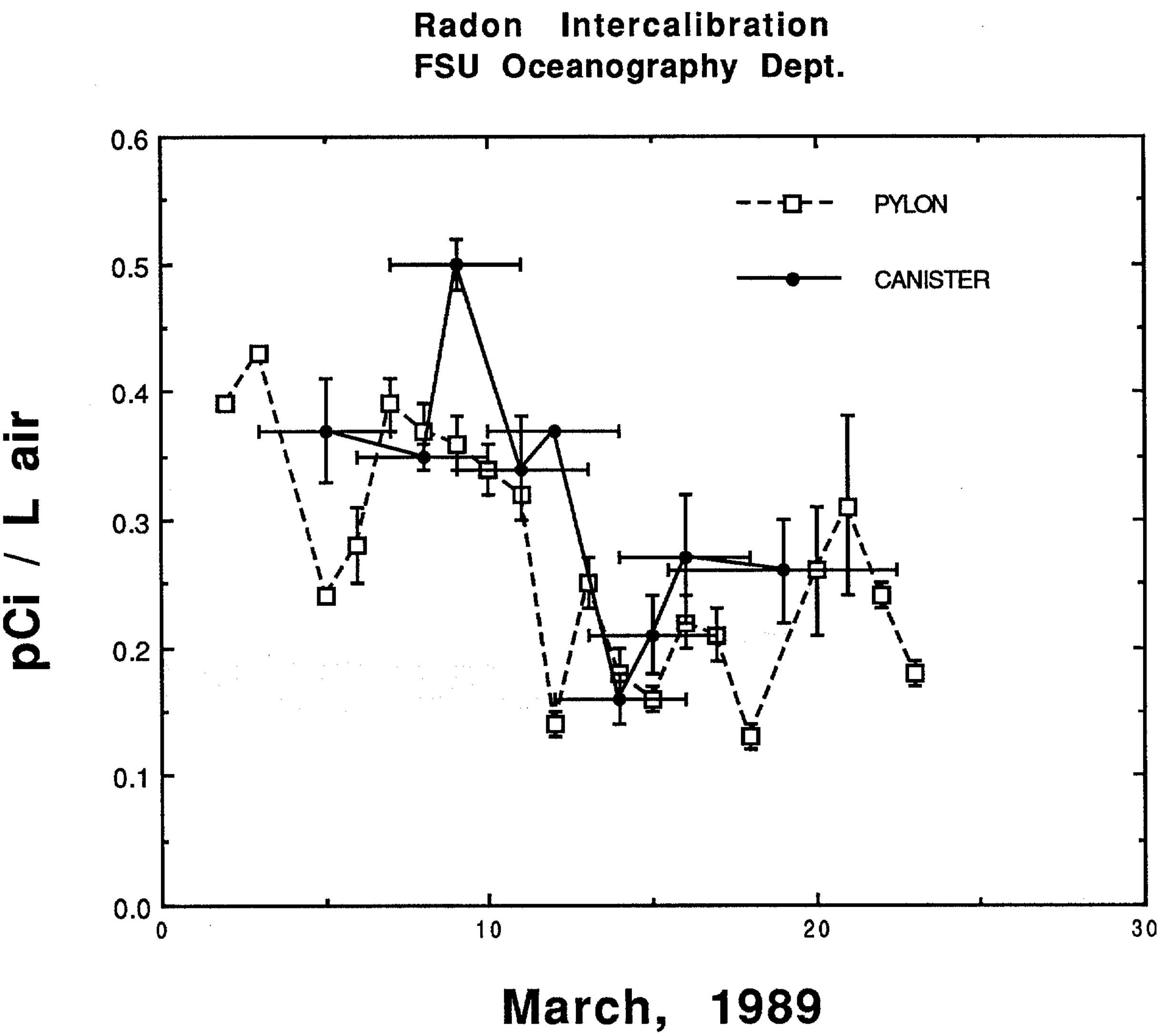


Fig. 9. Intercomparison of radon concentration measurements made in an interior room on the third floor inside the Department of Oceanography Building at Florida State University. Measurements were made using 3-day deployments for charcoal canisters and "grab" samples analyzed *via* a Pylon AB5/TEL Radon Detector system.

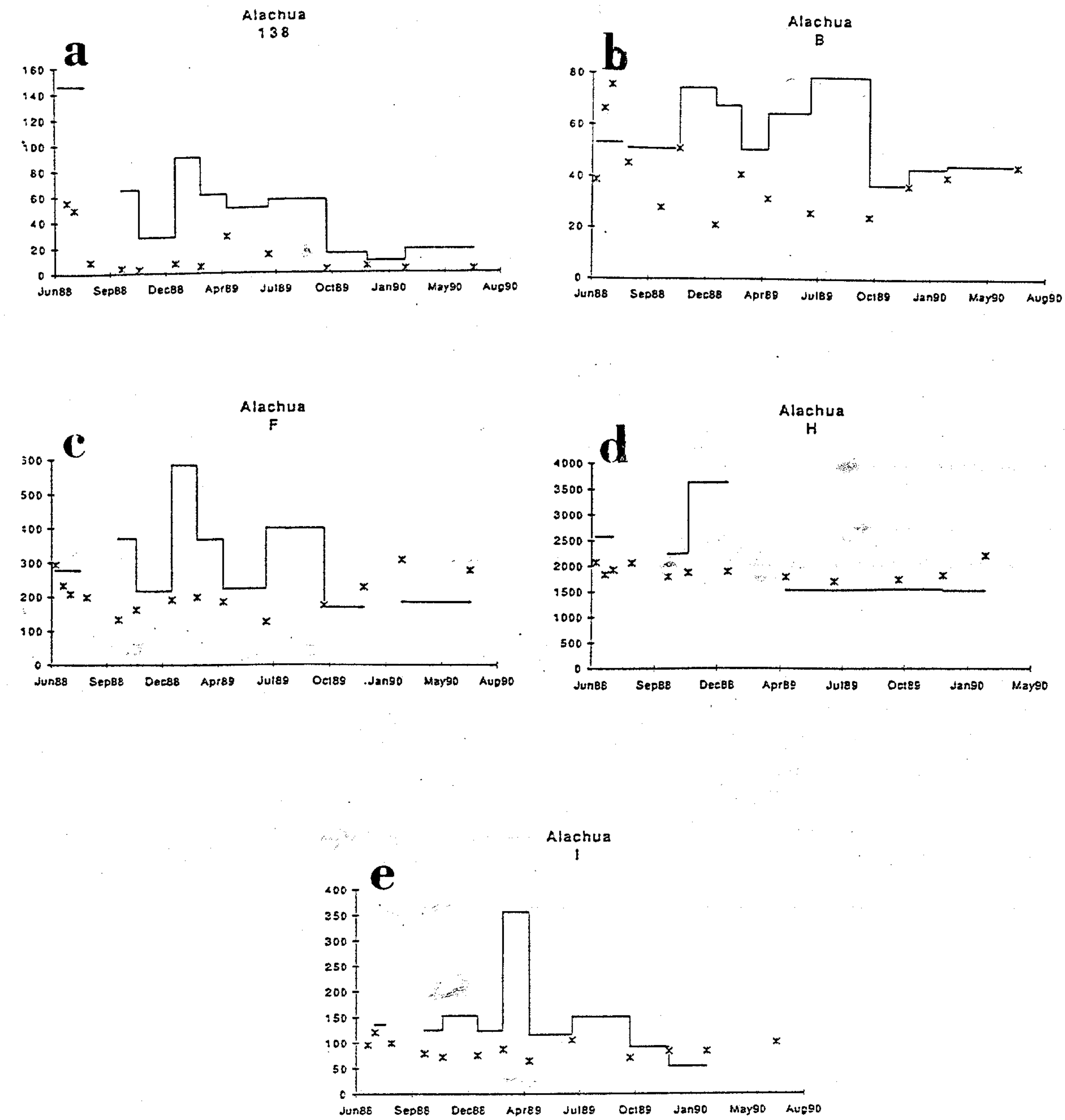


Fig. 10. Comparison between soil gas radon measurements made with l-day deployment of charcoal canisters (shown by x's) compared to one to three month deployment of track-etch detectors (shown by solid line) for stations in Alachua County, Florida: a) 138; b) B; c) F; d) H; and e) I.

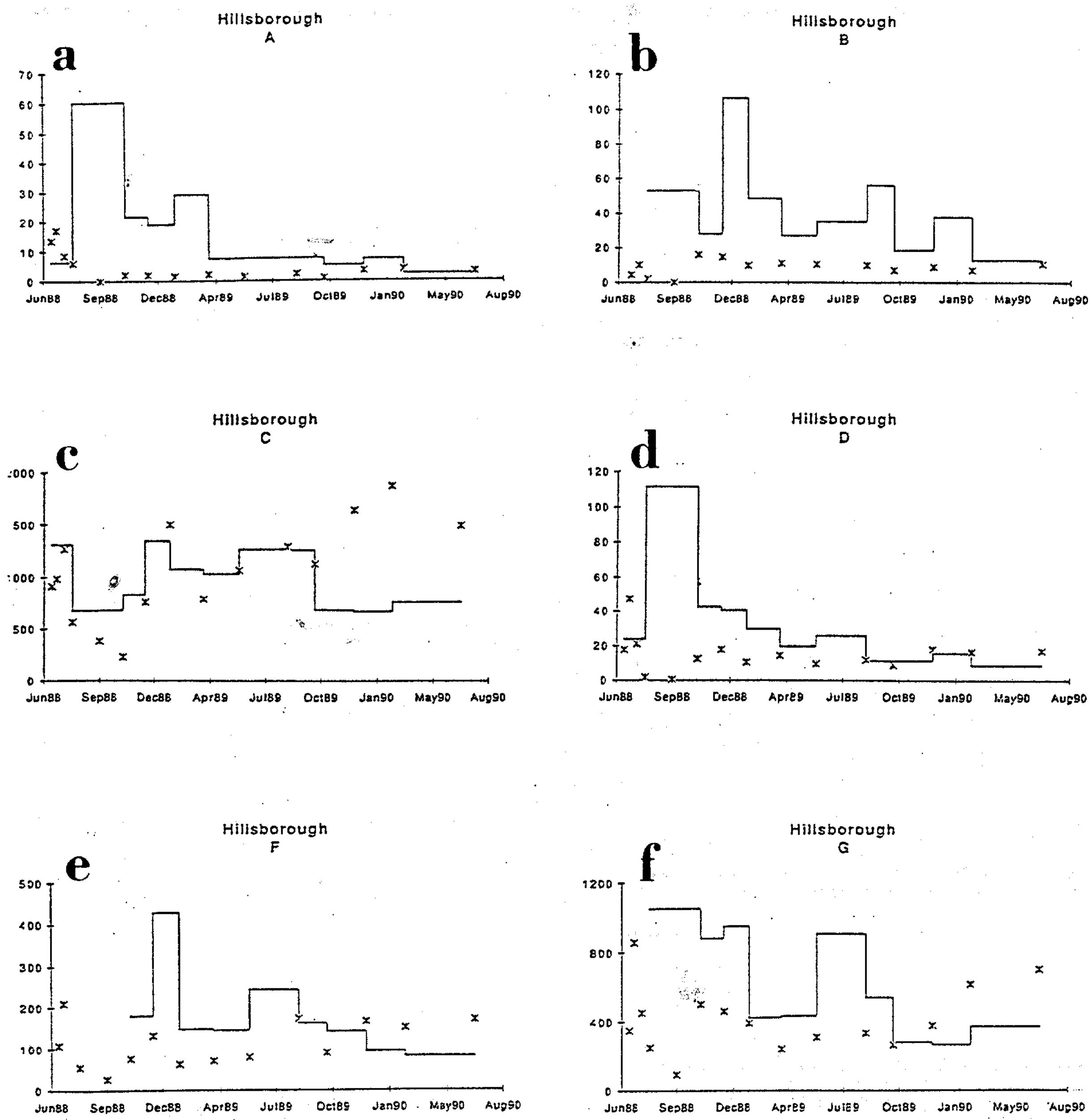


Fig. 11. Comparison between soil gas radon measurements made with l-day deployment of charcoal canisters (shown by x's) compared to one to three month deployment of track-etch detectors (shown by solid line) for stations in Hillsborough County, Florida: a) A; b) B; c) C; d) D; e) F; and f) G.

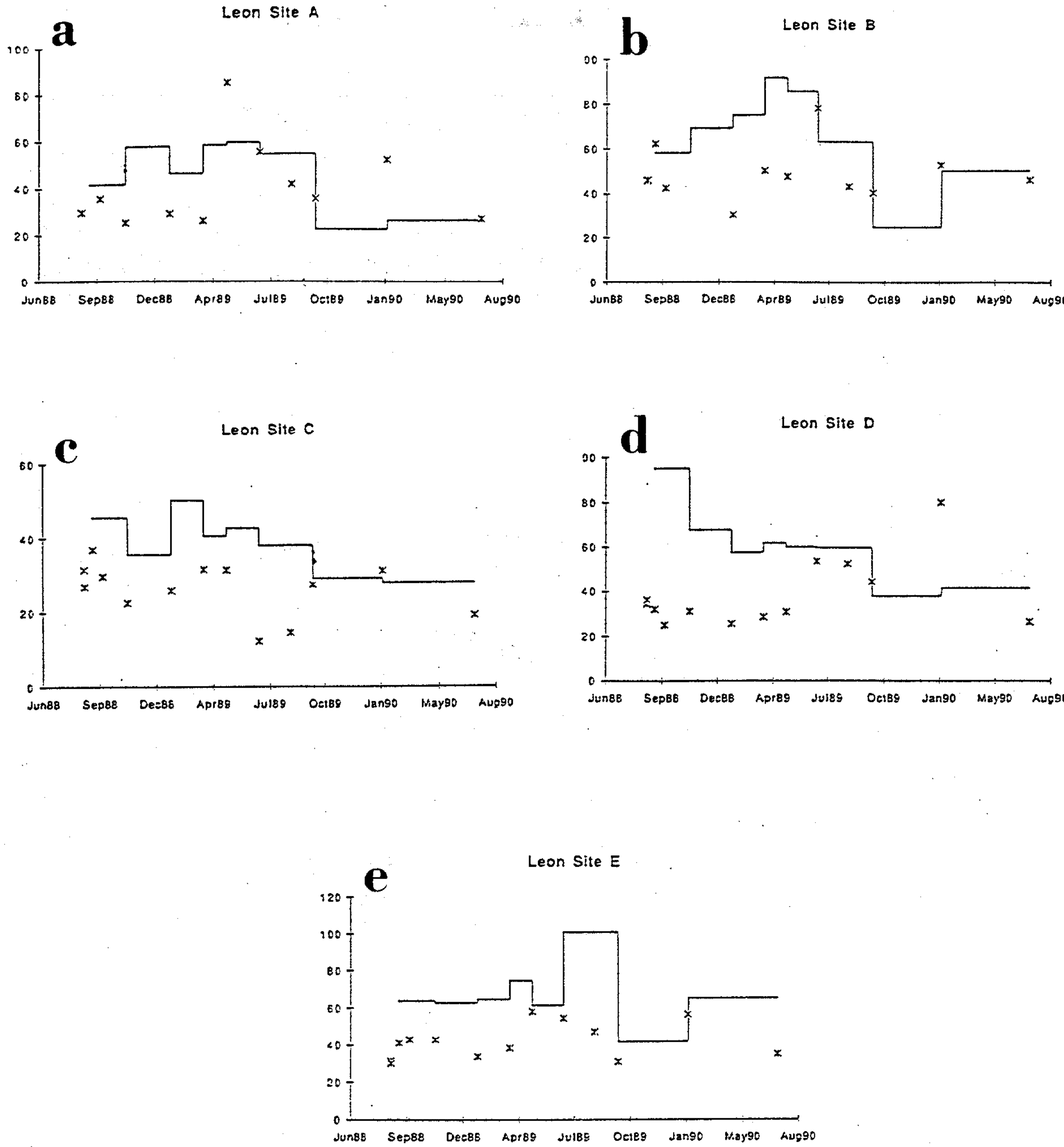


Fig. 12. Comparison between soil gas radon measurements made with l-day deployment of charcoal canisters (shown by x's) compared to one to three month deployment of track-etch detectors (shown by solid line) for stations in Leon County, Florida: a) A; b) B; c) C; d) D; and e) E.

measurements are shown as discrete data points (x's on the plots) since they represent essentially "instantaneous" measurements on a 2-year time scale. Since track etch detectors were usually changed each time a particular station was visited (approximately bimonthly), our time-series plots will normally show two canister concentrations, one at each end of the straight-line segment representing a long-term track etch deployment.

When these results are inspected, it is clear that the most general trend in the data is for the canister results to display lower concentrations than the respective track etch detectors. This is true for a variety of soil types and for both low and high concentrations although there is somewhat better agreement at higher concentrations (for example, see Fig. 10d, A-H, and Fig. 11c, H-C). Surprisingly, the charcoal canister trends are smoother than the track etch detector trends. Before this study was initiated, we suspected that the long-integration times of the track etch detectors would flatten out short-term (hours to days) variations and produce more of an "average" concentration not only over the deployment time but for the entire study period. In fact, many of our time-series plots show just the opposite, with track etch detector "events" superimposed upon a lower-concentration "baseline" which is usually much closer to the charcoal canister results. These "events" seem to occur at nearly the same time within one study area. If these "events" are ignored, especially the relatively isolated occurrences (see for example the July-October 1989 high radon event which occurred at stations A-B, A-F, and A-I; Fig. 10), the agreement between the two methods is considerably improved. We have no explanation for these "events" other than to suggest that they may have been caused by relatively rare meteorological events such as extreme low pressure fronts missed by our short-term canister deployments.

Even if the high "events" are ignored, most of these stations still show a 10-30% lower charcoal canister concentration than those by track etch detectors. As previously discussed, the precision and accuracy of our canister technique, as measured against other, "active" procedures, appears to be excellent. In actual fact, the overall agreement of the two techniques compared here is not that bad (Fig. 13). If a linear regression is fit to all track etch measurements versus complementary charcoal canister concentrations, the slope of the best-fit line is almost exactly unity (1.003) with an intercept on the y-axis (track etch) of 58.1 pCi/L and an $r^2 = 0.80$. This implies that while there is an average offset of ~60 pCi/L, the differences between the two detection systems tend to remain constant.

How can we explain this offset which causes the charcoal canister results to be consistently lower than the track etch detector concentrations? We have already demonstrated

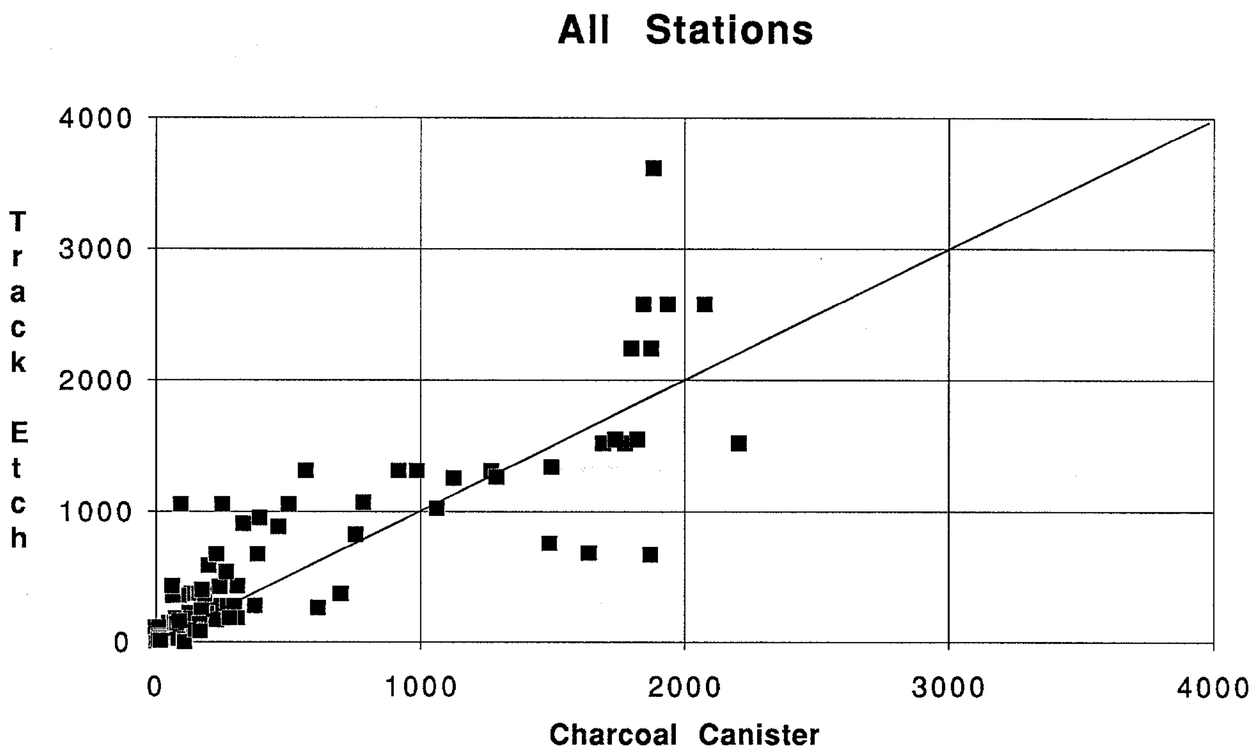


Fig. 13. Scatter plot of all measurements of soil gas radon as measured by track etch detectors (1-3 month deployment period) versus measurements by charcoal canisters (<1-day deployment). All concentrations in units of pCi/L. A least-squares linear regression of these data results in an equation: $y = 1.003x + 58.2$; $r^2 = 0.80$.

that our canisters record radon concentrations quite well for “constant concentration” conditions. However, the situation which exists in performing these “soil gas” measurements is actually quite different. When we dig a 15" hole in the ground to deploy a canister, the concentration of radon at the base of the hole is instantaneously lowered to atmospheric levels, i.e., essentially zero. After the canister is placed at the base of the hole (inside a plastic drinking cup) and the hole is backfilled with the same soil, the radon will diffuse back into the pore openings and eventually retain an equilibrium concentration similar to that present before the soil was disturbed. But how long does this take? Should the re-establishment of equilibrium ^{222}Rn levels require a time period of the same order as our deployment period then we have a situation completely different than the steady-state conditions normally encountered (or assumed) when attempting to measure radon concentrations.

An experiment we performed at station L-B on September 17-l8, 1989, will illustrate this problem. During this experiment we dug a large-diameter 15"-deep hole and deployed 3 charcoal canisters and 8 additional cups of the same type used for supporting our canisters inside the hole. Each of the 8 empty cups had 2 ports in the upper surface through which air could be circulated from the surface *via* tygon tubing secured to each port. When all canisters and cups were buried, the tygon tubing was maintained at the surface and pinched off with clamps. This experimental design allowed us to make individual measurements of the radon concentration within each cup at timed intervals by using a small portable air pump with in-line Lucas cells (alpha scintillation cells). We used this experimental system to monitor the change in radon concentration in the soil at this site over a time period comparable to our normal canister deployment times.

The results (Fig. 14) show that the return to equilibrium conditions (~40 pCi/L in this case) does take a significant amount of time (over six hours), at least at this station. The charcoal canister buried at the same time was slightly lower than the last few Lucas cell results (charcoal canister = 35.9 ± 3.6 pCi/L, Lucas cells = 41.3 ± 4.3 pCi/L) although the results are actually within the measurement error in this case. If this type of situation is typical, the radon concentration “integrated” by a charcoal canister would necessarily be somewhat lower than the true value since the measurement is being made during a time of changing concentration, from almost zero to some higher equilibrium concentration. A track etch detector deployed for weeks to months at a time will not suffer from this effect since the equilibration time (approximately a few hours) is very short relative to the deployment period.

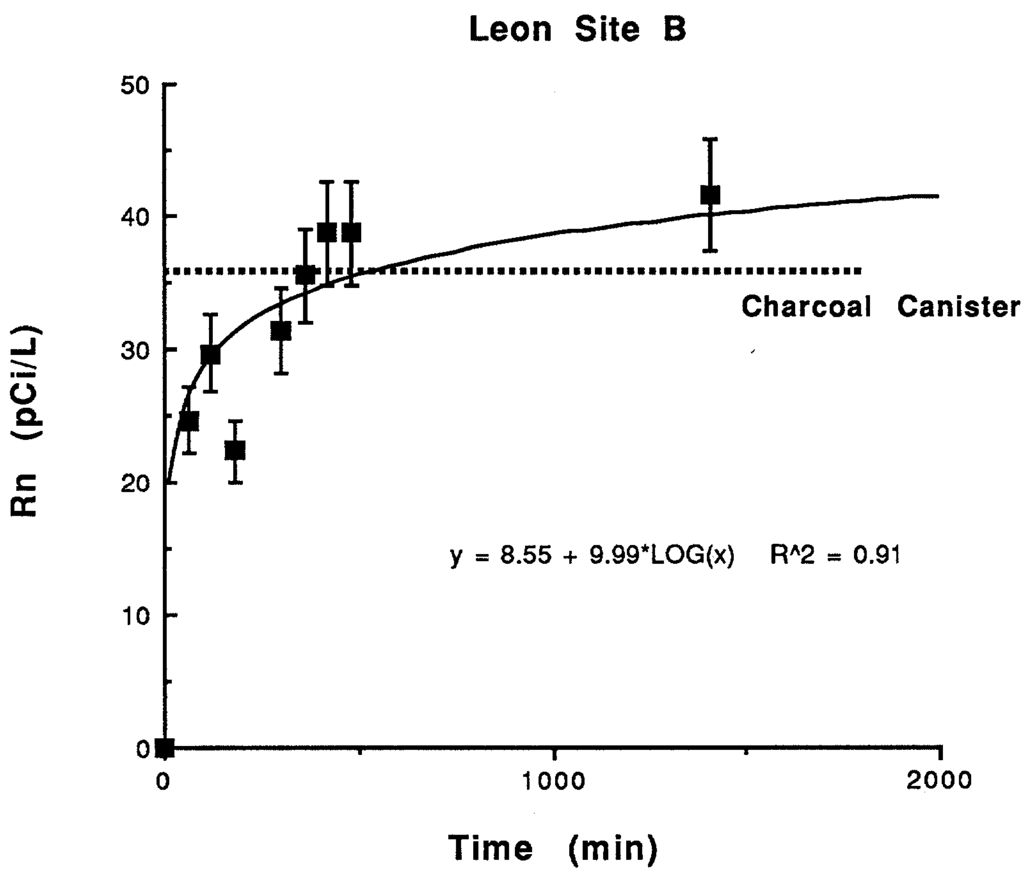


Fig. 14. Relationship between radon concentration and time inside plastic 16-oz. drinking cups used for deployment of our charcoal canisters in soil. Concentrations were measured by collection of grab samples *via* an in-line pump which circulated gas from the buried cups to Lucas alpha scintillation cells located at the surface. Results of a 1-day deployment of a charcoal canister deployed at the same time is shown for comparison.

In summary, the results of this intercomparison show two principal features of interest: (i) occasional high-radon “events” show up only in the track etch results, most likely because the short term deployments used for charcoal canisters are not frequent enough to see these transient phenomena; and (ii) on average, the track etch results are systematically higher than the canister concentrations, most likely because the equilibration time for soil gas radon is a significant fraction of the deployment period used for charcoal canister measurements. It is also likely that certain physical properties of soils (moisture, grain size, etc.) may play a role in determining equilibration times and thus influence the agreement between these two passive methods of measuring soil radon.

RADON EMANATION PROM SOIL

Radon emanation from soil was measured by a liquid scintillation method, first developed by Wadach and Hess (1985). Small (~5 gms.) samples of soil were placed in 20 ml glass liquid scintillation vials, covered with 5 ml of deionized water, and 10 ml of a mineral oil-based scintillator was added. Each sample was measured in triplicate to avoid problems encountered by the natural heterogeneity of soils. The vials were stored for about 3 weeks to ensure equilibrium between the ^{226}Ra and ^{222}Rn of the associated mineral grains. After that period, ^{222}Rn was measured *via* liquid scintillation counting in a similar manner to our water samples. The count rates are converted to activity units per gram of soil using our standards made from the NBS radium solution. This technique measures only the radon which was free to escape from the soil grains, migrate through the water and into the overlying scintillator -- the “effective” or “available” radon.

RADON FLUX MEASUREMENTS

In order to determine the radon flux from the soil, we used a method also based on charcoal canister deployment, except that it was located at the soil-air interface, rather then imbedded in the soil (Pearson, 1967; Megumi and Mamuro, 1972; Countess, 1976). A charcoal canister, fastened with a magnet inside a cylindrical container (a 4" high PVC pipe, covered at the top) open on the bottom, is sealed into the ground surface for approximately one day, allowing the radon which escapes into the overlying air to adsorb onto the charcoal surface. We have chosen to strip each site of vegetation before deployment to eliminate that variable from our assessment. This method is similar to that used for concentration measurements, except an additional parameter must be known, the radon adsorption efficiency. In addition, it is necessary to evaluate what, if any, effect moisture has on this quantity. After recovery of the canister and measurement of radon daughter activity by gamma spectroscopy, the radon flux may be calculated according to the equation:

$$F = \frac{\lambda^2 \cdot t_3 \cdot e^{\lambda t_2}}{(1 - e^{-\lambda t_1})(1 - e^{-\lambda t_3})} \cdot \frac{C_m}{f_{eff} \cdot f_{ads} \cdot A}$$

where:

F	= ^{222}Rn flux from soil (dpm cm^{-2} min^{-1});
C_m	= net count rate measured by NaI detector (cpm);
t_1	= sampling period (min);
t_2	= elapsed time from retrieval to counting (min);
t_3	= counting time (min);
f_{eff}	= counting efficiency (cpm/dpm);
f_{ads}	= radon adsorption efficiency, fraction;
A	= surface area of measurement (cm^2); and
λ	= decay constant of ^{222}Rn (1.26 x 10^{-4} min$^{-1)}$.

The counting efficiencies, f_{eff}, of our NaI detectors for the energies of interest and the canister geometry employed have been determined by running canisters with a known amount of ^{226}Ra dispersed throughout the charcoal. Counting efficiencies as well as background count rates are routinely determined in our laboratory to ensure consistency of results. The radon adsorption efficiency, f_{ads}, has been determined using a modified method of Megumi and Mamuro (1972). This technique relies upon the preparation of a radium-bearing compound known to emanate 100% of the ^{222}Rn generated during decay. We have prepared several such barium palmitate precipitates on filters, with known amounts of ^{226}Ra, which were then exposed to our canisters for timed intervals. The adsorption efficiency can then be determined since the ^{222}Rn emanation rate is known. We also evaluated differences in f_{ads} which relate to moisture buildup during deployment by measuring the weight gain during the deployment period. Our results (Fig. 15) suggest that the effects appear to be minor for short deployments with diffusion barrier canisters.

Two experiments to test the precision of our radon flux measurements were performed in April, 1989 in much the same manner as the radon concentration precision tests were conducted. The results were also similar with the precision for three canisters deployed right next to each other usually better than 10% (7 out of 8 times), while the “overall” variation, for all 12 canisters deployed at 4 sites within 5 feet of the center of the station, was significantly higher. An example of these tests is shown in Fig. 16 for station A-B.

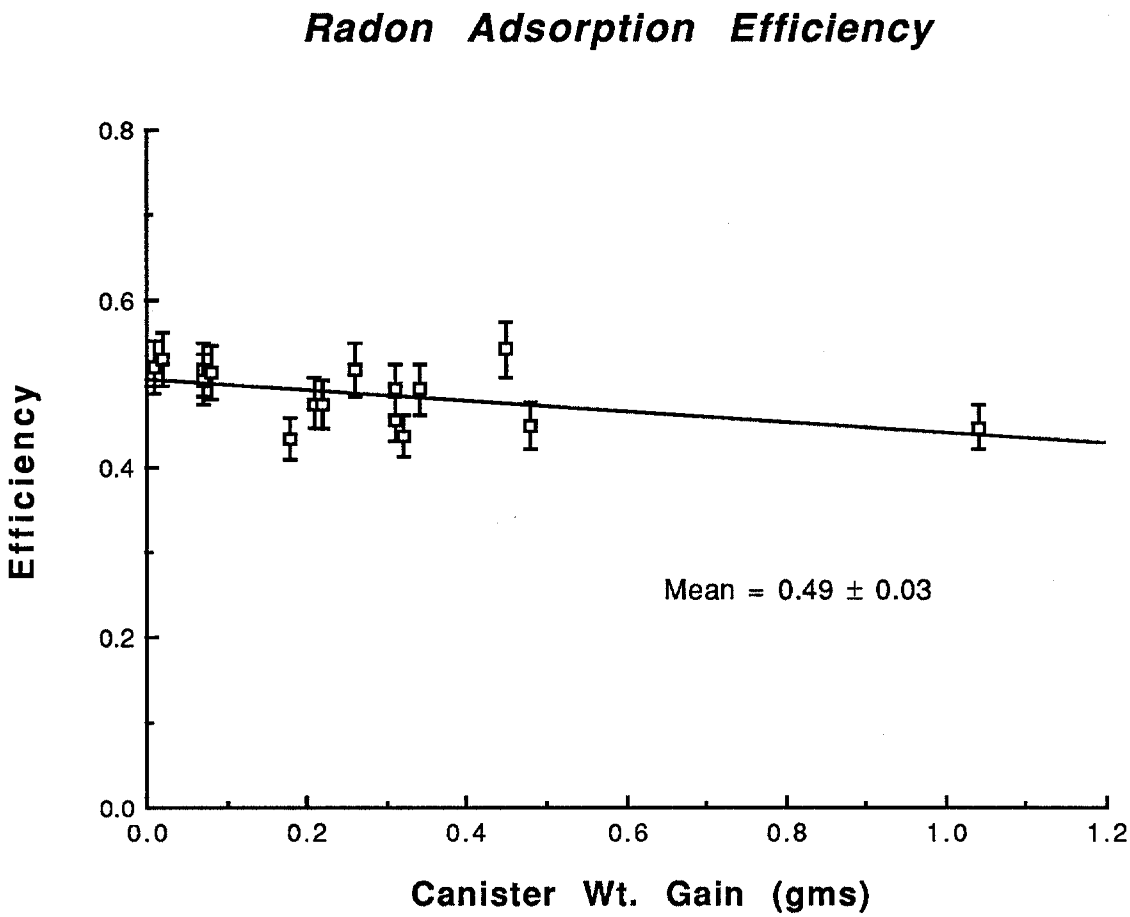


Fig. 15. Efficiency of radon adsorption, f_{ads}, versus moisture as measured by weight gain of charcoal canisters. Efficiencies were measured by collection of radon released from filter samples of barium palmitate spiked with known amounts of ^{226}Ra.

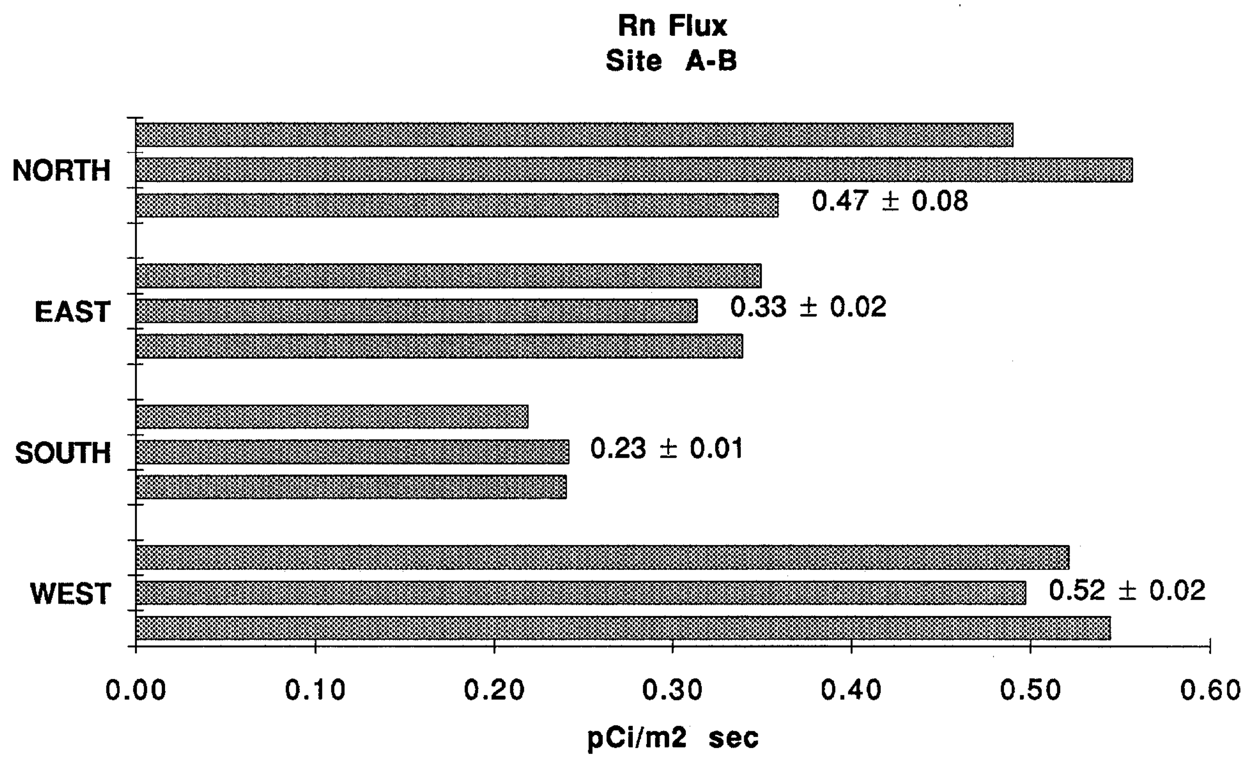


Fig. 16. Results of a precision test showing variations of radon flux both for the case when 3 canisters are deployed as close together as possible as well as when canisters are grouped at 4 separate locations within an approximate 25 square foot area centered at station B in Alachua County. As in the case of soil gas concentration measurements, canisters deployed directly next to each other produced values with significantly greater precision than for the separate clusters of canisters.

Testing the accuracy of our flux measurements is very difficult since standardized flux chambers are not readily available. However, it is reasonable to evaluate our approach against a more established technique. One of the best known approaches for measuring radon flux is *via* a semi-enclosed chamber (Martens *et al.,* 1980). Using this technique, an inverted chamber is placed over the ground and at least two radon measurements are made at timed intervals. The increase of radon in the chamber may be converted to flux by the equation:

$$F = \frac{V\lambda[C_f - C_o e^{-\lambda t}]}{A[1 - e^{-\lambda t}]}$$

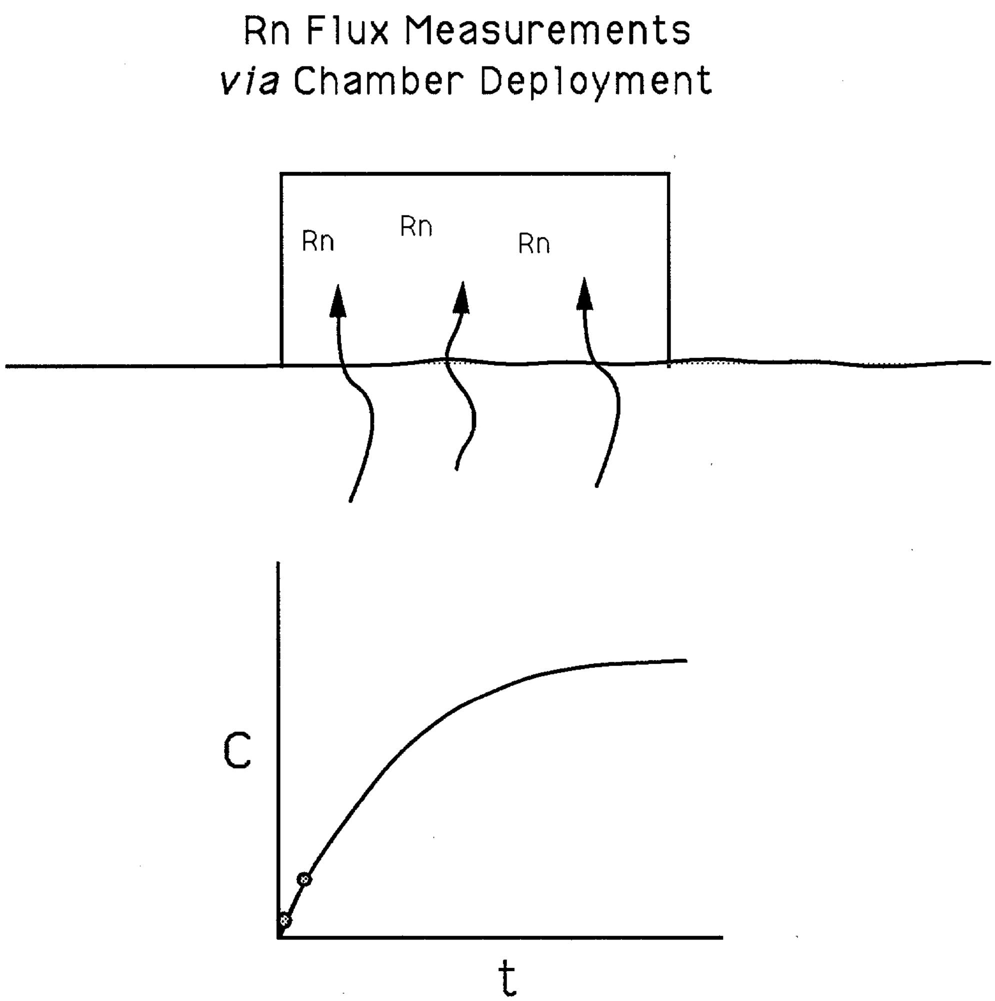
where:

F	= flux (pCi m^{-2} sec^{-1})
V	= volume of the chamber (m^3);
A	= crossectional area of the chamber bottom (m^2);
λ	= decay constant of ^{222}Rn ($1.26x10^{-4}min^{-1}$);
C_f	= final radon concentration (pCi/L); and
C_o	= initial radon concentration (pCi/L)

Since the objective is to measure them of radon increase, it is important to make the <u>concentration</u> measurements relatively quickly, when the rate of increase is still relatively linear. Since the entry of radon into the chamber will be largely diffusion controlled, the rate of diffusion will decrease as the concentration of radon increases inside the chamber (Fig. 17).

Use of our charcoal canister technique, however, only requires one measurement (Fig. 18). This is because we have calibrated our canisters for flux measurements using a flux standard. The fact that charcoal canisters are very inexpensive and may be conveniently deployed inside small PVC chambers makes this a very useful technique, especially when large numbers of measurements are being made. In fact, the flux measurements are operationally easier than the soil concentration measurements because no holes are required. Our “flux holders” are simply inserted, open end down, at the soil surface and retrieved the next day.

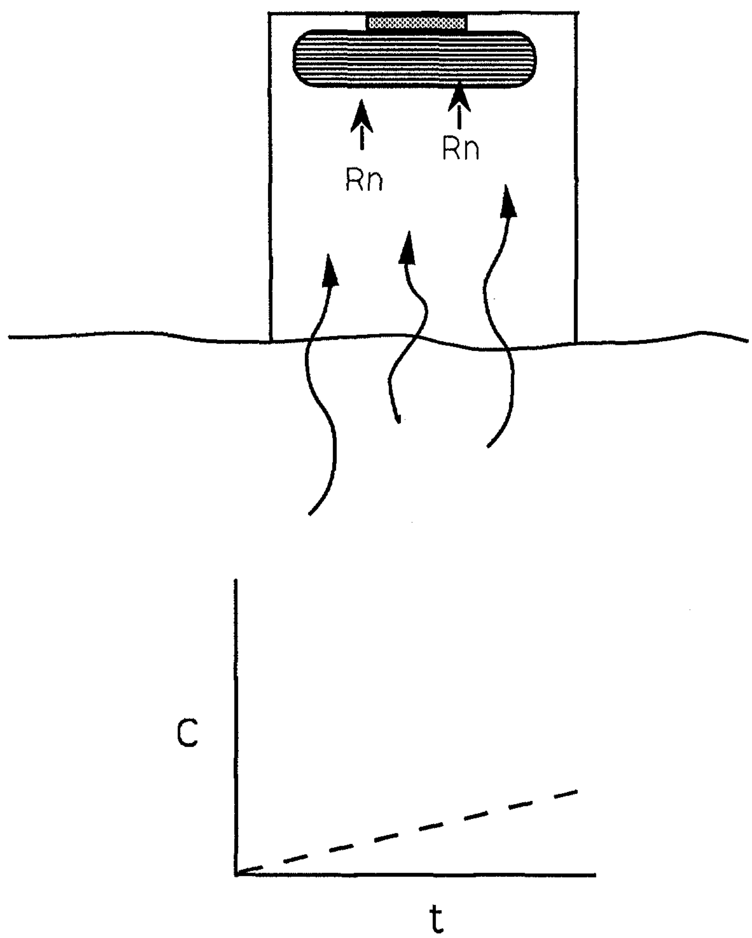
We arranged with Dr. Jeff Chanton for an intercomparison of flux measurements using Pylon TEL’s coupled together with a large (0.406 m^2) stainless steel chamber. We positioned 8 charcoal canisters in our “flux holders” along the outside (2 on each side) of the stainless steel chamber while Chanton used portable air pumps to circulate the air, as required, inside the



$$F = \frac{V\lambda\,[\,C_f - C_o e^{-\lambda t}\,]}{A\,[\,1 - e^{-\lambda t}\,]}$$

Fig. 17. Diagramatic view of radon flux measurements made *via* a semi-closed chamber approach. Symbols defined in the text.

Rn Flux Measurements
Charcoal Canister Approach



$$F = \frac{\lambda^2 \bullet t_3 \bullet e^{-\lambda t_2}}{(1 - e^{-\lambda t_1})(1 - e^{-\lambda t_3})} \bullet \frac{C_m}{f_{eff} \bullet f_{ads} \bullet A}$$

Fig. 18. Diagrammatic view of radon flux measurements made *via* the charcoal canister approach used in this investigation. Symbols defined in the text.

chamber with an in-line TRL. Concentration measurements were made for the chamber a few hours apart and the radon flux calculated according to the equation shown above. All of our flux measurements were based on overnight, single deployments for each canister. We repeated the experiment 3 times (April 6, April 25, and May 3, 1989). The results showed good agreement between the two techniques with only slightly lower chamber fluxes (Fig. 19). All results agreed within a 95% confidence interval. The tendency for slightly lower concentrations in the chamber approach may have been due to a reduction in the actual radon flux under the stainless steel chamber because of radon build up during the experiment.

As discussed previously, it is important to measure the radon concentration in the chamber technique of assessing radon fluxes before the concentration has built up to a point where further diffusion is inhibited. Since our flux measurement technique utilizes "mini-chambers" of sort, we felt that it would be prudent to assess any possible relationship between deployment time and calculated flux. We felt that there should not be any direct relationship since much of the radon entering the "flux holder" is adsorbed onto the resident charcoal canister and our calibration method is approached in exactly the same manner as the actual measurements are made. Therefore, reduction in radon diffusive fluxes into the "flux holders" has already been accounted for during the calibration runs.

We designed an experiment to evaluate whether our calculated flux values were dependent on length of deployment. We deployed eight pre-weighed canisters in PVC "flux holders" at station L-B all at the same time on May 5, 1989. Over the next day, we recovered pairs of canisters at approximately 6, 12, 22, and 25 hours after deployment. The canisters were weighed and counted as soon as possible after recovery. The results (Table 2) show that there is no apparent relationship between calculated fluxes and length of sampling. Furthermore, the overall precision of the eight individual measurements is within ±10%, approximately the same level we estimate as the overall uncertainty of a single flux or soil concentration measurement.

RADIOCHEMICAL ANALYSIS OF SOIL

Determinations of uranium-series nuclides ^{238}U *via* (^{234}Th), ^{226}Ra, and ^{210}Pb and thorium-series nuclides ^{228}Ac and ^{208}Tl in soil were made in surface soil samples as well as samples from the three cores collected at our study sites. These measurements were made by high-precision, nondestructive gamma-ray spectrometry using a well-type intrinsic germanium (IG) detector (Kim and Burnett, 1983). Soil samples were homogenized by grinding, and then

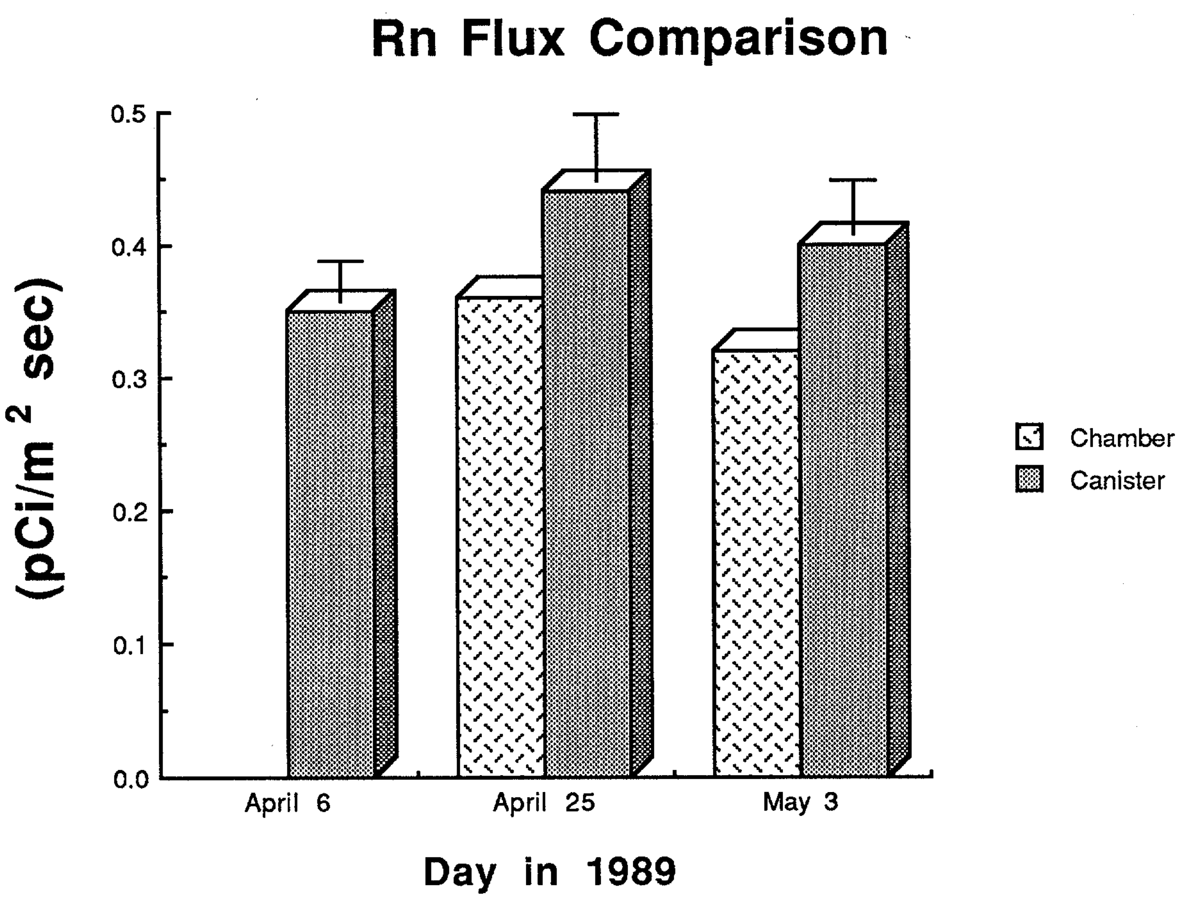


Fig. 19. Comparison of radon flux measurements made by chamber and charcoal canister techniques during April and May, 1989 at station B, Leon County site. The results shown for the charcoal canister represent the mean and standard deviation of eight simultaneous measurements. No chamber measurement was made on April 6th.

Table 2. Results of four radon flux measurements, each made in duplicate at station B at the Leon County test site on May 5-6, 1989 over varying length of deployment times.

Deployment Time (min)	Radon Flux $pCi/m^2 \cdot sec$
374	0.39 ± 0.05*
773	0.41 ± 0.01
1310	0.39 ± 0.06
1487	0.41 ± 0.03

Overall = 0.40 ± 0.05** $pCi/m^2 \cdot sec$

*Standard deviation of two measurements made at the same time.

**Standard deviation based on eight individual measurements.

dried to a constant weight. After loading 1-2 grams of each sample into plastic sample vials and sealing with epoxy to prevent radon escape, the samples were stored for 3 weeks to ensure equilibration of radon daughters. Gamma activities were then measured and ^{238}U was determined from the ^{234}Th photopeaks at 63 and 93 keV, ^{210}Pb from the photopeak at 46.5 keV, ^{226}Ra was determined *via* peaks at 242, 295 and 352 keV (^{214}Pb) as well as 609 keV (^{214}Bi), ^{228}Ac from the peak at 338 keV and ^{208}Tl from the photopeak at 583 keV. The counting efficiency of our IG detector has been calibrated by running several natural standards (soils and rocks) supplied by EPA and the National Bureau of Standards.

NEW TECHNIQUE FOR SEPARATION OF Pb-Bi-Po

Because it was desired to analyze all radon daughters with significant half-lives (^{210}Pb = 22.4 yrs; ^{210}Bi = 5.02 days; and ^{210}Po = 138.4 days) from the same samples, we spent some time developing an improved method for separation of these elements -- necessary before low-level counting can begin. Using conventional ion-exchange techniques for this analysis, approximately 2 days of processing time are necessary for each sample. Using our new approach, based on electrochemical separation, each sample can be processed in less than about 6 hours. Counting times are independent of separation technique and vary with sample activity -- about 1 - 2 days is typical.

Overview

An improved method of determination for ^{210}Pb, ^{210}Bi and ^{210}Po in both natural waters and solid materials has been developed. Polonium-210 is spontaneously plated onto a silver disc from a dilute hydrochloric acid solution. Bismuth-210 is electrodeposited onto a platinum gauze cathode directly from the same solution using a graphite rod anode. After bismuth processing, ^{210}Pb is then electrodeposited from a fluoroborate medium onto the same platinum gauze used as an anode. All nuclides are subsequently measured using standard low-level alpha and beta counting techniques.

The speed of this method (approximately 6 hours per sample after pretreatment) is a distinct advantage over existing techniques as ^{210}Bi must be quickly separated from ^{210}Pb because of its 5.02 days half-life. Another advantage of this method is that the chemical form of the sample solution is conducive to established separation schemes for analyzing other decay-series isotopes (U, Th, Pa, etc.) after these short-lived nuclides have been processed.

Introduction

Lead-210 (half-life = 22.3 yrs), ^{210}Bi (half-life = 5.02 days) and ^{210}Po (half-life = 138.4 days) are naturally-occurring radon daughters known to be useful as tracers for certain geochemical phenomena. For example, Fry and Menon (1962), Poet *et al.(* 1972), Tsunogai and Fukuda (1974) and Moore et al. (1974) have estimated atmospheric residence times of aerosols from $^{210}Bi/^{210}Pb$ and $^{210}Po/^{210}Pb$ activity ratios. These isotopes are also of interest as progeny of environmental radon. Harada et al. (1989) measured ^{210}Pb, ^{210}Bi and ^{210}Po in Florida groundwater and showed that ^{210}Po occasionally occurs in great excess of its radioactive predecessors. Noshkin *et al.* (1984) have also measured these isotopes in muscle, liver and bone of fish.

Typically, the separation of bismuth from lead is carried out by precipitation, ion exchange, electrodeposition and solvent extraction. Fry and Menon (1962) and Tsunogai and Fukuda (1974) separated bismuth from lead by precipitation of bismuth oxychloride from a dilute hydrochloric acid solution. Small amounts of lead may contaminate the bismuth oxychloride precipitate. Ishimori (1955) demonstrated that ion exchange techniques are useful for the separation of these nuclides. Poet *et al.* (1972) applied this type of bismuth purification after separation from lead by precipitation. Harada *et al.* (1989) also used an ion exchange technique for Pb-Bi separation in their groundwater study. Although bismuth may be quantitatively separated from lead by this method, it is a tedious and long procedure, requiring up to 2 days. MacKenzie and Scott (1979) demonstrated that ^{210}Bi and ^{210}Po were spontaneously plated onto copper foil from a dilute hydrochloric acid solution. This method, however, is not strictly quantitative because a chemical yield monitor is not added. Solvent extraction techniques were employed by Blais and Marshall (1988) who successfully used liquid scintillation counting to determine ^{210}Pb in the presence of variable amounts of ^{210}Bi and ^{210}Po even in samples with moderate quenching.

It is necessary that ^{210}Bi be separated from ^{210}Pb as soon as possible after sample collection in order to measure ^{210}Bi activity with high precision. This is not only because of loss by radioactive decay but because a significant amount of ^{210}Bi is produced from its parent, ^{210}Pb, in a short time. In order to achieve quick separation of ^{210}Bi from ^{210}Pb in natural materials, we applied electrodeposition techniques which Brown (1926) and Lingane (1958) had earlier developed for gravimetric analysis of bismuth. By our improved method, ^{210}Bi can be separated from ^{210}Pb within about 6 hours after the end of pretreatment. We designed our method so that other natural decay-series nuclides (uranium isotopes, thorium isotopes, ^{231}Pa, etc.) can also be measured if desired in the same sample preparation by further treatment using an established cation exchange technique (McCabe *et al.*, 1979).

Experimental

Apparatus

A constant-potential stabilized power supply was used to control the applied potential for electroplating. A 60 mesh cylindrical platinum gauze electrode (45 mm in height and 35 mm in diameter) was used for electrodeposition of lead as an anode and bismuth as a cathode. A platinum coil electrode made of platinum wire (10 mm in length, 1 mm in diameter) was used as a cathode during electrodeposition of lead. A graphite rod electrode (58 mm in length and 8 mm in diameter) was used as an anode for electrodeposition of bismuth.

Silicon surface barrier detectors (PAUL DOWNEY & CO. Model P450-26-100M) routed to a 16K-channel pulse height analyzer (CANBERRA Series 95) and a low background 2 π gas flow proportional counter (CANBERRA model 2404) were used for low-level alpha and beta counting.

Reagents and Materials

All reagents used were analytical grade.

Lead carrier: 23.73g of $Pb(NO_3)_2$ were dissolved in 500 mL of 0.5 N nitric acid solution for a final concentration of 29.69 mg Pb^{2+}/mL.

Bismuth carrier: 43.15 g of $Bi(NO_3)_3 \cdot 5H_2O$ were dissolved in 500 mL of 0.5 N nitric acid solution for a final concentration of 37.18 mg Bi^{3+}/mL.

Iron carrier: 48 g of $FeCl_3 \cdot 6H_2O$ were dissolved in 300 mL of 8 N hydrochloric acid. The iron was purified by extraction into isopropyl ether and then stripped with double deionized water. In order to decompose any remaining isopropyl ether, 7 mL of concentrated nitric acid were added and the solution was heated. The final solution was diluted to 200 mL, resulting in an iron concentration of 50 mg Fe^{3+}/mL.

Po-209 tracer: A yield tracer, calibrated at two concentrations, 18.62 dpm/ml and 186.6 dpm/mL, was prepared in 0.5 N nitric acid. The high activity tracer was only used for work on polonium-enriched groundwater at the Hillsborough County test site (Harada *et al.*, 1989).

20% (w/v) hydroxylamine hydrochloride solution: 20 g of hydroxylamine hydrochloride was dissolved in 100 mL of double deionized water.

HNO_3-H_2O_2 mixture: 20 mL of 30% H_2O_2 was added to 80 mL of 3 N nitric acid solution.

Pretreatment

For solid samples (soil, sediment, etc.), a suitable amount of dried sample is decomposed with 3 mL concentrated nitric acid, 2 mL of 60% perchloric acid and 1 mL of 46% hydrofluoric acid in a Teflon acid digestion bomb (160° C; 12 hours) after adding 1 mL of ^{209}Po tracer and 0.5 mL each of Fe, Pb, and Bi carriers. The decomposition solution is then transferred to a 100 mL graphite bottom Teflon beaker. The solution is heated until fumes of perchloric acid persist for fifteen minutes.

Immediately upon collection, liquid samples (groundwater, seawater, etc.) are acidifed with 20 mL of concentrated nitric acid per liter of sample followed by addition of yield tracers and carriers, and vigorous stirring. After standing for 6 hours or more to ensure isotopic equilibrium, the solution is neutralized with ammonia water to precipitate iron hydroxide. The precipitate is collected by decantation and centrifugation and dissolved with 2 mL of concentrated nitric acid, 2 mL of 60% perchloric acid and 0.5 mL of hydrofluoric acid. The solution is transferred to a 100 mL graphite bottom Teflon beaker with a small amount of double deionized water, and treated as the solid samples described above.

Separation Procedure

A flowchart of our new separation scheme is shown in Fig. 20. Fifteen mL of 8 N hydrochloric acid is added to the residue from perchloric fuming after pretreatment and iron is removed by a single extraction into an equivalent volume of isopropyl ether. The aqueous phase is transferred to a 100 mL graphite bottom Teflon beaker and heated on a hot plate until the volume is reduced to about 5 mL. After diluting to 50 mL with double deionized water, 5 mL of 20% hydroxylamine hydrochloride solution and 50 mg of ascorbic acid are added. Polonium is then spontaneously plated onto a silver disc with its back side covered by electric tape at 90°C for 3 hours. After washing the silver disc with a few mL of double deionized water and a small amount of ethanol, the alpha activities of ^{209}Po and ^{210}Po are measured by a spectrometry.

The solution is then transferred to a standard 100 mL Teflon beaker with 30 mL of 0.5 N hydrochloric acid. After addition of 0.5 g of hydroxylamine hydrochloride, bismuth is electrodeposited onto the platinum gauze cathode at 1.4 volts and 60° C for 30 minutes, using a rotating graphite rod as an anode. The mid-point of this electrodeposition period is recorded as

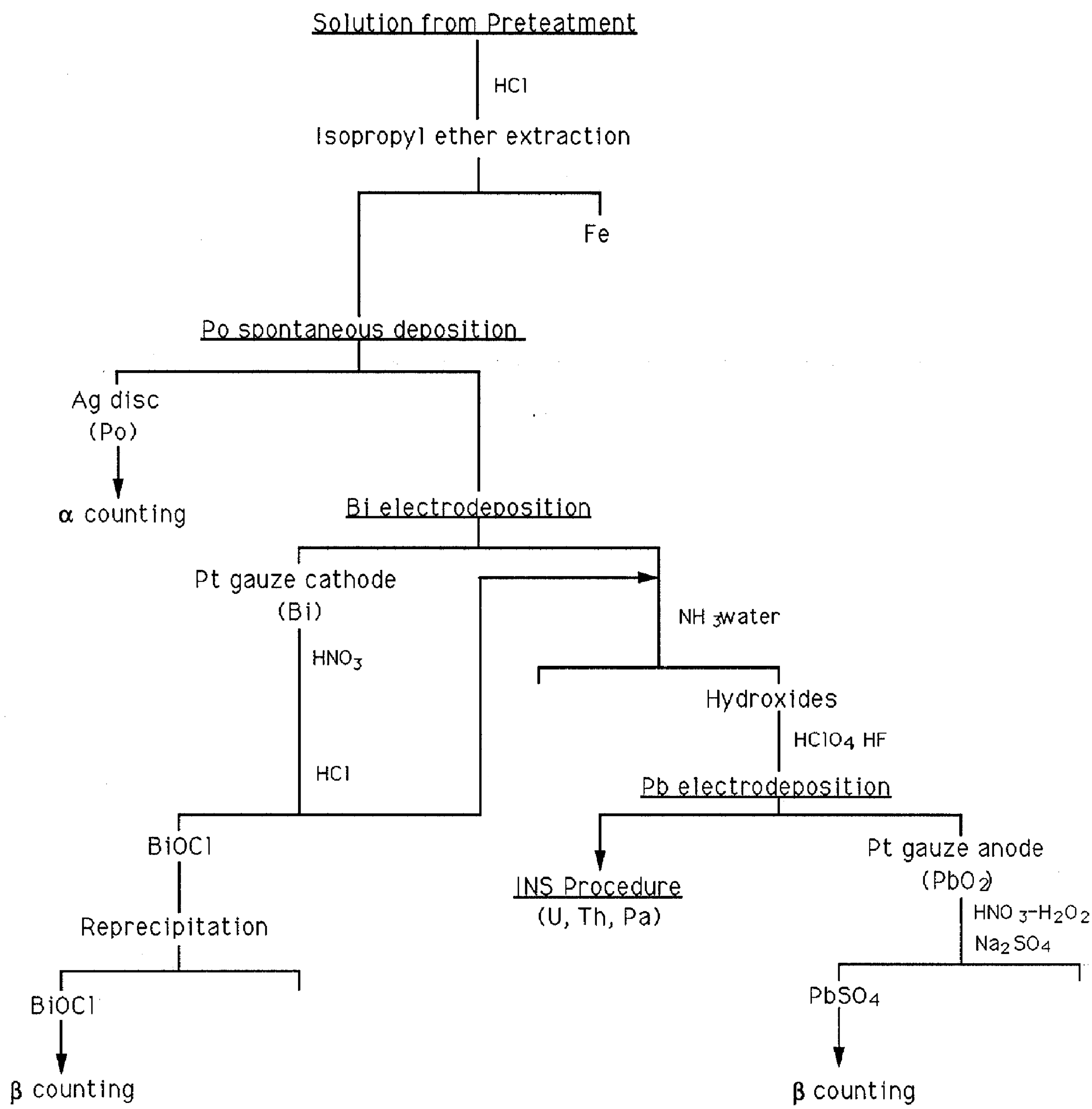


Fig. 20. Flow chart of a new procedure developed in our laboratory for electrochemical separation of ^{210}Pb, ^{210}Bi, and ^{210}Po from natural water samples.

the time of Pb-Bi separation, used for correction of ^{210}Bi in-growth or decay since sample collection. Bismuth is leached from the platinum cathode with a few mL of concentrated nitric acid and the cathode is washed with a small amount of double deionized water. The solution is evaporated to dryness and the residue dissolved with 30 mL of 1 N nitric acid. After boiling, 5N ammonia water is carefully added until a faint opalescence appears. The bismuth oxychloride precipitate is made by adding 2-3 mL of 0.2 N hydrochloric acid to the solution, and curing by heating until the supernatant is completely clear. This precipitate is collected by centrifugation, washed with hot water, dissolved with 1 N nitric acid and reprecipitated. Since some lead may still be present (we found it better not to wash the electrode to prevent loss of bismuth after electro-deposition), the supernatant and wash water from the bismuth oxychloride precipitate is combined with the Pb fraction and saved for ^{210}Pb analysis. We found the reprecipitation step to be very important for complete purification of the bismuth oxychloride precipitate. This is especially true in the presence of other beta-emitting nuclides. The bismuth oxychloride precipitate is collected onto a pre-weighed Gelman GA6-S filter (pore size = 0.45µm, diameter =25 mm) and washed with a small amount of hot water and ethanol. The filter is dried at 60° C until constant weight is obtained.

The Pb fraction is treated with 5 mL of concentrated nitric acid and 5 mL of hydrogen peroxide on a hot plate until all reducing agents are completely oxidized. After addition of 10 mg of iron carrier, iron hydroxide is precipitated by adjusting the pH to 8 with ammonia water. The resulting precipitate is collected by centrifugation and dissolved with 2 mL of perchloric acid and 1 mL of concentrated nitric acid. The solution is then transferred to a graphite bottom Teflon beaker and prepared in a fluoroborate matrix, suitable not only for Pb electroplating, but U-Th-Pa cation exchange as well (McCabe *et al*., 1979). The sample solution is heated until fumes of perchloric acid appear and after cooling, the beaker is weighed. A few mL of concentrated nitric acid is added, the solution is heated on a hot plate until fumes of perchloric acid persist for twenty minutes. After cooling, the beaker is weighed and perchloric acid is added to make up the weight loss. At this point, 0.5 mL of hydrofluoric acid is added and the solution is transferred to a standard 100 mL Teflon beaker with double deionized water and diluted to 40 mL. If further actinide analysis is desired, the solution is heated for about seven hours to break down aluminum fluoride complexes. Free fluoride ions are required for proper operation of the ion exchange procedures of McCabe *et al.* (1979) for separation of uranium, thorium, and protactinium. The final step in the preparation of the sample matrix is the addition of 1-2 g of boric acid, added to solubilize insoluble fluorides. Lead is then electrodeposited onto the platinum gauze anode as lead oxide at 2.3 volts and 60° C for 45 minutes using a platinum coil as a cathode. After washing the electrode with a small amount of double deionized water, the lead oxide on the platinum gauze anode is dissolved with a HNO_3-H_2O_2 mixture and evaporated to dryness. The residue is then dissolved with 30 mL of 1 N nitric acid and 30 mL of saturated sodium sulfate is added in order to form a lead sulfate precipitate after adjusting the pH to 2-3. After curing the precipitate by gentle heating on a hot plate, it is collected onto a pre-weighed Gelman GA6-S filter and washed with a small amount of double deionized water and ethanol. The precipitate is dried at 60° C until constant weight is obtained. Chemical yields of bismuth and lead are determined gravimetrically by weighing the prepared bismuth oxychloride and lead sulfate precipitates, respectively. The beta activity due to ^{210}Bi is counted immediately for the BiOCl source and after an approximately 3-4 weeks ingrowth period for the $PbSO_4$ source.

Results and Discussion

Spontaneous Plating of Polonium

In order to separate ^{210}Po from the other nuclides and to make an acceptable counting source for alpha spectrometry, we used a somewhat modified version of the method described by Flynn (1968). The small amount of perchloric acid which remains in the polonium plating solution does not interfere with the spontaneous deposition. Chemical yields are generally better than 90% . We used one inch diameter silver discs with their backside covered with electric tape in 100 mL graphite bottom Teflon beakers instead of using a specially designed plating cell.

Electrodeposition of Bismuth

During the developmental work of this technique, we determined the optimum conditions for the specific electrodeposition of bismuth from dilute hydrochloric acid solutions. In order to determine the most suitable applied voltage and acid concentration conditions, we added a known amount (18.59 mg) of Bi^{3+} to various concentrations of hydrochloric acid and electrodeposited the bismuth at various applied voltages at 60° C for 30 minutes (Fig. 21a). The bismuth was subsequently stripped from the platinum gauze electrode with concentrated nitric acid, diluted, and measured by a standard calorimetric technique (Sandell, 1965). The recoveries of bismuth on the platinum gauze cathode did not show any significant difference when the strength of the hydrochloric acid varied from 0.5 N to 1.5 N. There is a significant effect of the voltage applied across the cell, however, with no detectable bismuth plating out below 1.2 volts. On the other hand, the average recoveries over 1.4 volts were at least 94% . This is thought to be a minimum figure because we experienced some loss of bismuth from the cathode caused by an uneven bismuth coating resulting from the evolution of hydrogen during

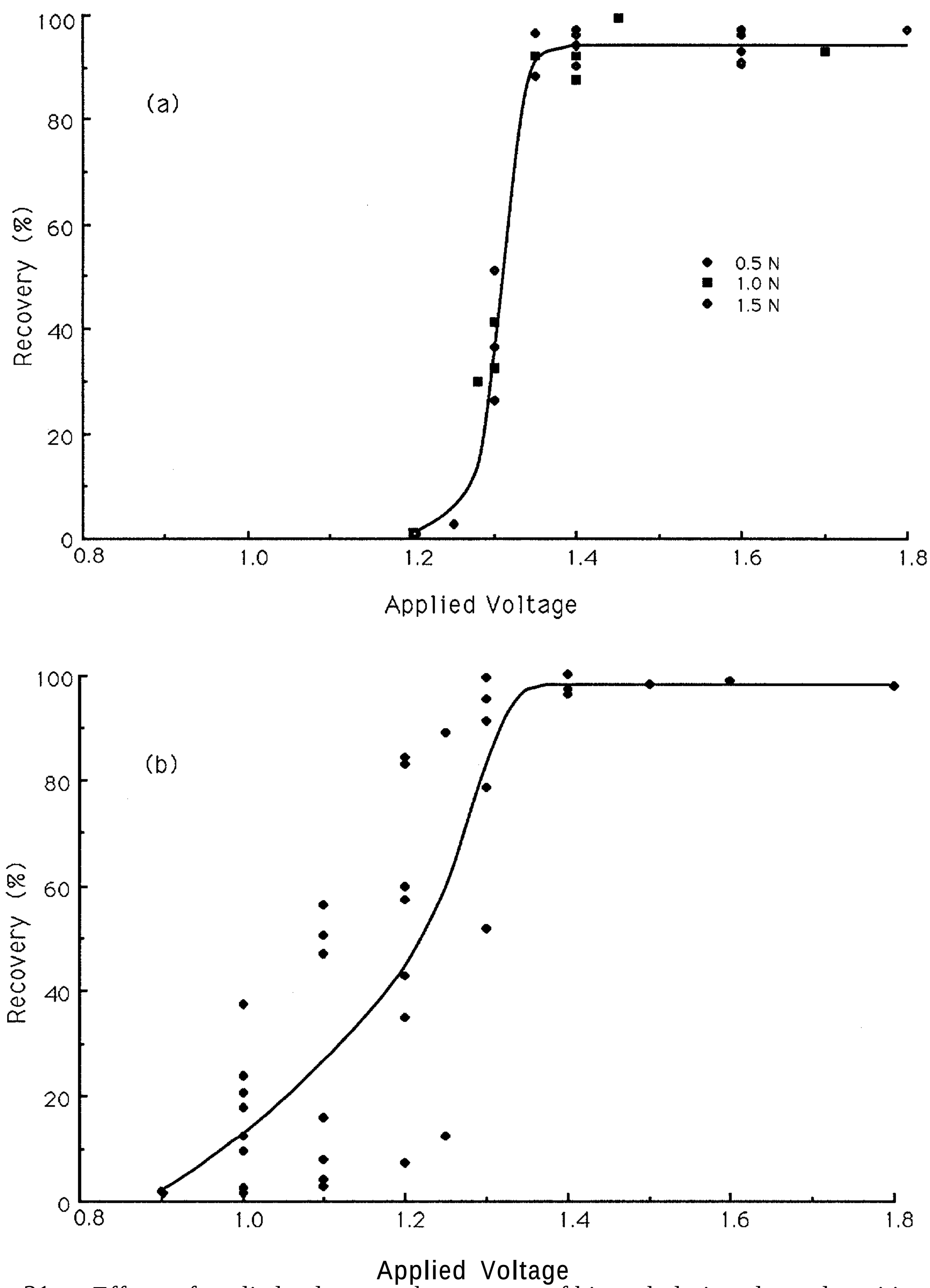


Fig. 21. Effects of applied voltage on the recovery of bismuth during electrodeposition: (a) from 0.5 N, 1.0 N and 1.5 N HCl solution; and (b) from 0.5 N HCl solution with 50 mg ascorbic acid, 1.5 g hydroxylamine hydrochloride and small amounts of nitric acid. All electrodeposition runs were for 30 minutes.

plating. Although small amounts of nitric acid, added as a cathodic depolarizer to prevent evolution of hydrogen, helped this situation, we still noted loss of bismuth if the electrode was washed.

Because of the need to add hydroxylamine hydrochloride and ascorbic acid to our sample solutions for polonium plating, we also tested bismuth recoveries from solutions which contained 50 mg ascorbic acid, 1.5 g hydroxylamine hydrochloride, and a few drops of concentrated nitric acid (Fig. 21b). We found that recoveries over 1.4 volts were consistently greater than 98% . Recoveries below 1.3 volts were extremely variable with essentially no bismuth being plated out below 0.9 volts. On the other hand, a small amount of lead was deposited with bismuth over 1.8 volts. Although we do not understand the reason for high variability below 1.3 volts, it is clear that these reducing agents do not interfere with the bismuth deposition above 1.4 volts. Furthermore, the addition of nitric acid has prevented the problems associated with hydrogen evolution. Using the stated conditions, the bismuth yields are generally about 85% .

Electrodeposition of Lead

The separation of ^{210}Pb from other nuclides was carried out by using a modified version of the method of Lingane (1958) and Matsumoto and Wong (1977). In our method, lead is electrodeposited onto a platinum gauze anode as lead oxide from a matrix of acids in a fluoroborate medium, also suitable for cation exchange techniques used to quantitatively separate uranium, thorium, and protactinium (McCabe *et al.*, 1979).

Analytical Results of Natural Materials

We used standard reference materials supplied by the U.S. Environmental Protection Agency (Environmental Monitoring Systems Laboratory, Las Vegas, NV); “Climax Mill Tailings” and “Composite Sand Tailings” for analysis of ^{210}Pb, ^{210}Bi and ^{210}Po. The analytical results (Table 3) show that our values agree with the certified values (^{210}Bi and ^{210}Po are assumed to be in secular equilibrium with ^{210}Pb) within 1σ counting error.

We also applied this method to the study of Florida groundwater (Table 4). The groundwater results are in good agreement with earlier analysis of these isotopes from the same well by Harada et al. (1989) using ion exchange techniques. The source of the extremely high excess ^{210}Po in these surficial groundwaters remains an ongoing investigation in our laboratory (Burnett *et al.,* 1987; Harada *et al.*, 1989).

Table 3. Analytical results of standard soil materials. All activities in dpm/g. Errors for our analyses are ± 1 σ based on counting statistics.

	EPA Climax		EPA Composite	
Isotopes	This work	Certified value	This work	Certified value
^{210}Pb	707 ± 7	696 ± 14	1034 ± 7	1010 ± 20
^{210}Bi	703 ± 3	----	1029 ± 10	----
^{210}Po	704 ± 10	----	1030 ± 12	----

Table 4. Activities of ^{210}Pb, ^{210}Bi and ^{210}Po for 3 samples of groundwater from station 18, a shallow well in Hillsborough County, Florida. "A" and "B" are duplicate samples. All activities are in dpm/L. Errors are ± 1σ based on counting statistics.

Collection Date	^{210}Pb*	^{210}Bi	^{210}Po**
4/15/88	A 0.382 ± 0.065	16.4 ± 0.6	1350 ± 16
	B 0.358 ± 0.058	15.4 ± 0.3	
6/30/88	A 0.521 ± 0.076	15.5 ± 0.2	1320 ± 18
	B 0.420 ± 0.056	15.7 ± 0.2	
7/14/88	A 0.483 ± 0.077	16.1 ± 0.4	1312 ± 32
	B 0.399 ± 0.069	14.6 ± 0.2	

* Corrected for ingrowth from ^{222}Rn.

**Smaller subsamples were analyzed separately for polonium because of the extremely high activity encountered at this station (Harada *et al.*, 1989).

Accuracy of our radon daughter results, as well as other analyses reported here, are ensured by frequent analysis of geochemical standards supplied by the National Institute of Science and Technology (NIST) and the EPA. We also participate in laboratory intercalibration exercises such as those sponsored by the International Atomic Energy Agency.

PROJECT FINDINGS

RADON FLUX AND CONCENTRATIONS IN SHALLOW SOIL AND GROUNDWATER

Alachua County Test Site

During the period from June, 1988 to June, 1990, we organized fourteen fieldtrips to the Alachua test site. Water samples were collected from each of twenty-two wells, five of them existing shallow wells (~20' depth) and the remainder being monitor wells of either 15’ or 25’ which were installed for our study (see Fig. 4 for a site description). During the course of this study, our monitor wells at stations C and E had to be abandoned after only a few months of sampling because of the property owner’s need to make use of that area for agricultural purposes. Two new wells were installed at site “J” in early 1989 to make up for the loss of these other wells. An experimental well, “FX”, was installed at site F which had open slots in the PVC well casing at depths of 15, 20, 25, and 30 feet. This was done in an attempt to sample water from different depths with only one well casing. After a few months of sampling this well, it was determined that all of the water was entering the well from the shallowest depth and no matter which depth interval was sampled, the water was characteristic of the same water sampled in F15, the 15' well. We decided, therefore, to suspend sampling operations from the FX well. The complete results from this site are presented in tabular form in the Appendix of this report.

All radon in water results are shown as time-series plots for wells which have two depths (A, B, C, and F; Figs. 22, a-d) and all others (Fig. 23). Several of the wells (25 ft well at A, Fig. 22a , for example) show significantly lower ^{222}Rn on the very first sampling than at any other time during the two year period. We are quite certain that this was due to surface contamination that occurred during the establishment of the monitor wells. We sampled the wells within hours after they were installed in June, 1988.

Three of the four stations which have two sampling intervals show that the shallower water located at 15 feet below ground surface has the highest radon concentration at around 30,000 pCi/L although the radon content reached levels above 60,000 pCi/L at station C. Station A (Fig. 22a) shows an opposite trend with the deeper well showing the higher concentration at about 30,000 pCi/L. This is apparently the same aquifer but reached at a different level because of land elevation differences. All other wells monitored at the Alachua site show radon concentrations between 10,000 - 40,000 pCi/L. Although there is approximately a difference of a factor of four between different wells, the time-series plots show that there is a fairly high degree of temporal consistency at any one station. Most of the radon in water concentration data for any one well have coefficients of variation of approximately 10%.

Soil gas radon concentrations were measured by charcoal canister deployment at each site where a water sample was collected (Figs. 24, a-b). These results show a total range between sites of about three orders of magnitude and also show considerable variation at any one site. If the soil gas "radon events" observed in our track etch results (see Part II of this report) are included, the variation is even more significant. The highest soil radon concentrations occurred at station H in the extreme northwest part of the site, and were lowest at station 138 in the extreme southwest comer. Station 138 is also in the lowest elevation of this study area and is directly next to a swampy area which contained standing water throughout the entire period of this investigation. Coefficients of variations of the soil radon data at any one station were most commonly in the range of 30-50% with some stations showing temporal variations of greater than 100%.

Not as many radon flux measurements were made during this study because of a longer technique development period (see Part II) and because of a higher instance of loss of samples, usually because our "flux holders" tended to be kicked over by cows during the overnight deployment periods. Time-series plots (Figs. 25, a-b) show that the soil flux results are similar to the soil concentration results in that there is both considerable variation between sites

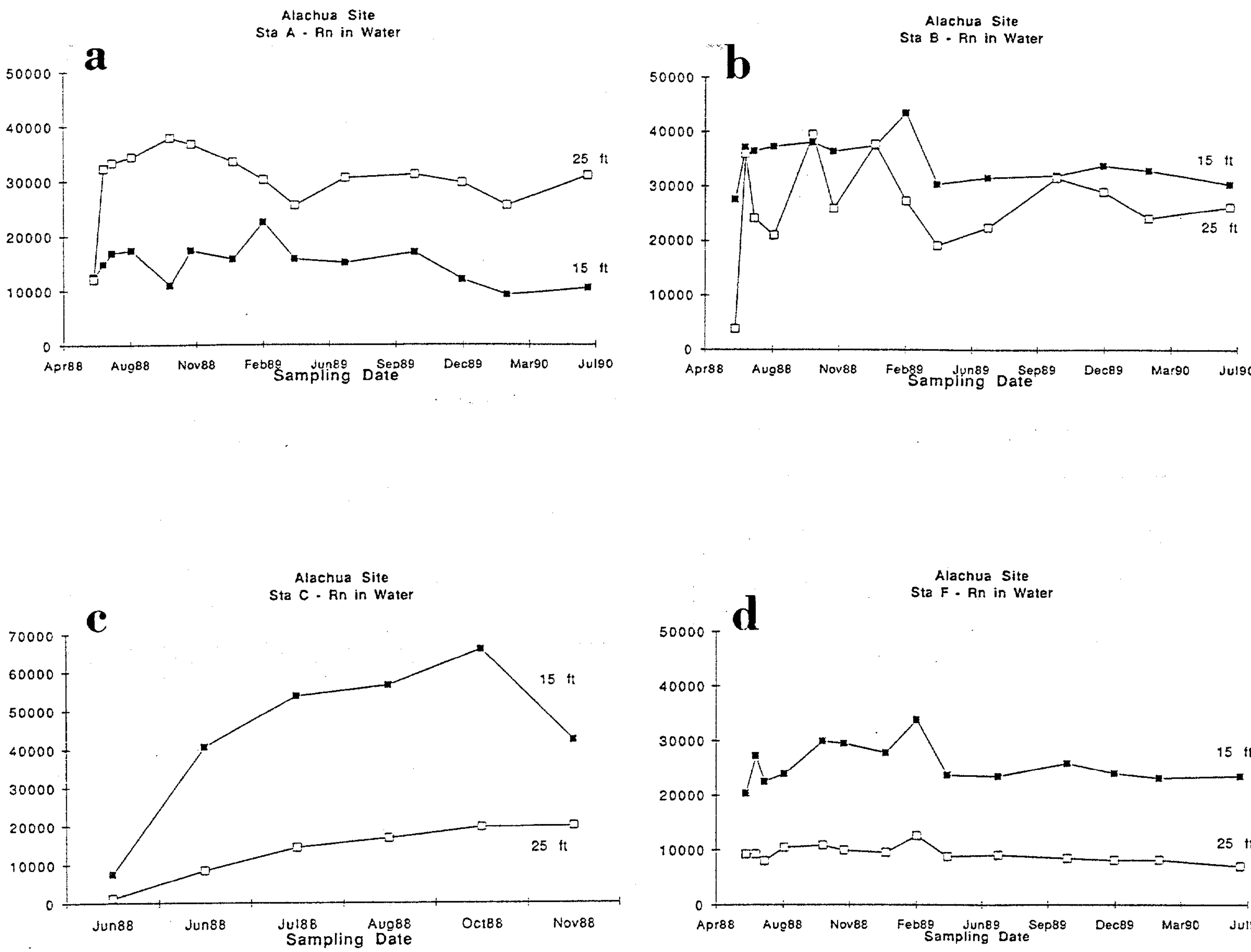


Fig. 22. Radon concentrations (pCi/L) in groundwater samples versus sampling date for stations in Alachua County that have sampling depths at both 15 and 25 feet below ground surface: (a) A; (b) B; (c) C; and (d) F.

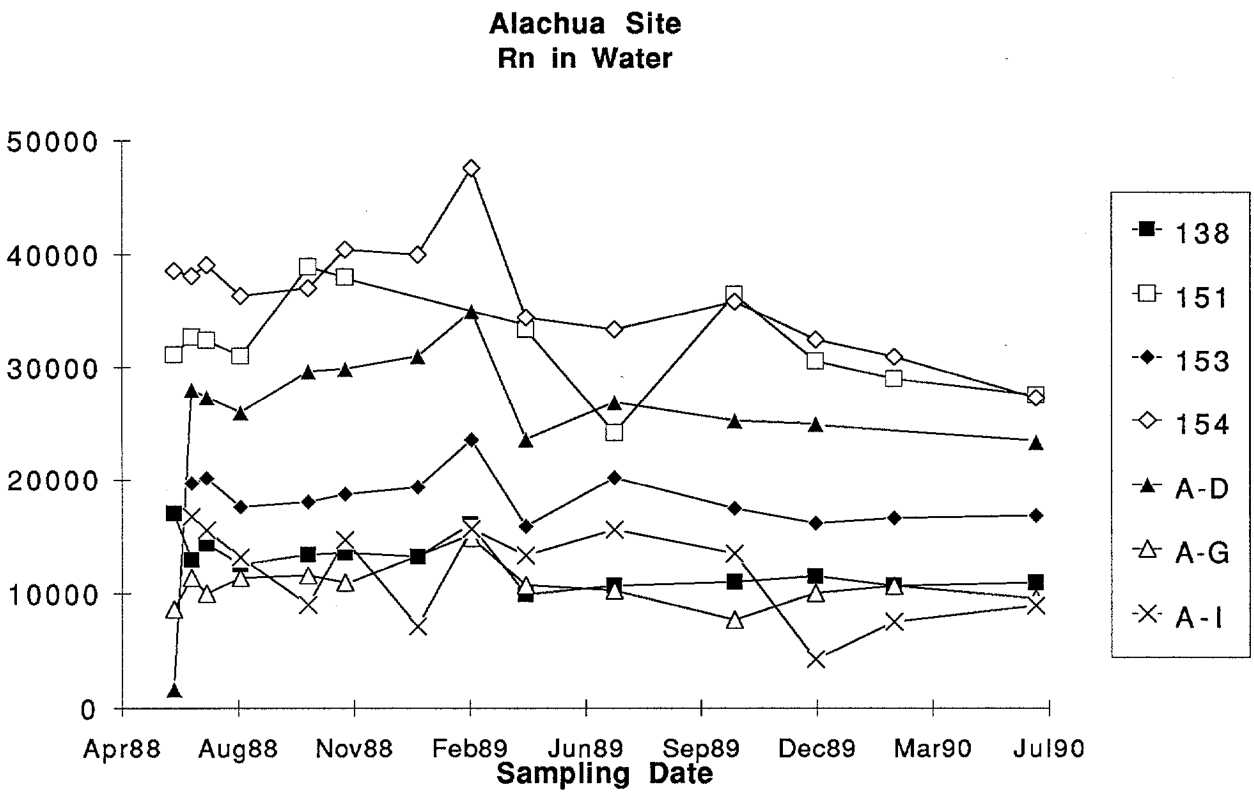
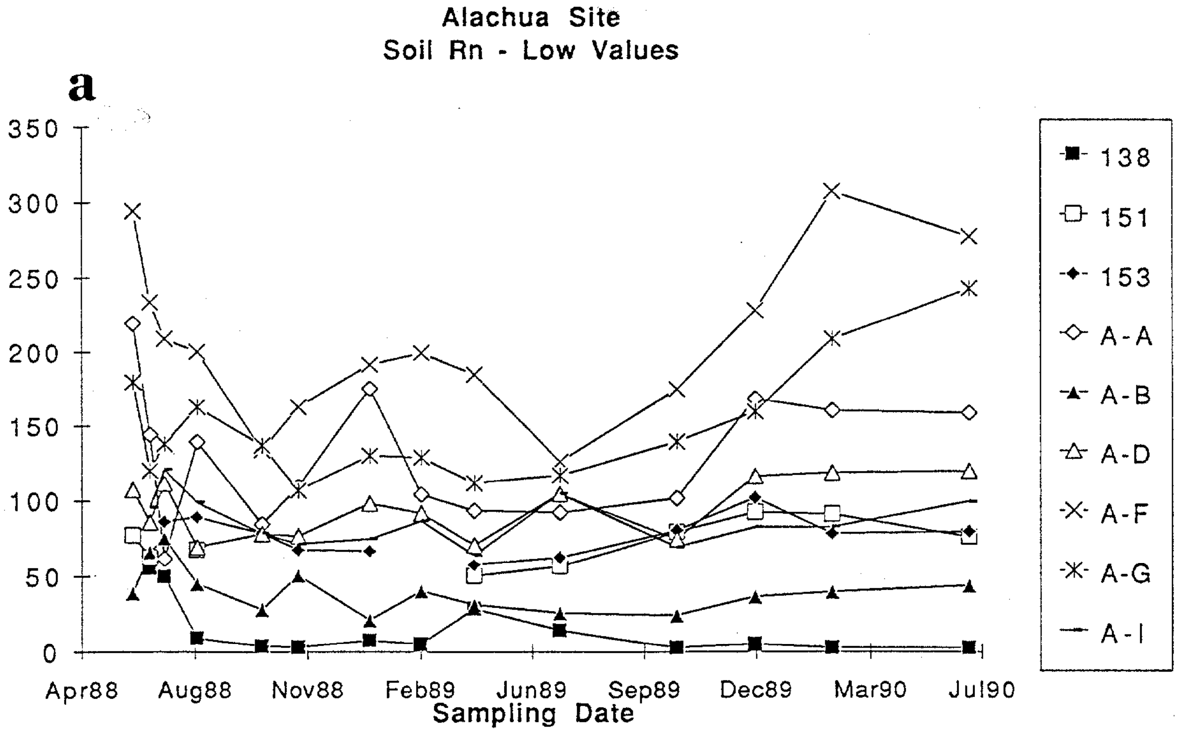


Fig. 23. Radon concentrations (pCi/L) of all remaining wells at the Alachua County test site plotted *versus* date of sampling. Station designations with numbers refer to existing wells while letters refer to monitor wells installed for this study.



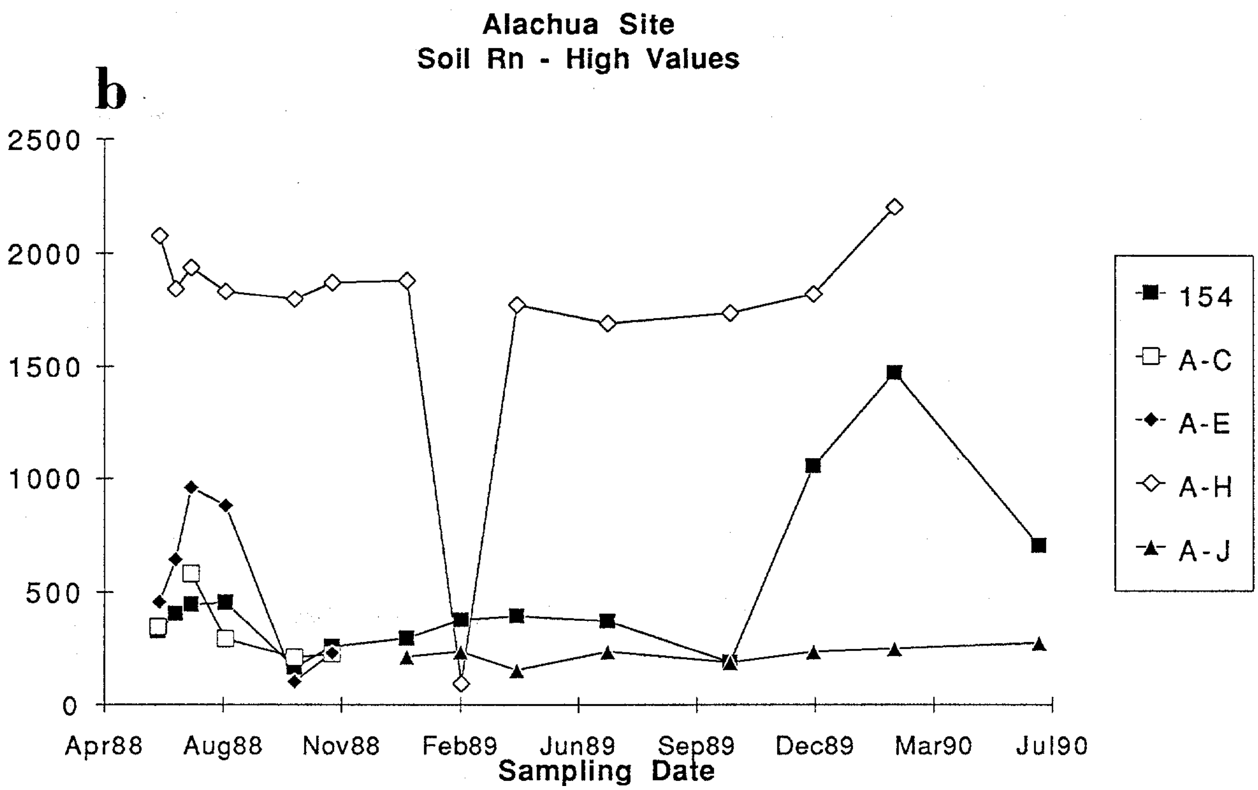
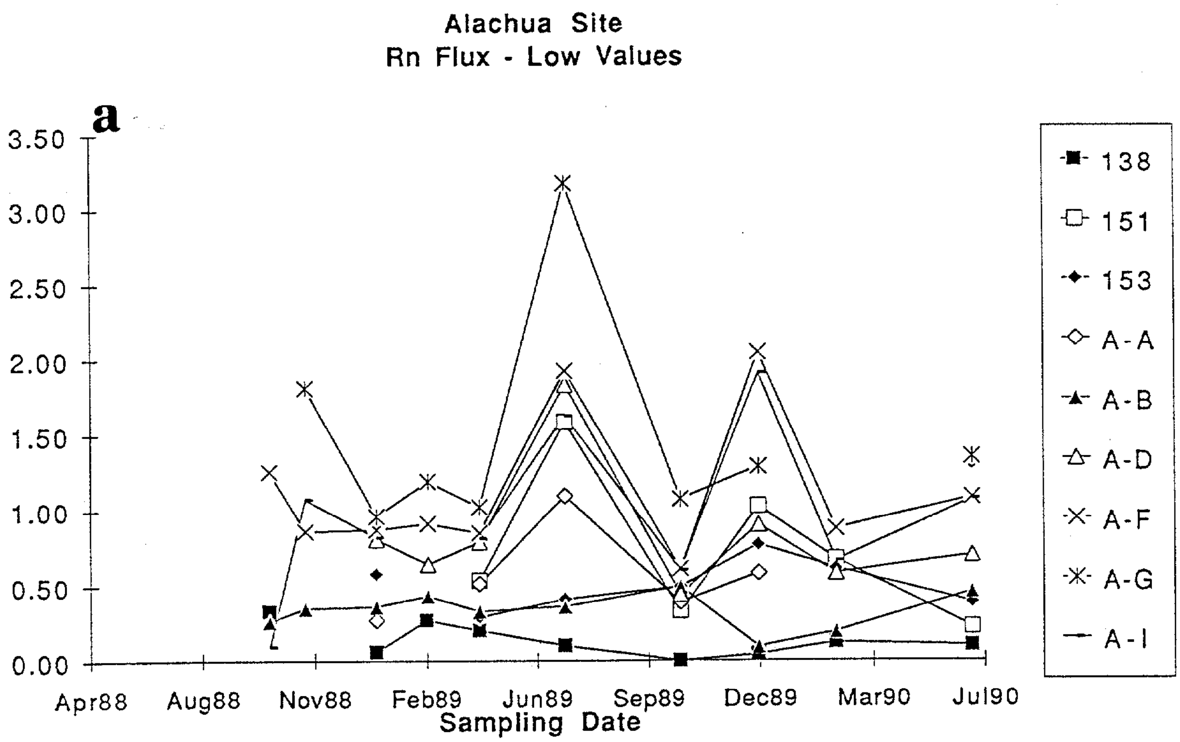


Fig. 24. Radon concentrations (pCi/L) in soil, measured *via* charcoal canisters at 15" below the surface, *versus* sampling date for the Alachua County test site: (a) low values; and (b) high values.



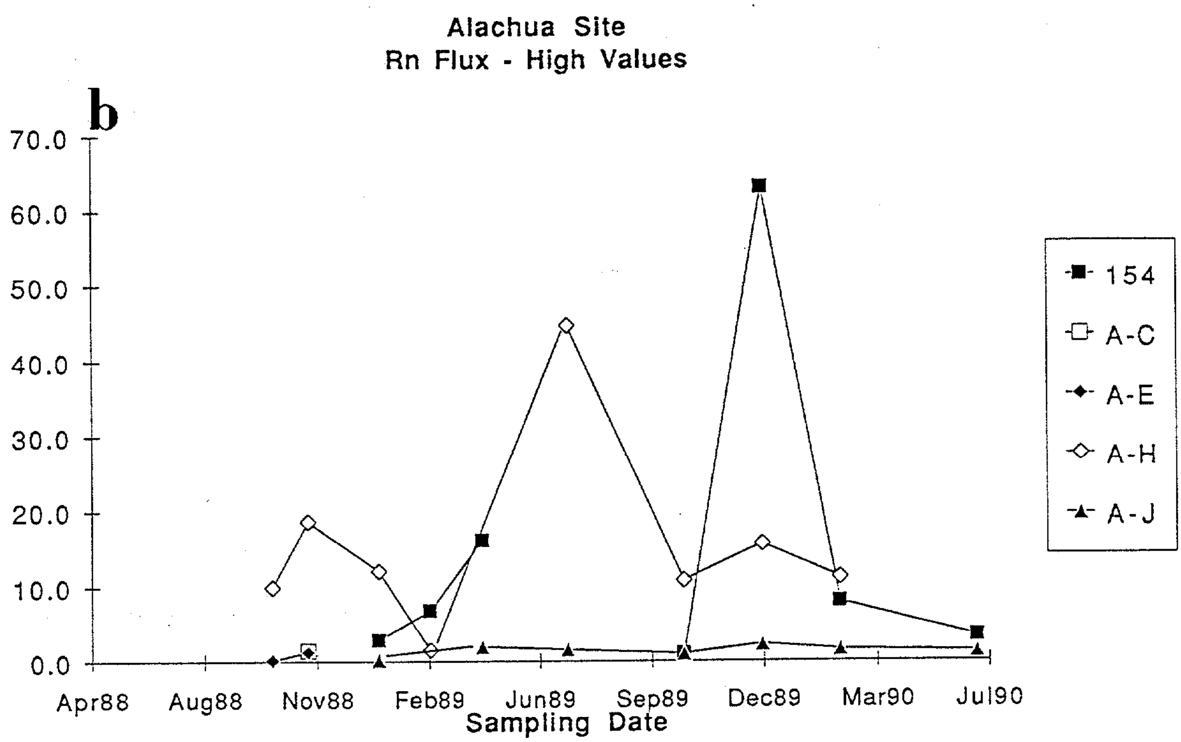


Fig. 25. Radon flux measurements ($pCi/m^2 \cdot sec$) versus sampling date for stations at the Alachua County test site: (a) low values; and (b) high values.

(approximately 100-fold) as well as considerable temporal variation at any one site. Although there is a general tendency for the sites with the highest radon concentration (H, J, and 154 for example) to have the highest flux, there is no clear one-to-one response between the two parameters. The temporal trends in radon flux, for example, show a distinct rise in flux during the June, 1989 sampling at several stations (Fig. 25). This is not reflected in most of the same stations in the concentration data (Fig. 24). Station F, in fact, actually shows a significant drop to the lowest concentration recorded during the entire study at that site while the flux is at about its highest level. These observations support the view expressed earlier concerning the difficulty of producing internally consistent and reliable results when dealing with a system with as much natural variation as soil.

Hillsborough County Test Site

During the two year study period we made fifteen fieldtrips to the Hillsborough County test site. Water samples were collected from twenty-one wells, three of which were existing wells of approximately 20' depth and the remainder were monitor wells installed at 15 and 30 feet below ground surface for this study (see Fig. 5 for a site description). We also installed an experimental well at this site, well "BX", with screens in the casing at depths of 15, 20, 25, and 30 feet. Our experience with this experimental well was basically the same as at the Alachua site, i.e., water appears to enter from the shallowest level thus contaminating deeper parts of the well. We stopped sampling well BX after the first several months of our study. Results from all stations at this site are given in tabulated form in the Appendix of this report.

The radon in water results for the stations that have wells at two sampling depths show differences that are reasonably explained by the station locations. For example, stations A, B, D, and E (Figs. 26, a-d) all have very similar results with the deeper wells at about 30 feet below ground surface, having the higher concentrations at approximately 20,000 pCi/L. These stations are all located within about 300 feet of each other in a rectangular area in the northeast part of the study area (see Fig. 5 site map). The results are also consistent with those from the well at station 18 (also about 20,000 pCi/L) which is located adjacent to well B. The other three stations with two sampling depths (C, F, and G; Figs. 27, a-c) all have higher concentrations in the shallower 15' wells which are, at least in the cases of C and G, about the same radon concentrations as the deeper wells at stations A, B, D, and E. This is most likely an effect of the sloping land surface which is lower at C, G, and F. The core recovered at station B shows that uranium-enriched phosphatic material occurs at about 25 feet below the ground surface at this site. It is not surprising, therefore, that radon is highest in the deeper

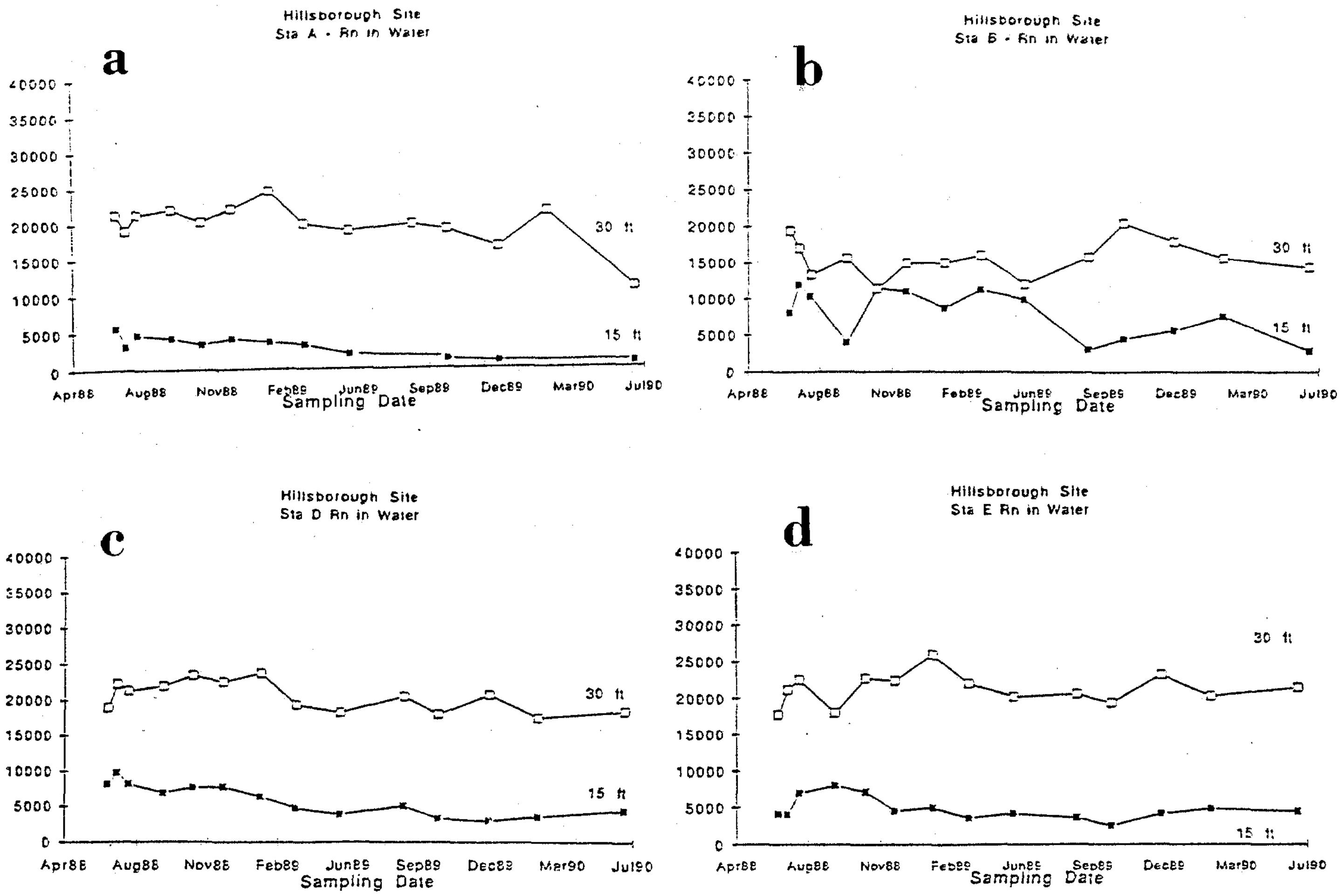


Fig. 26. Radon concentrations (pCi/L) in groundwater samples versus sampling date for stations in the northeast corner of the Hillsborough County test site that have sampling depths at both 15 and 30 feet below ground surface: (a) A; (b) B; (c) D; and (d) E.

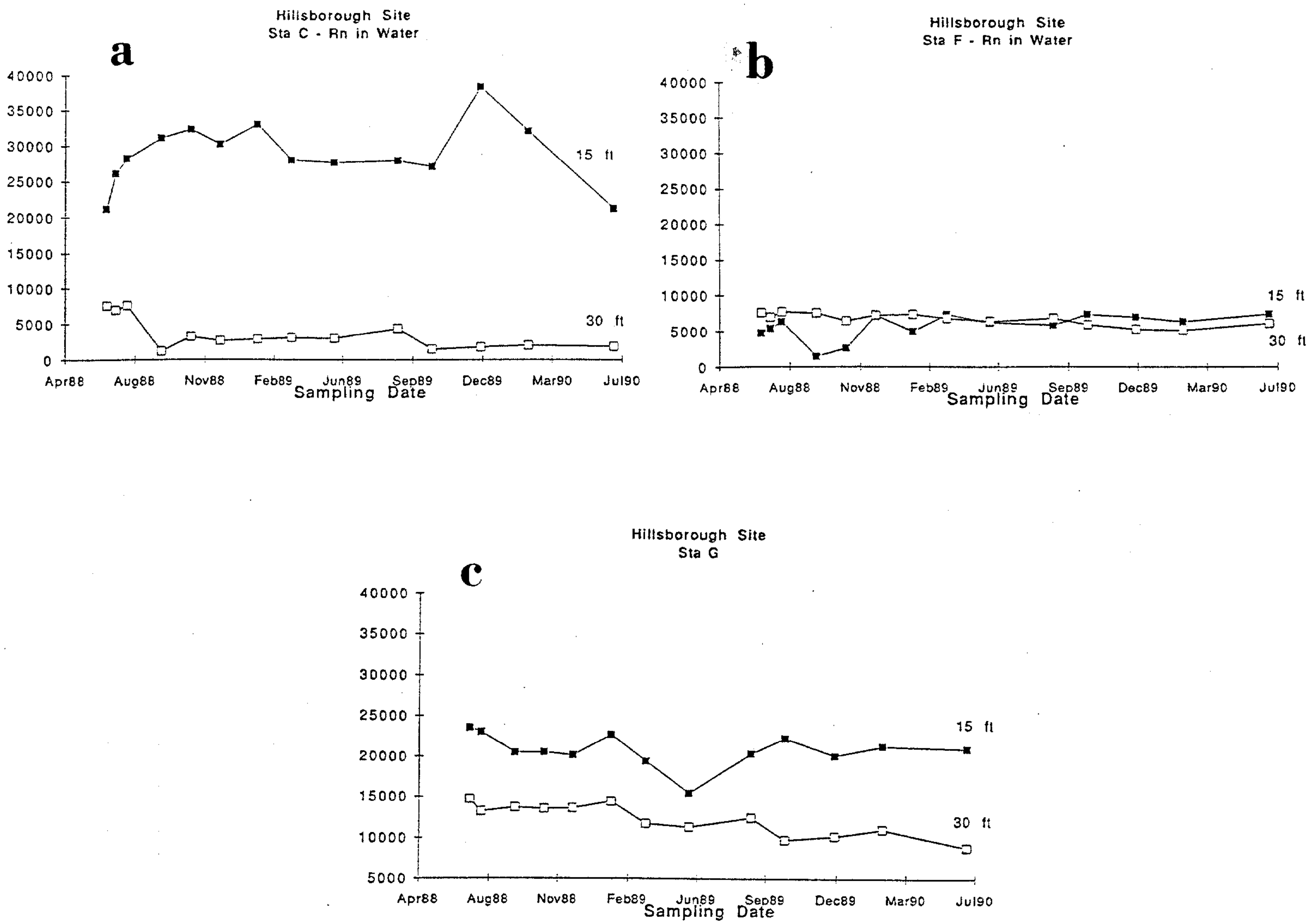


Fig. 27. Radon concentrations (pCi/L) in groundwater samples versus sampling date for the remaining stations in Hillsborough County that have sampling depths at both 15 and 30 feet below ground surface: (a) C; (b) F; and (c) G.

30' wells at the adjacent stations. The lithology and radiochemistry of the core material will be discussed in a later section of this report.

The radon in water values for the remaining wells (10, 11, 18, I, J, and K; Fig. 28) show a similar range of values from close to 5,000 to 40,000 pCi/L. As was the case at the Alachua County test site, variation of radon concentrations in water is much greater spatially (about a factor of 8) than is the temporal variation at any one station. Several of the wells at this site had variations of less than 10% over the entire course of the study.

Results of soil gas radon (Fig. 29, a-b) display considerable more "noise" than the water results. Concentrations of radon in soils throughout the test area have a range of several orders of magnitude. The temporal variation at any one site is less although still very high. Most stations have temporal variations in their soil radon content greater than 50% over the study period and several stations were greater than 100%. There are no recognizable patterns in the soil data which correlate with trends in the water results. Not many trends in the soil data are common among the different stations at the site. One exception to this observation is the obvious decline in soil radon which is centered on August, 1988. Almost every station shows a significant drop at this time which we believe is related to a series of very heavy rainfalls which occurred during this period.

Radon flux results (Figs. 30, a-b) are similar to the concentration results in that the records show an extreme degree of noise covering several orders of magnitude over the study site. Within any one station, the variation is less, but still high at about 50%. Trends in the radon flux data do not seem to be common between stations (we had not started making radon flux measurements during the high rainfall period around August, 1988) at this site. We do observe some correspondence, however, between radon concentration and flux results for the same stations. For example, the secular trend of increasing radon concentration in the data for station C (Fig. 29b) is clearly seen in the corresponding flux data for that station (Fig. 30b).

Leon County Test Site

Although six wells were available for sampling at our Leon County test site (one existing monitor well established by the U.S.G.S. which samples the deep Floridian Aquifer and five shallow wells were installed for our study) only three wells (B, E, and USGS) produced water reliably during the study period. The remaining three wells (A, C, and D) were all "wet" when first established but quickly became dry and failed to produce water again during the study

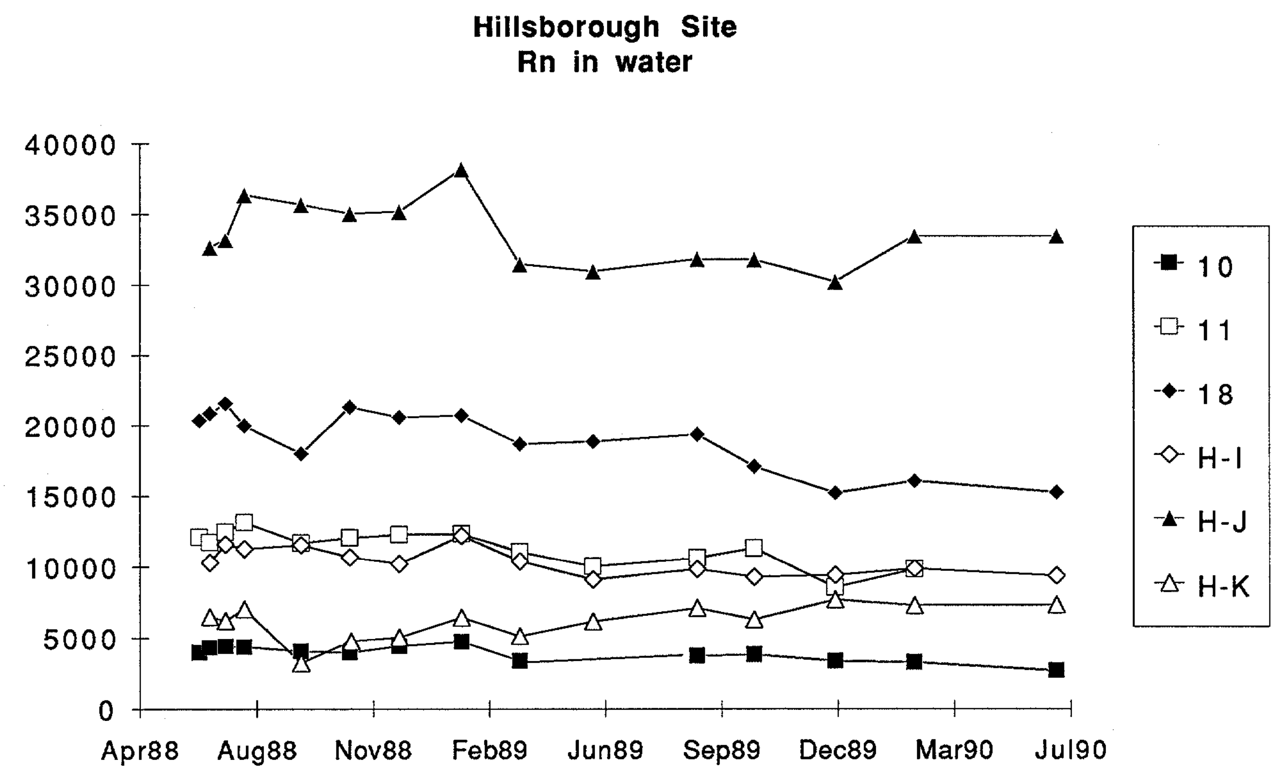


Fig. 28. Radon concentrations (pCi/L) of all remaining wells at the Hillsborough County test site plotted versus date of sampling. Stations designated by numbers refer to existing wells while letters refer to monitor wells installed for this study.

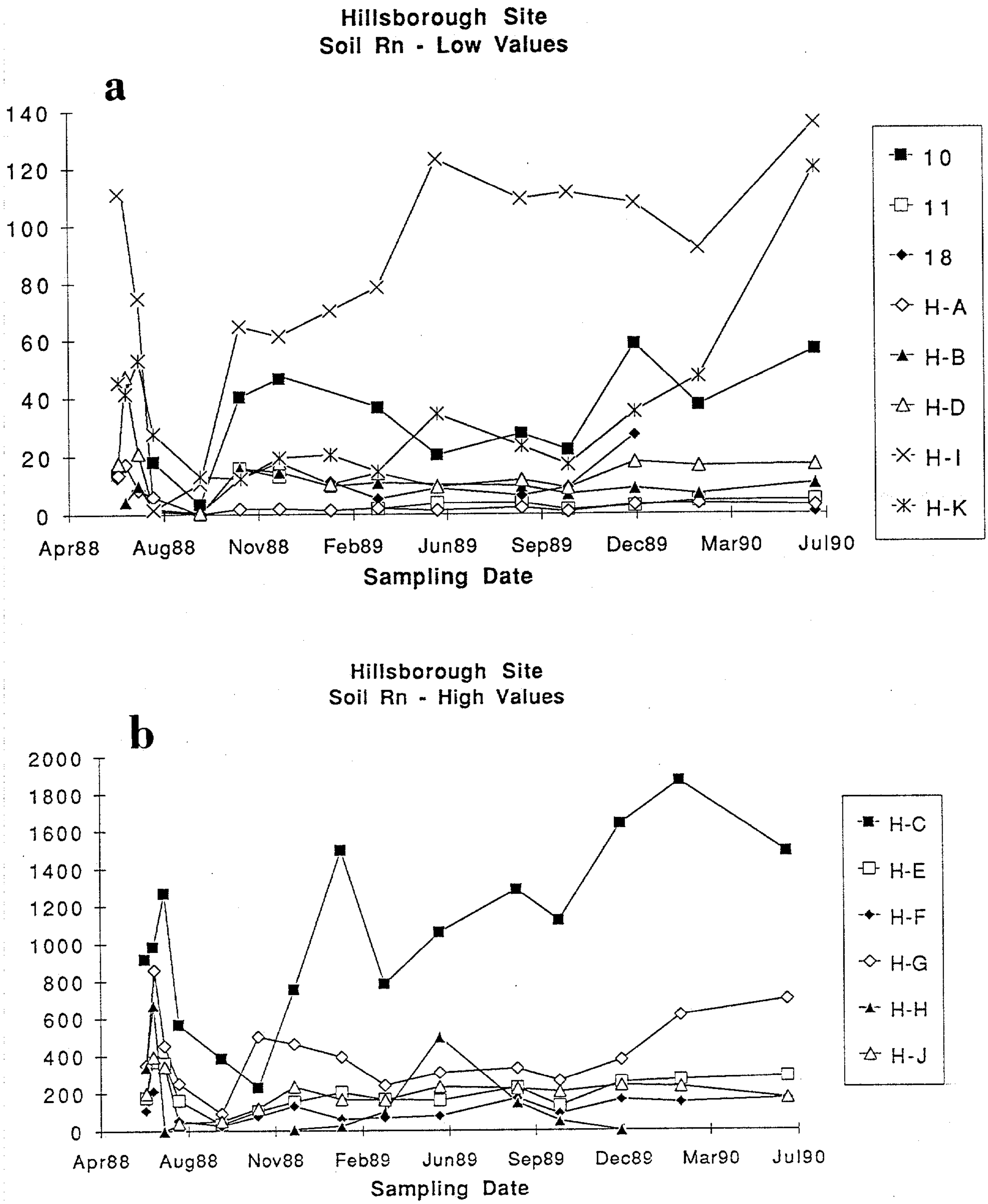
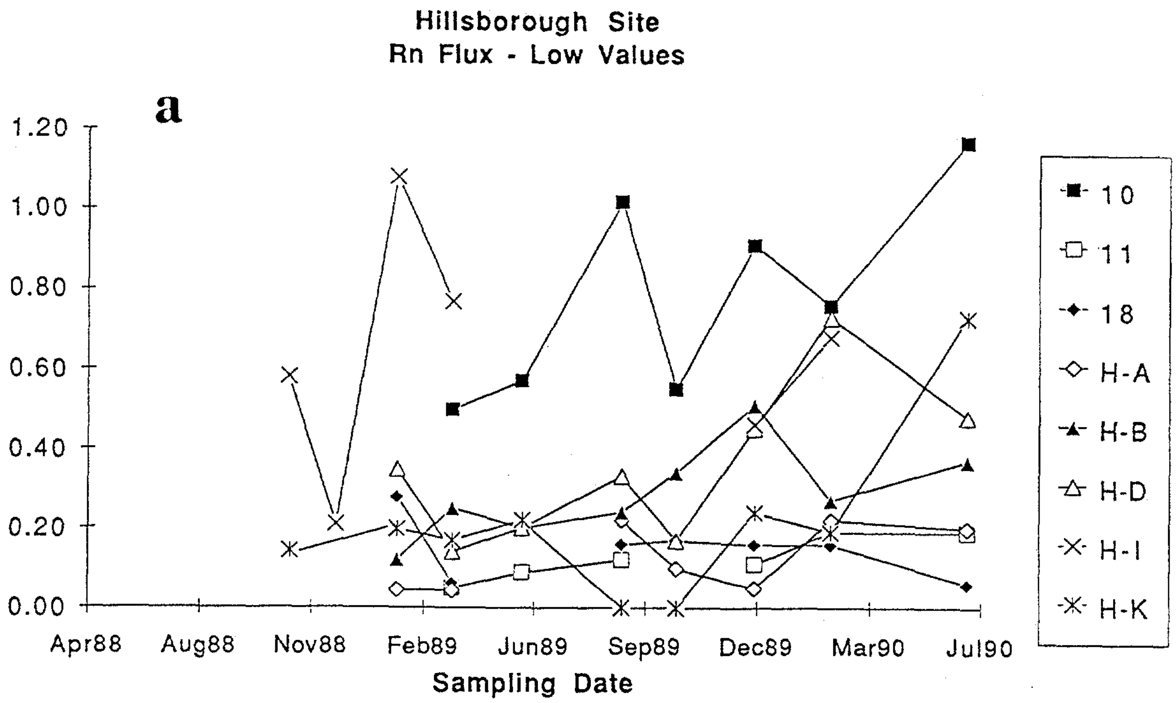


Fig. 29. Radon concentrations (pCi/L) in soil, measured *via* charcoal canisters at 15" below the surface, versus sampling date for the Hillsborough County test site: (a) low values; and (b) high values.



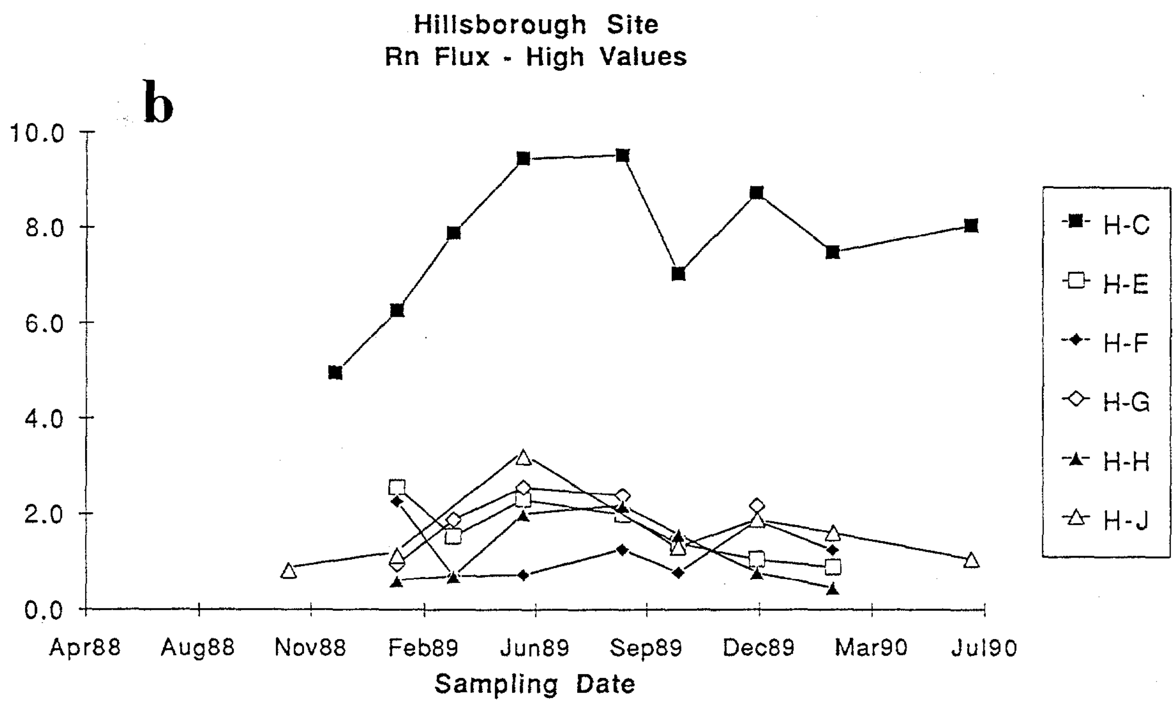


Fig. 30. Radon flux measurements (pCi/$m^2 \cdot$sec) versus sampling date for stations at the Hillsborough County test site: (a) low values; and (b) high values.

period. This was obviously one consequence of the extended drought this area has experienced over the past few years. All results for the Leon County test site are compiled in tabular form in the Appendix.

Time-series plots for radon in water (Fig. 31), soil radon (Fig. 32), and radon flux (Fig. 33) at the Leon County test site are somewhat different than those observed in the more extensive data sets from Alachua and Hillsborough Counties. For the two sites in Leon County where we have shallow monitor wells (B and E) both the soil concentration and radon flux show lower temporal variations than the radon in water results. The very sandy soil at the Leon County site appears to be relatively uniform and has produced comparatively constant soil concentration and flux results. The water results, however, show variations of approximately 50%, much higher than anticipated based on results from the other two test areas. Radon concentrations reached an especially low level (below detection at station "E") around June, 1989, a period of relatively high rainfall. We believe that the variations noted are a consequence of the coupling which exists between the nearby standing body of water (Lake Bradford) and the water table aquifer in this area. Although lakes are usually supplied water *via* seepage from unconfined aquifers, there is evidence in our data that Lake Bradford occasionally "seeps" back into the aquifer. The lowering of ^{222}Rn concentrations at both stations B and E from over 300 pCi/L to values less than 50 pCi/L indicates an intrusion of low-radon surface water into the aquifer. This observation suggests that monitor well sites near standing bodies of water should be avoided if the intention is to sample aquifer waters without exterior influences.

Soil Measurements

Some of the variations in the concentrations of radon in soil and water as well as the flux of radon can be explained by consideration of the "source term", i.e., the physical and radiochemical characteristics of the soil. We have examined soil samples from three cores, one at each study area, and surface samples collected at every station where soil radon measurements were made. All samples have been megascopically described for general characteristics (color, grain size, etc.) and the core samples were further analyzed by x-ray diffraction (XRD) techniques for identification of the main minerals present. Radiochemical analysis for most soil samples was provided by high-resolution gamma-ray spectroscopy for the uranium-series radioisotopes ^{238}U, ^{226}Ra, and ^{210}Pb as well as thorium-series nuclides ^{228}Ac and ^{208}Tl. An estimate of "available" radon in the soil was made by a liquid scintillation

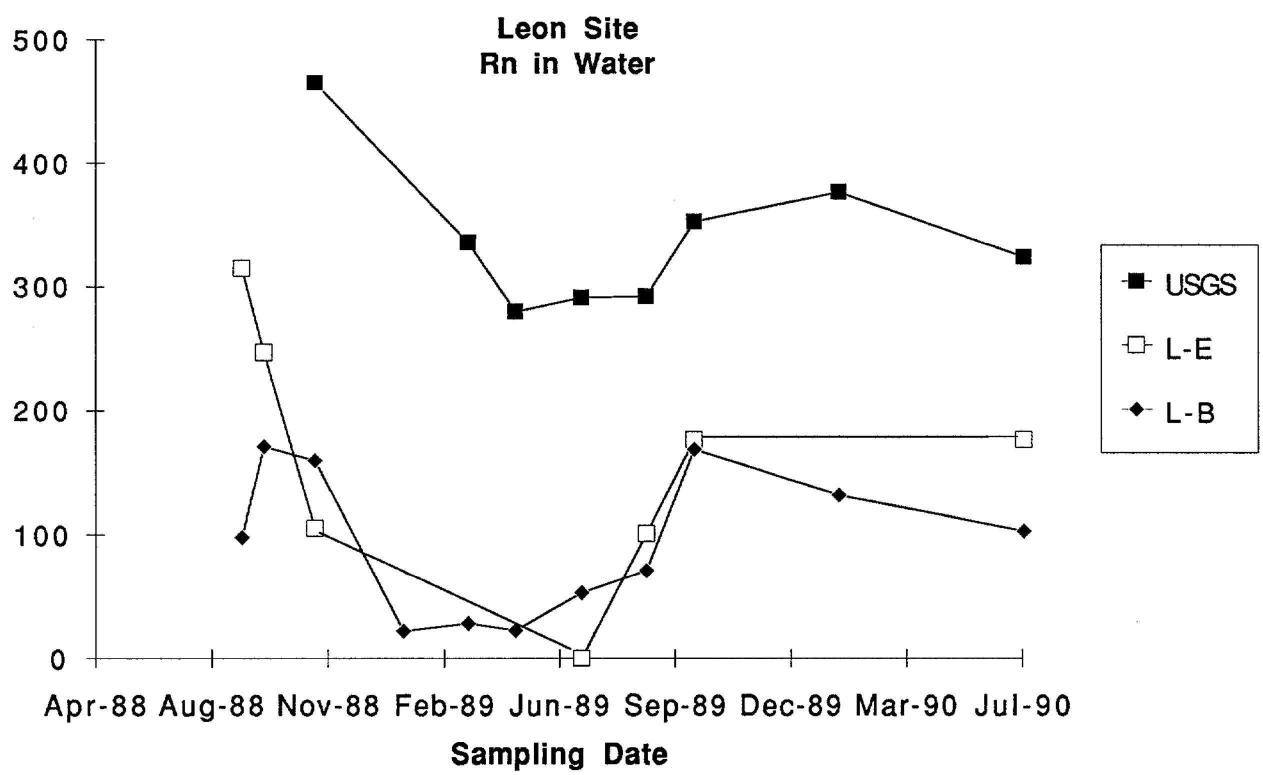


Fig. 31. Radon concentrations (pCi/L) of all wells at the Leon County test site plotted *versus* date of sampling. The USGS well is an existing monitor well which samples the Floridian Aquifer, the other two wells are shallow monitor wells installed for this study.

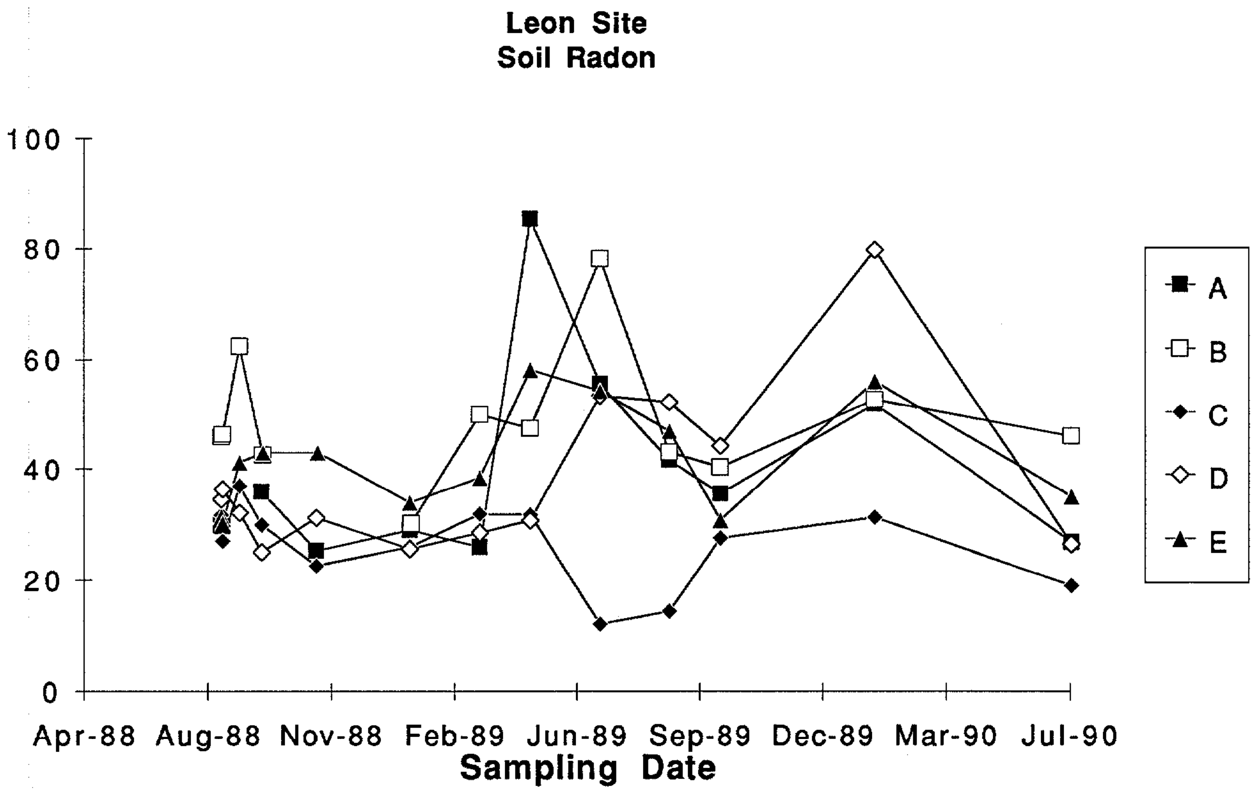


Fig. 32. Radon concentrations (pCi/L) in soil, measured *via* charcoal canisters at 15" below the surface, versus sampling date for all stations at the Leon County test site.

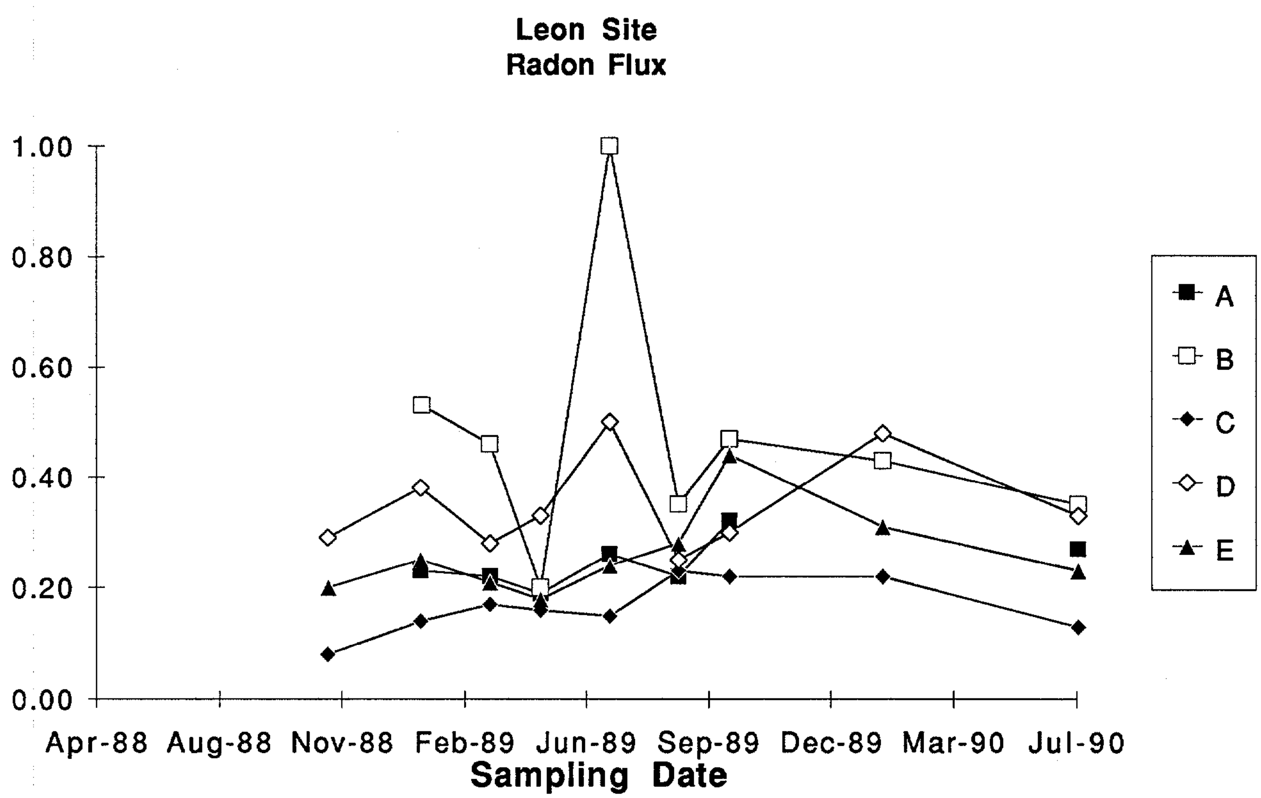


Fig. 33. Radon flux measurements (pCi/m$^2\cdot$sec) versus sampling date for all stations at the Leon County test site.

technique (see methods section). All of the radiochemical results are tabulated in the Appendix of this report.

We also measured soil moisture in several dozen soil samples collected at the same time a charcoal canister was deployed for concentration measurements. When soil radon concentrations are plotted against soil moisture (Fig. 34a), it is clear that the highest concentrations tend to occur in a relatively narrow range of soil moistures, centered at about 10% water content. When replotted on a different scale so that the lower concentration values can be examined, the result appears to be virtually the same. These observations are consistent with theories of radon emanation proposed by Rama and Moore (1984) and others (see Nazaroff *et al.*, 1988) concerning emanation processes of radon from soil grains. These theories suggest that some moisture is important in the pore spaces between grains to retard the path length of the radon atom (by alpha recoil from its parent radium). Completely saturated soils, however, will retain the radon in the fluid phase. It seems, therefore, that a low optimum moisture will enhance emanation and allow diffusion into the open pore spaces of the soil.

The core samples were taken during the drilling of the monitor wells at stations A-C (Alachua County), H-B (Hillsborough County), and L-D (Leon County). All of these core stations are near the central part of the respective study area. Examination of these cores showed that H-B is composed of sand alternating with clayey sand, a clay layer at ~10-14 feet and visible phosphate pellets below ~26 feet (Fig. 35). X-ray diffraction analysis confirmed apatite as a major phase below 25 feet. The core from A-C had a thinner sandy layer (~ 6 feet) and was underlaid by clayey sand. Apatite was detected in every sample below 15 feet by XRD analysis. The L-D core had the thickest sand layer at over 18 feet. No apatite and only minor amounts of clay were detected by XRD in the core from the Leon test site.

When the radiochemical results for the core samples are plotted against depth (Fig. 36), the general pattern of uranium decay-series activities follows the distribution of apatite fairly closely with higher activities of ^{238}U and its daughters occurring closer to the surface in the Alachua core relative to that from Hillsborough County. The Hillsborough core has its activity in a relatively narrow zone and has a maximum concentration of about a factor of two higher than the Alachua core. As expected for the predominantly quartz-rich sand at the Leon County site, all radioisotopes are present at very low activities, generally less than 1.0 dpm/g.

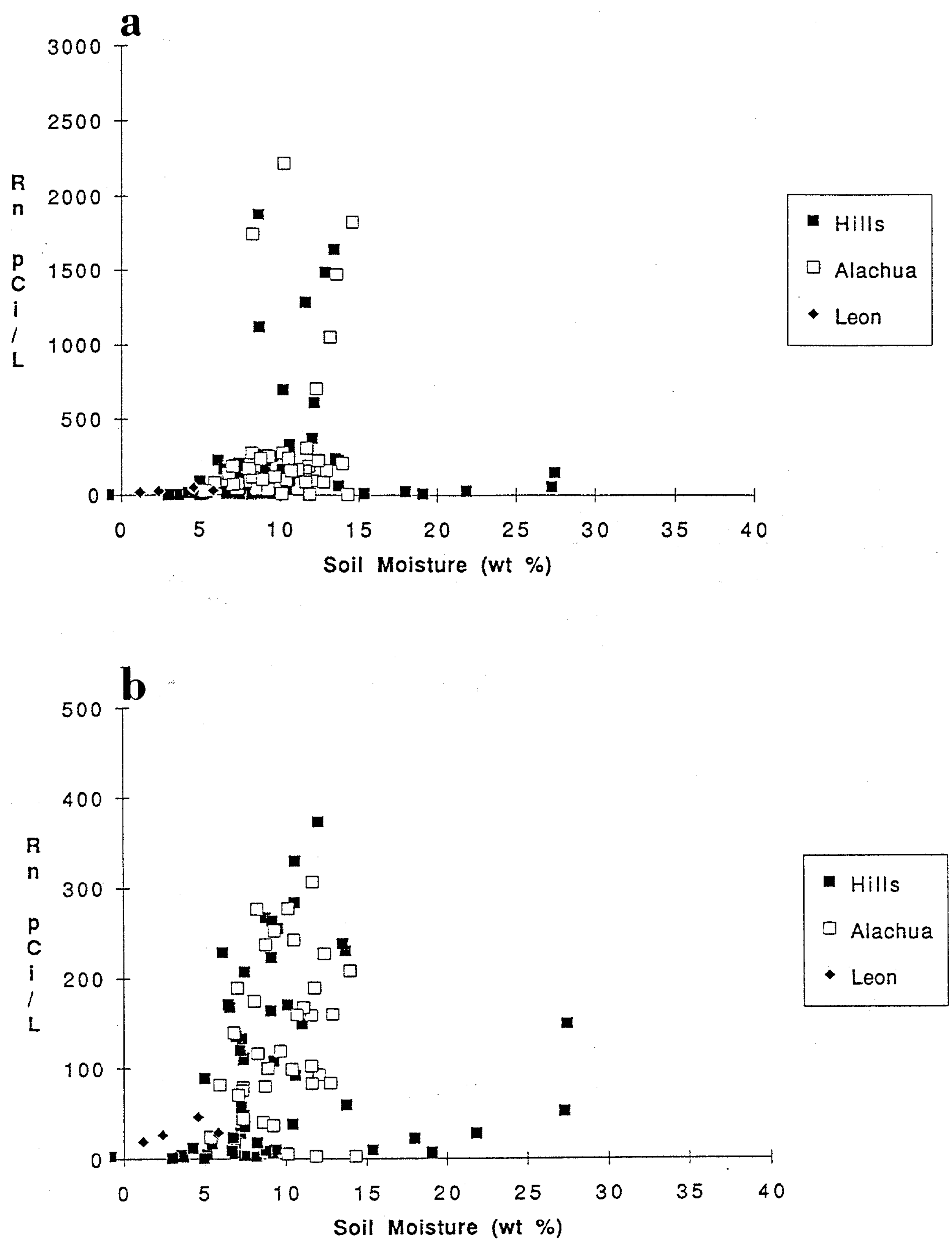


Fig. 34. Radon concentration measurements in soil samples *versus* percent moisture for soil samples collected from each station at the time of measurement: (a) all results; and (b) samples with radon concentrations less than 500 pCi/L.

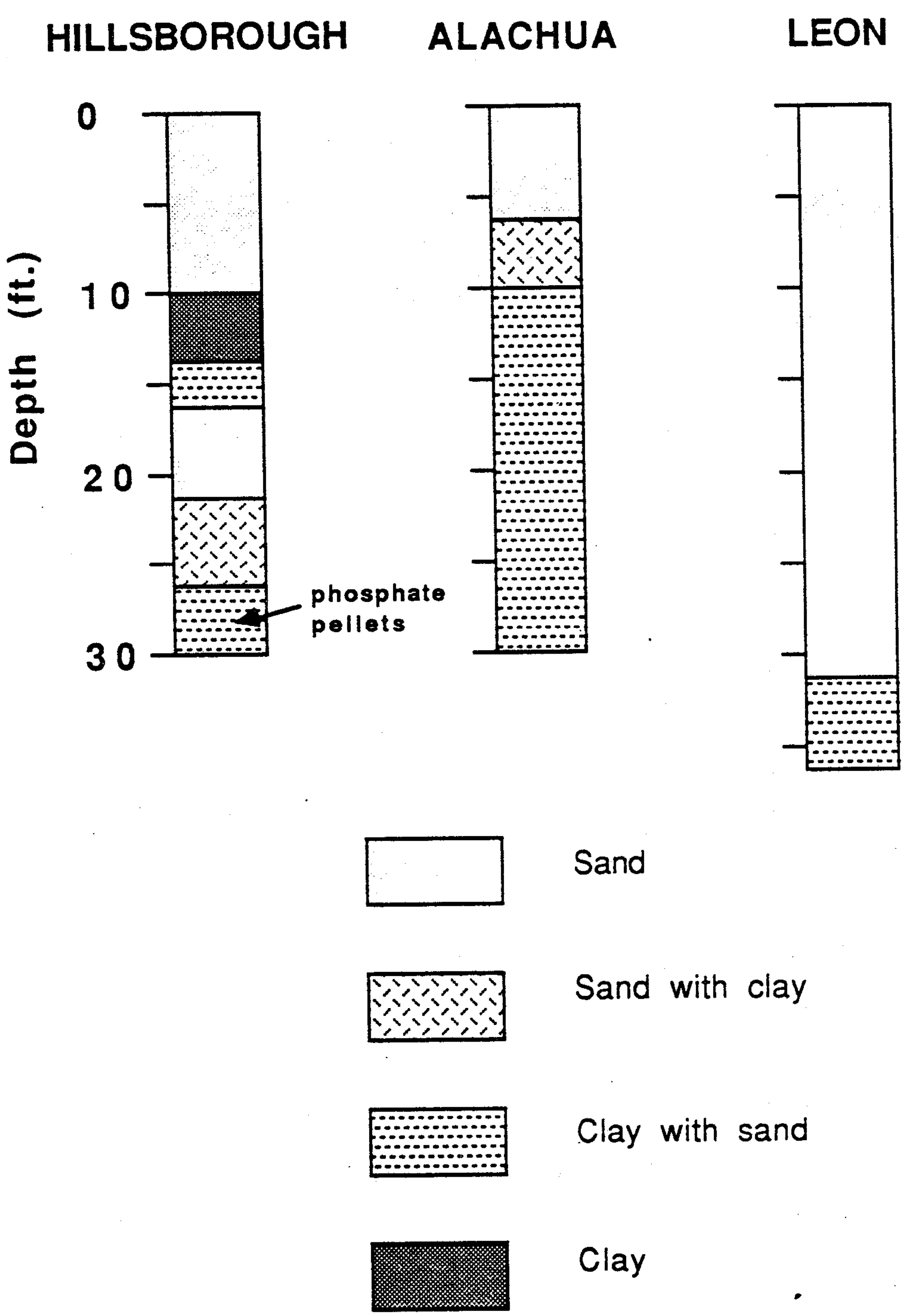


Fig. 35. Descriptive logs of cores recovered from stations A-C (Alachua County), H-B (Hillsborough County), and L-D (Leon County).

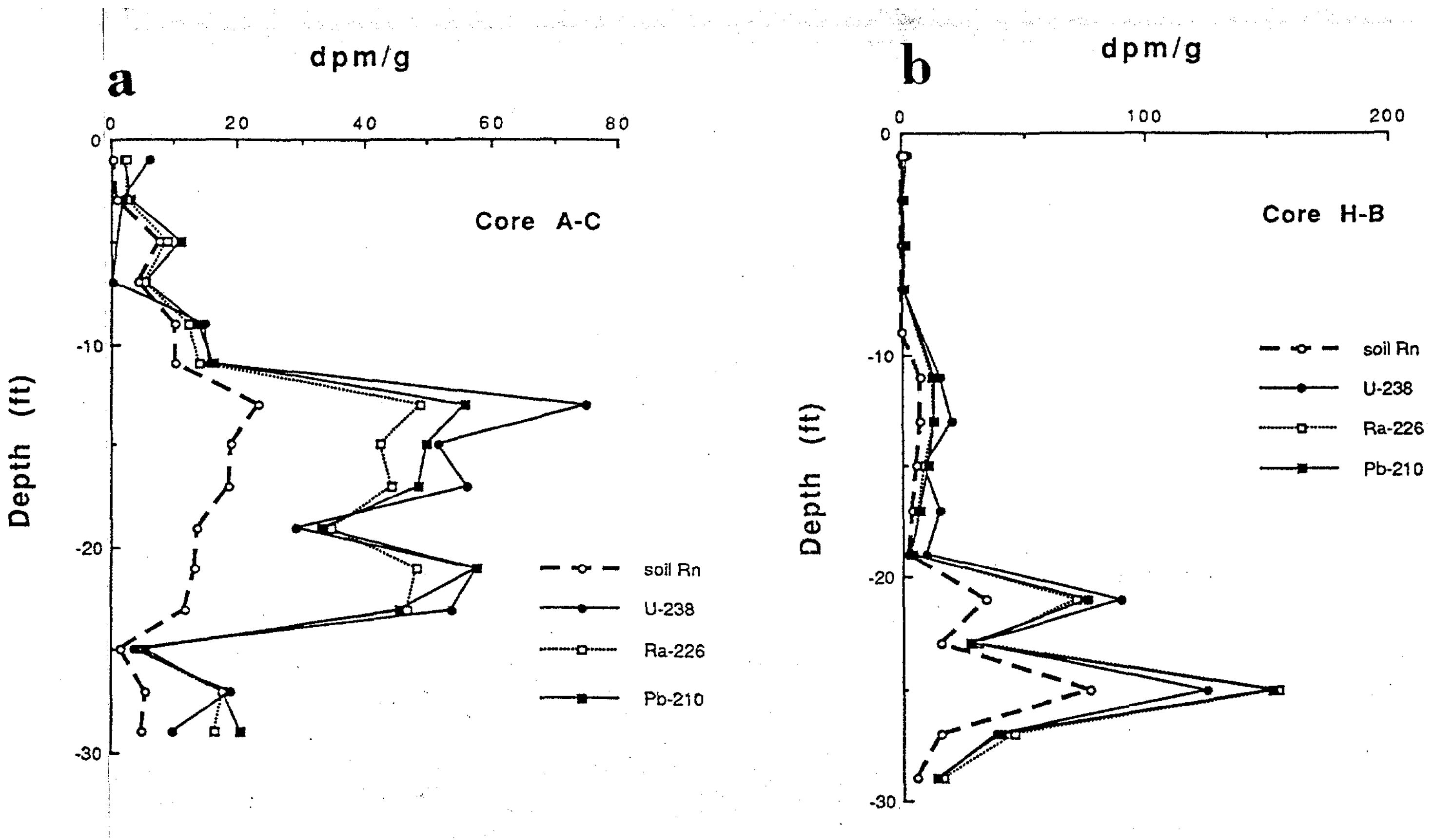


Fig. 36. Activities of the natural decay-series isotopes ^{238}U, ^{226}Ra, ^{210}Pb, and "available" ^{222}Rn *versus* depth for core samples: (a) A-C; and (b) H-B.

In terms of radon source strength, the measurements of “available” radon should be the best indication. In order to show this more clearly, we have plotted the soil ^{222}Rn measurements, together with the corresponding ^{226}Ra results, versus depth for cores A-C and H-B (Fig., 37). It is clear that the radon available for release from the soil closely parallels the radium distribution. In most samples emanated radon is about 50% of the ^{226}Ra activity or “potential” radon (Figs. 38 and 39).

It is interesting to compare these core results to the radon in water concentrations measured at the two monitor wells at each of the two corresponding stations: Alachua station C (Fig. 22c) and Hillsborough station B (Fig. 26b). At station A-C, the shallower well at 15 feet had a much higher radon concentration (up to over 60,000 pCi/L) than the 25-foot well (~10,000 pCi/L). This is not surprising in view of the radiochemical profiles which show the highest activities of all nuclides, as well as available radon, at about this core depth. The wells at station H-B are opposite, having higher concentrations in the deeper 30-foot well (~20,000 pCi/L) compared to the 15-foot well (5,000 - 10,000 pCi/L). This agrees with the general distribution of radionuclides in the core which has at maximum at about 25 feet below the surface. The fact that the water in the Alachua County station C shallow well has much higher radon concentrations than either of the wells at Hillsborough station B, is most likely a consequence of having the well depth at the Alachua site correspond almost exactly to the depth of maximum available radon.

The fact that the radon soil concentration and flux measurements tended to be higher at all the stations at the Alachua County test site compared to those measured in Hillsborough and Leon Counties must be related to the “source term” being significantly closer to the surface in Alachua County. Thus, the radon potential at these three comparative sites is very much a function of local geology.

Summary

If all of our results are combined and relationships between radon in water, soil radon, and radon flux investigated, the general trends discussed for each of the study sites still hold (see Tables 5, 6, and 7 for a statistical summary of each station). A plot of soil radon concentration versus radon in water for all stations (Fig. 40) shows that, overall, soil radon varied by over three orders of magnitude while most water results were all within one magnitude. A similar plot for radon flux versus water radon (Fig. 41) shows the same pattern. The only two of these parameters which are reasonably well correlated are radon flux

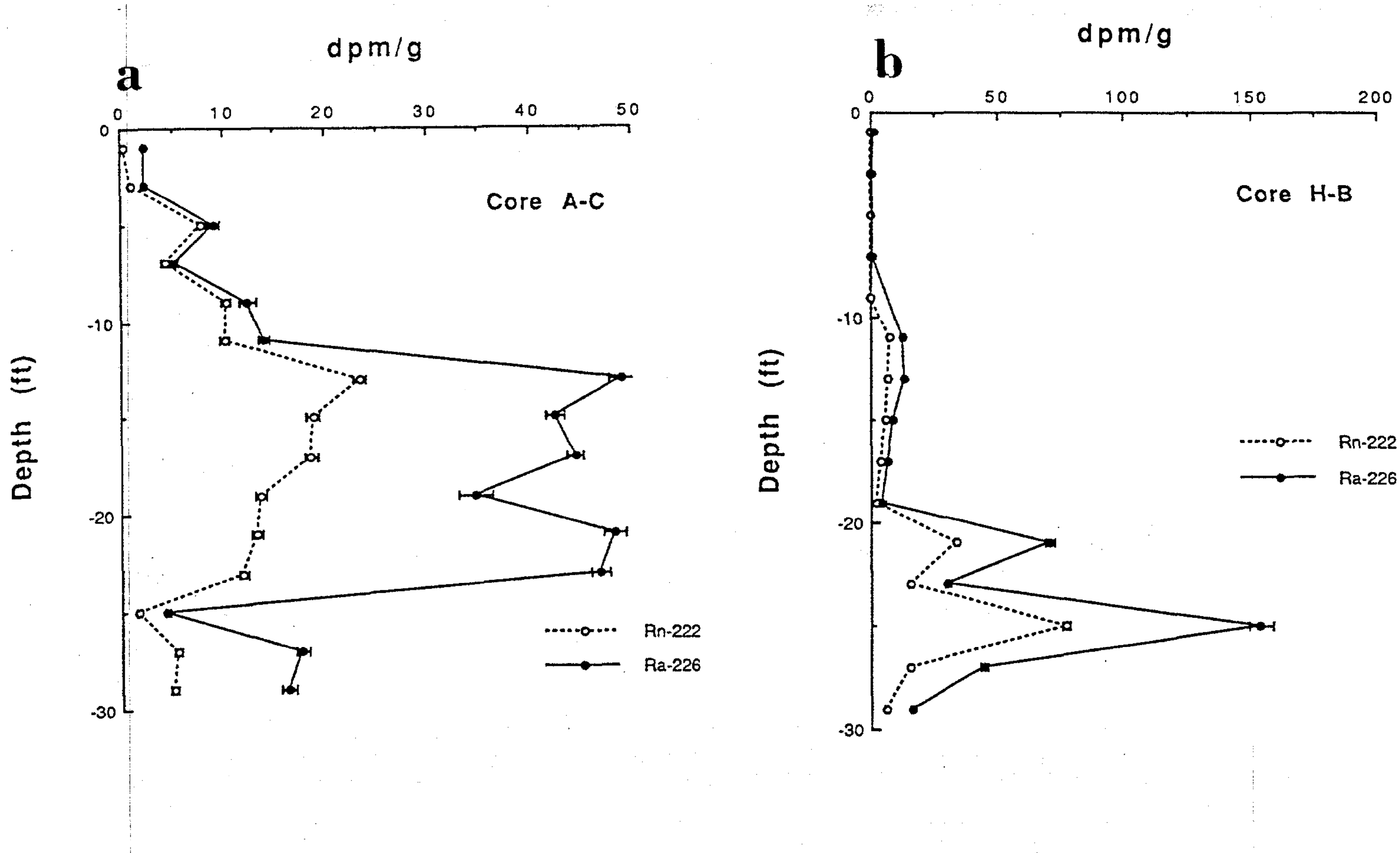


Fig. 37. Activities of ^{226}Ra ("potential" radon) and ^{222}Rn as determined by extraction and LSC *versus* depth for cores: (a) A-C; and (b) H-B.

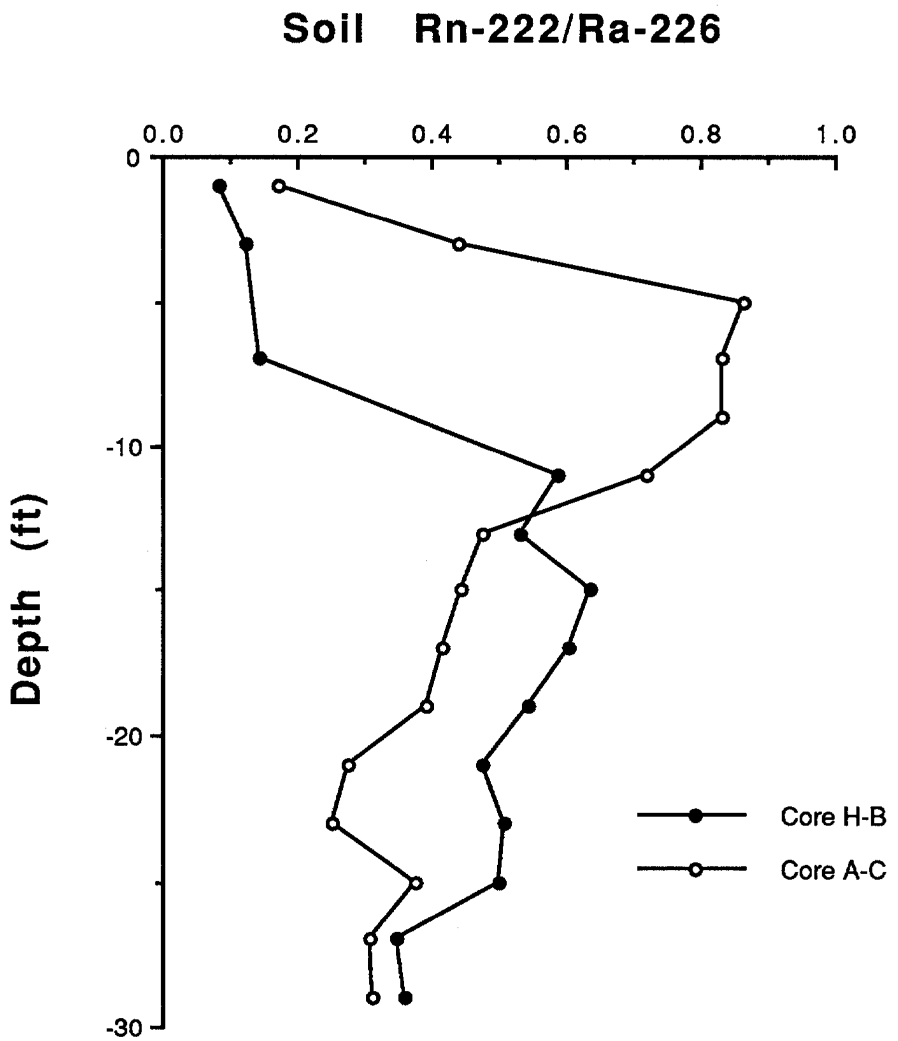


Fig. 38. Activity ratio of “available”-^{222}Rn/total-^{226}Ra *versus* depth in cores H-B and A-C.

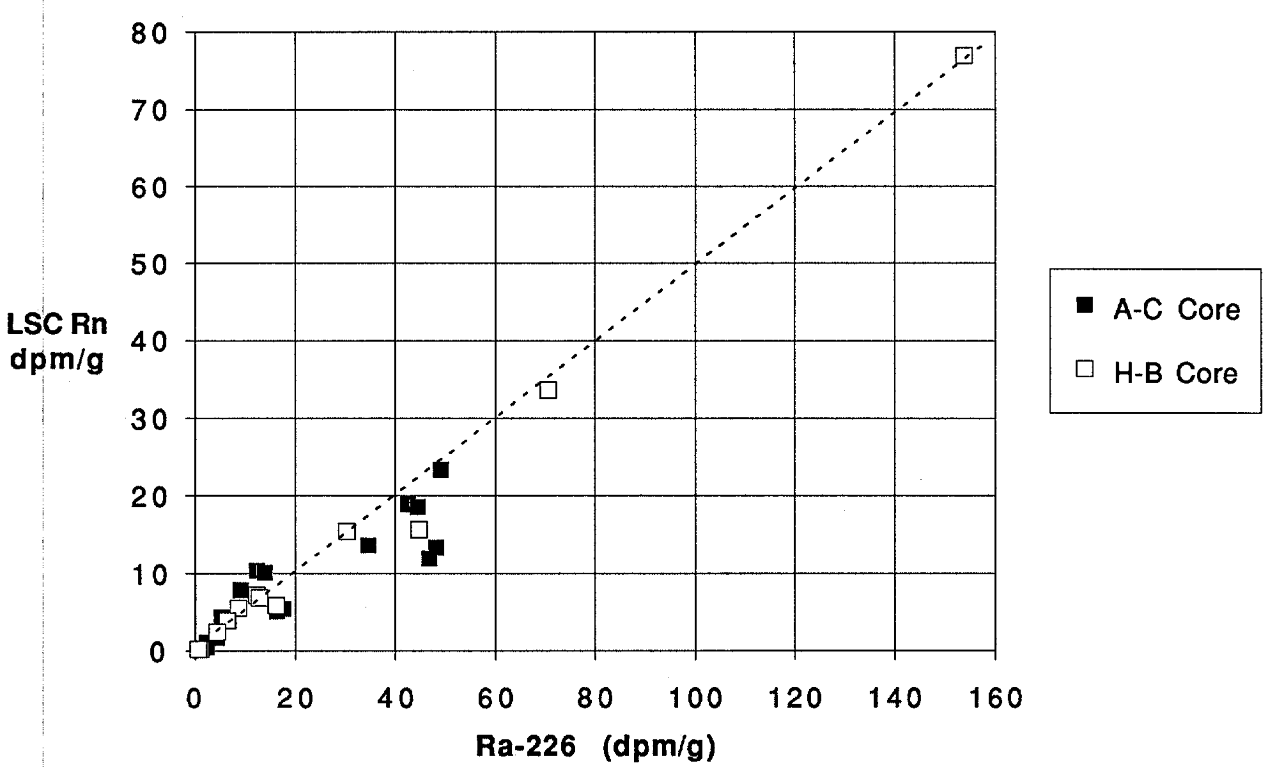


Fig. 39. Scatter plot of "available" ^{222}Rn *versus* total ^{226}Ra in soil samples from cores A-C and H-B. The trend line for an emanation coefficient of 0.5 is shown for comparison.

Table 5. Statistical summary by station of all results of radon in water measurements. Complete results for each station area given in the appendix.

Station No.	Minimum	Maximum	Average	sd	n
	pCi/L				
		Alachua County Site			
138	9931	17011	12720	2094	14
151	24175	38957	32111	4286	12
152	30933	40779	34857	3316	8
153	15886	23530	18489	2114	13
154	27246	47588	36556	4897	14
A15	9162	22385	14798	3509	14
A25	12071	37805	30229	6274	14
B15	27615	43341	34599	4119	14
B25	3862	39370	26221	8933	14
C15	1150	66150	28974	21920	12
C25	1150	19892	13388	7356	6
D25	1714	35045	25586	7874	13
E15	811	3951	1873	1210	5
E25	678	4524	3331	1597	5
F15	20316	33828	25600	3645	14
F25	7036	12535	9223	1383	14
FX	15342	26862	23338	3380	10
G15	7769	14907	10620	1696	13
H15	2969	11519	6263	3033	8
I15	4321	16750	11961	4023	13
J15	6120	19649	12682	5038	6
J25	282	2046	972	646	6
		Hillsborough County Site			
10	2718	4751	3876	593	12
11	8593	13119	11374	1222	14
18	15212	21617	18944	2173	15
A15	818	5565	3074	1521	12
A30	11023	24377	19821	3124	14
B15	2841	11918	7858	3291	14
B30	11301	20412	15602	2551	14
BX	2838	7434	5558	1440	11
C15	21168	38206	28818	4514	14
C30	1163	7609	3540	2240	14
D15	2930	9673	5848	2183	14
D30	17506	23516	20408	2065	14
E15	2482	8020	4786	1553	14
E30	17714	25848	21209	2135	14
F15	1471	7394	5696	1796	14
F30	5126	7662	6614	815	14
G15	15433	23539	20777	2050	13
G30	8854	14671	12158	1846	13
H15	16753	24478	21031	2397	8
H30	22708	36261	29109	4979	8

Table 5. Radon in water summary (continued).

Station No.	Minimum	Maximum	Average	sd	n
	pCi/L				
I15	9136	12174	10383	956	14
J15	30256	38172	33534	2279	14
K15	3257	7758	6200	1239	14
		Leon County Site			
A	--	--	--	--	--
B	<50	171	94	58	11
C	--	--	--	--	--
D	--	--	--	--	--
E	101	315	187	83	6
USGS	280	465	340	61	8

Table 6. Statistical summary by station of all results of radon in soil measurements. Complete results for each station area given in the appendix.

Station No.	Minimum	Maximum	Average	sd	n
	----------	pCi/L	----------		
		Alachua Test Site			
138	2.7	56	15	18	13
151	50	92	73	15	9
152	92	183	137	32	10
153	58	102	77	13	11
154	168	1472	495	360	14
A15	62	219	130	44	14
B15	21	76	41	16	14
C15	212	579	332	149	5
D25	70	120	95	19	14
E15	104	958	546	345	6
F15	126	307	209	55	14
G15	107	243	149	39	14
H15	97	2206	1737	511	13
I15	64	121	87	16	13
J15	155	276	225	38	8
		Hillsborough Test Site			
10	4	59	34	17	11
11	2	16	6	5	8
18	1	27	9	8	9
A15	1	17	5	5	14
B15	2	16	9	4	13
C15	228	1871	1056	467	15
D15	1	47	15	11	15
E15	35	366	204	91	15
F15	26	210	111	54	14
G15	92	859	412	196	15
H15	8	671	209	240	9
I15	2	135	82	40	14
J15	44	394	201	92	15
K15	12	120	35	27	15
		Leon Test Site			
A	25	86	39	18	12
B	30	78	49	12	12
C	12	37	26	7	13
D	25	80	38	16	13
E	30	58	42	10	13
USGS	18	52	32	11	7

Table 7. Statistical summary by station of all results for radon flux measurements. Complete results for each station given in the appendix.

Station No.	Minimum	Maximum	Average	sd	n
	----------	pCi/L	----------		
		Alachua Test Site			
138	0.0	0.3	0.1	0.1	9
151	0.2	1.6	0.7	0.5	6
152	0.4	1.9	0.9	0.6	5
153	0.3	0.8	0.5	0.2	7
154	1.0	63.1	14.5	22.0	7
A15	0.3	1.3	0.7	0.4	6
B15	0.1	0.5	0.3	0.1	10
C15	1.4	1.4	1.4		1
D25	0.4	1.8	0.8	0.4	8
E15	0.2	1.3	0.7	0.8	2
F15	0.6	2.0	1.1	0.5	10
G15	1.0	3.2	1.5	0.7	8
H15	1.5	44.7	15.5	12.8	8
I15	0.1	1.9	1.0	0.5	9
J15	0.2	2.3	1.4	0.7	7
		Hillsborough Test Site			
10	0.5	1.2	0.8	0.3	7
11	0.0	0.2	0.1	0.1	5
18	0.1	0.3	0.2	0.1	7
A15	0.0	0.2	0.1	0.1	7
B15	0.1	0.5	0.3	0.1	8
C15	4.9	9.5	7.7	1.5	9
D15	0.1	0.7	0.4	0.2	8
E15	0.9	2.6	1.7	0.6	7
F15	0.7	2.3	1.3	0.6	7
G15	1.0	2.6	2.0	0.6	5
H15	0.5	2.2	1.2	0.7	7
I15	0.2	1.1	0.6	0.3	6
J15	0.8	3.2	1.2	0.8	7
K15	0.1	0.7	0.3	0.2	7
		Leon Test Site			
A	0.2	0.3	0.2	0.0	7
B	0.2	1.0	0.5	0.2	8
C	0.1	0.2	0.2	0.1	9
D	0.3	0.5	0.4	0.1	9
E	0.2	0.4	0.3	0.1	9
USGS	0.2	0.3	0.3	0.0	7

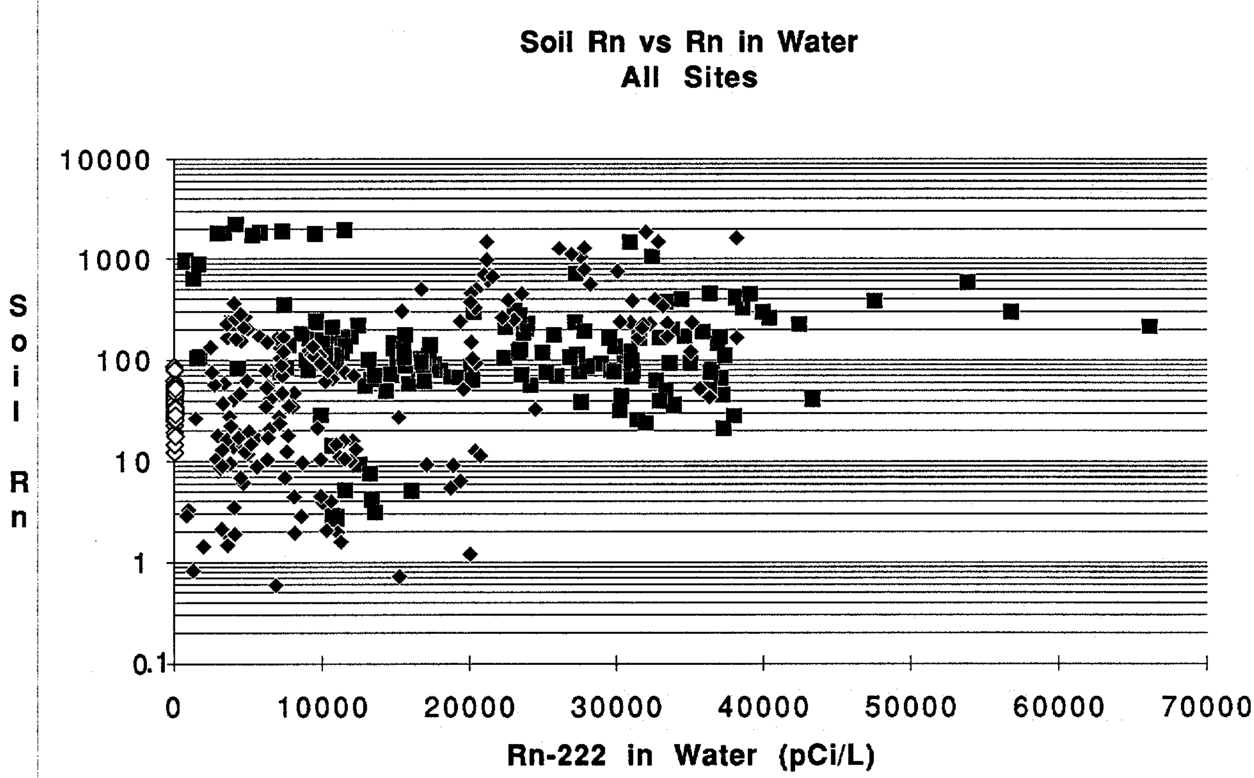


Fig. 40. Scatter plot of all soil gas concentration measurements made *via* charcoal canisters *versus* all groundwater radon measurements for all stations at all three test areas: Alachua County (solid squares); Hillsborough County (solid diamonds); and Leon County (open diamonds). A log scale has been used on the vertical axis in order to effectively display all soil gas concentration measurements which vary by over three orders of magnitude. Units of soil concentration are pCi/L.

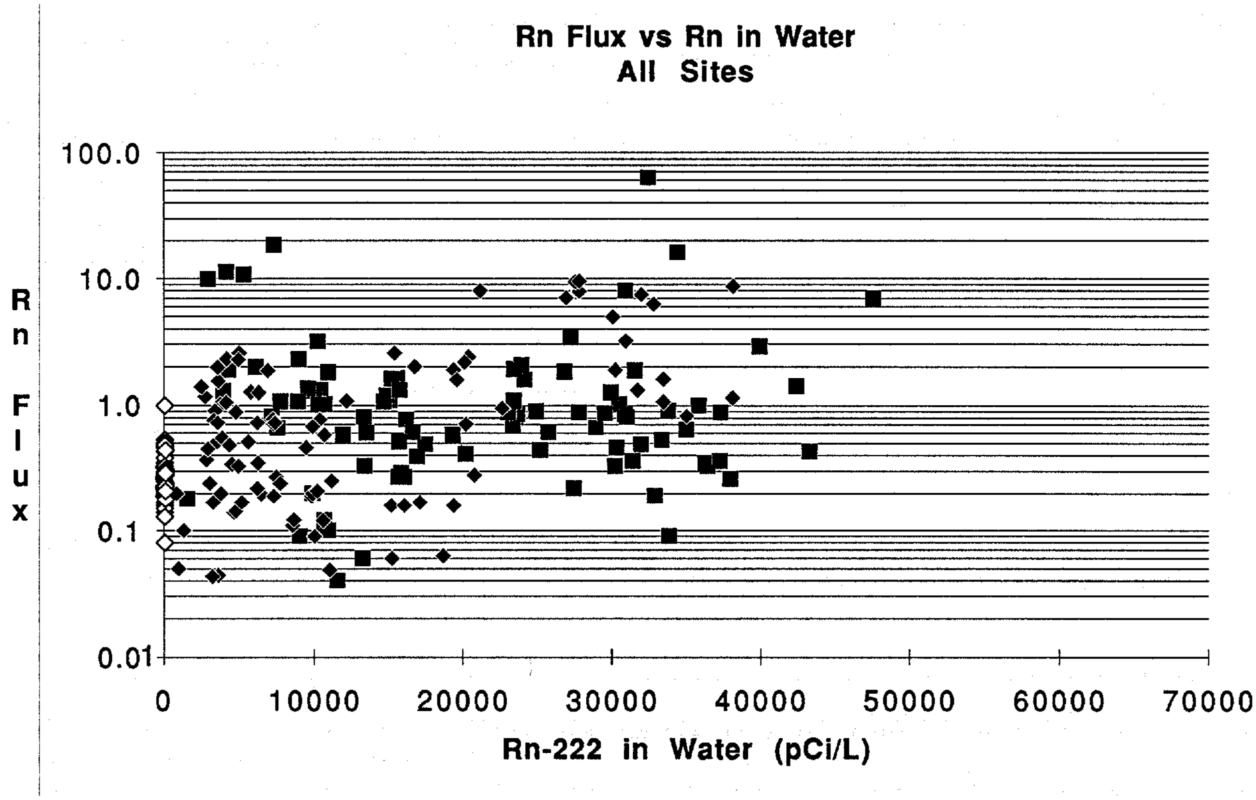


Fig. 41. Scatter plot of all radon flux measurements (pCi/m^2·sec) made versus all groundwater radon measurements for all stations at all three test areas: Alachua County (solid squares); Hillsborough County (solid diamonds); and Leon County (open diamonds). A log scale has been used on the vertical axis in order to effectively display all flux measurements which vary by almost three orders of magnitude.

and soil radon (Fig. 42), an expected result as the diffusional transport of radon depends upon the concentration gradient between soil and the overlying atmosphere.

In spite of the lack of direct correlations between these parameters, it is interesting to note that when the results from each study site are averaged, the three types of data all show the same general trend (Fig. 43). It is clear from these averaged results that the Leon County site is lowest in "radon potential" based on any of the three measurements. Likewise, the Alachua County site is highest based on all parameters, and the Hillsborough County site is intermediate. Although these conclusions are hardly surprising based on two years of measurements, this observation should be considered in light of the details of our individual measurements in order to evaluate how to best assess the potential source term for an area. It is clear that if a limited number of measurements are to be taken to evaluate the radon potential of an undeveloped site, that it would be preferable to make use of a parameter that is reasonably constant throughout the year. Otherwise, one can never be sure if a measurement or a limited set of measurements, is truly characteristic of that site. Our results plainly show that shallow groundwater is less variable in both time and space than soil concentrations or flux measurements. Since any of these measurements will eventually demonstrate the same general result when integrated over a long period at one study site, we suggest that water table aquifer measurements be made, at least in areas where the water table is shallow. This should provide less variable results than soil-based measurements and is thus more likely to produce a more accurate assessment of the radon potential of an undeveloped area.

RADON DAUGHTERS IN SHALLOW GROUNDWATER

As part of our research on the source of excess polonium in shallow groundwaters of Florida, we have analyzed a series of selected samples for all three radon daughters, ^{210}Pb, ^{210}Bi, and ^{210}Po. Previous studies in Florida, for the most part, have been limited to only ^{222}Rn and ^{210}Po analysis. Our approach has been to analyze samples from selected stations at the Alachua, Hillsborough, and Leon test sites. Samples collected for this purpose from the Leon County area were from wells which were used as part of our preliminary study and included wells in Wakulla County as well. Results of our analyses (Fig. 44, a-c) indicate that although there is some disequilibrium between ^{210}Bi and ^{210}Pb, it is not typically as great as that between ^{210}Po and its predecessors. In the Leon/Wakulla area, ^{210}Pb and ^{210}Bi are near equilibrium with ^{210}Po in small to moderate excess. The greatest disequilibrium between ^{210}Bi/^{210}Pb and ^{210}Po/^{210}Bi occurs in the only sample which contained measureable dissolved sulfide (Table 8). Results from the Alachua test site show a deficiency in Bi relative

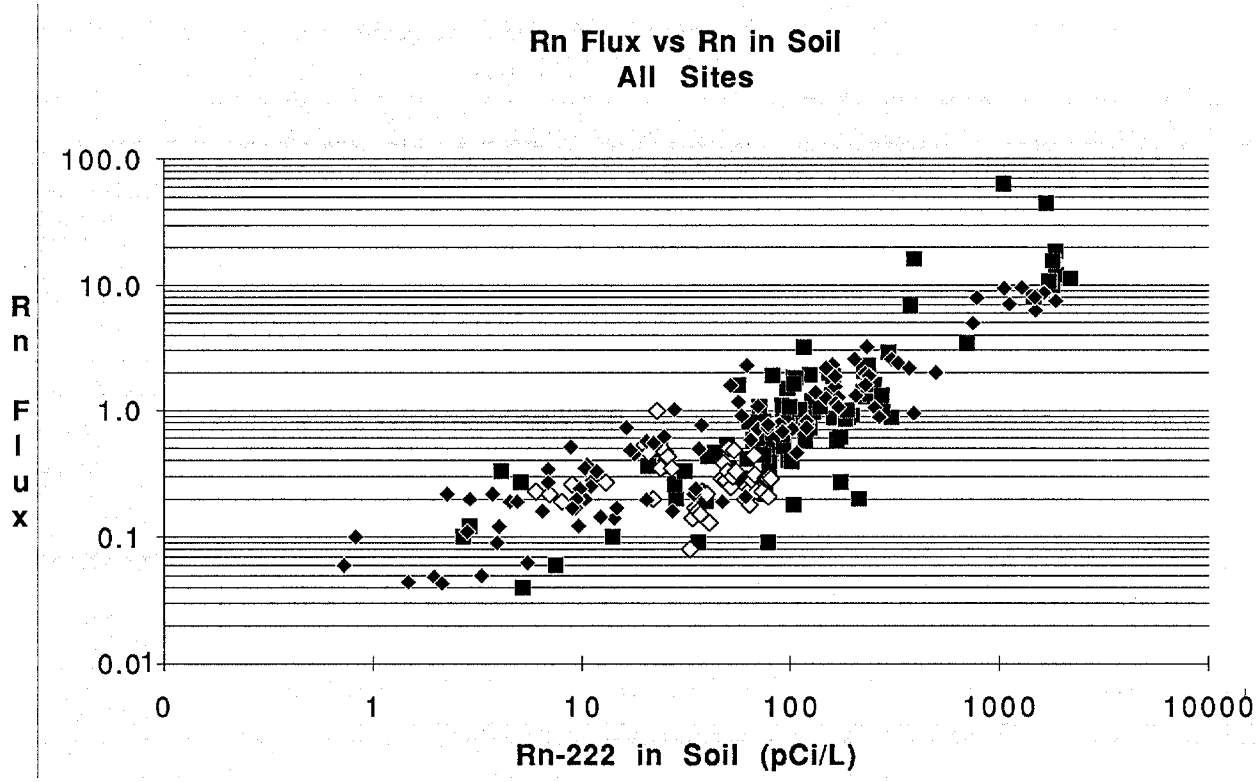


Fig. 42. Log of the radon flux values versus log of all soil gas concentration results for all three test areas: Alachua County (solid squares); Hillsborough County (solid diamonds); and Leon County (open diamonds). The most highly correlated data set is that for Hillsborough County with an $r^2 = 0.87$. The r^2 of all data is only 0.40.

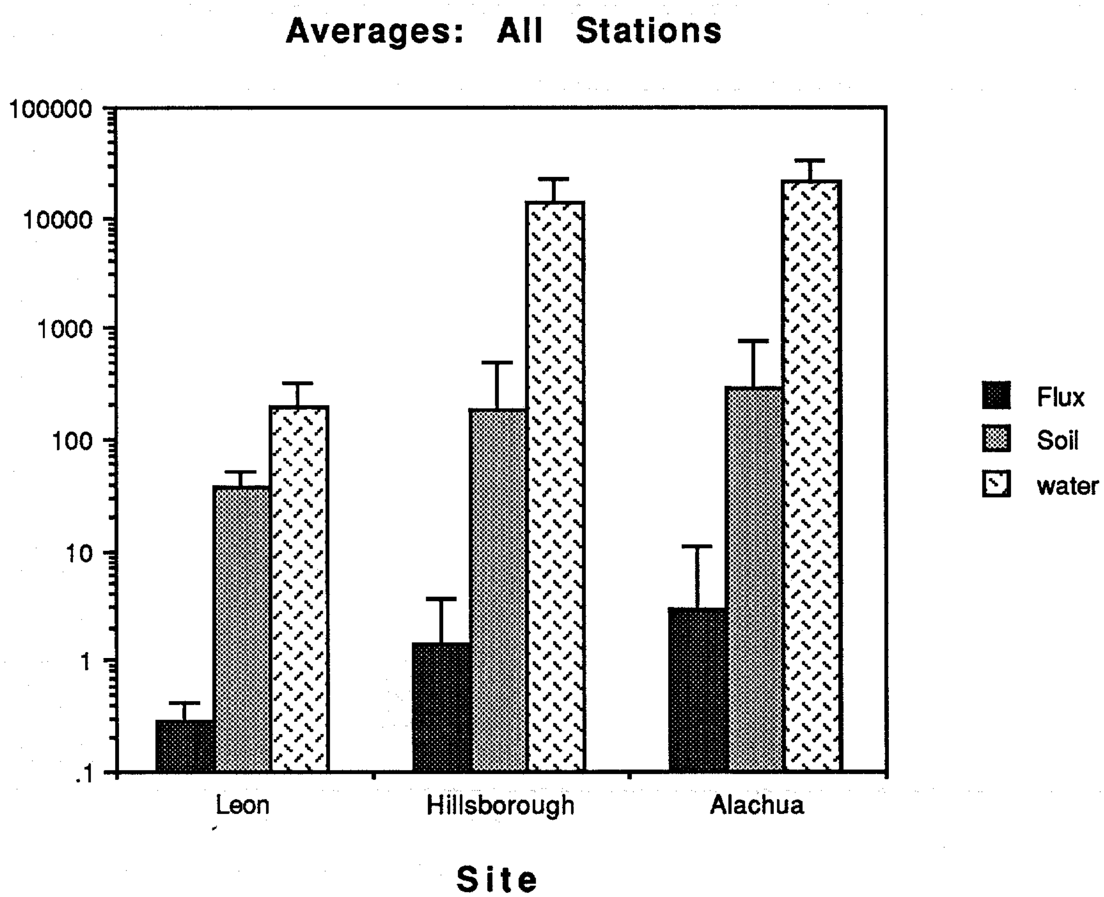


Fig. 43. Averages and standard deviations of measurements of radon flux (pCi/$m^2 \cdot$sec); radon concentrations in soil *via* charcoal canister deployments (pCi/L); and radon concentration in groundwater results (pCi/L) from all stations at all three test areas.

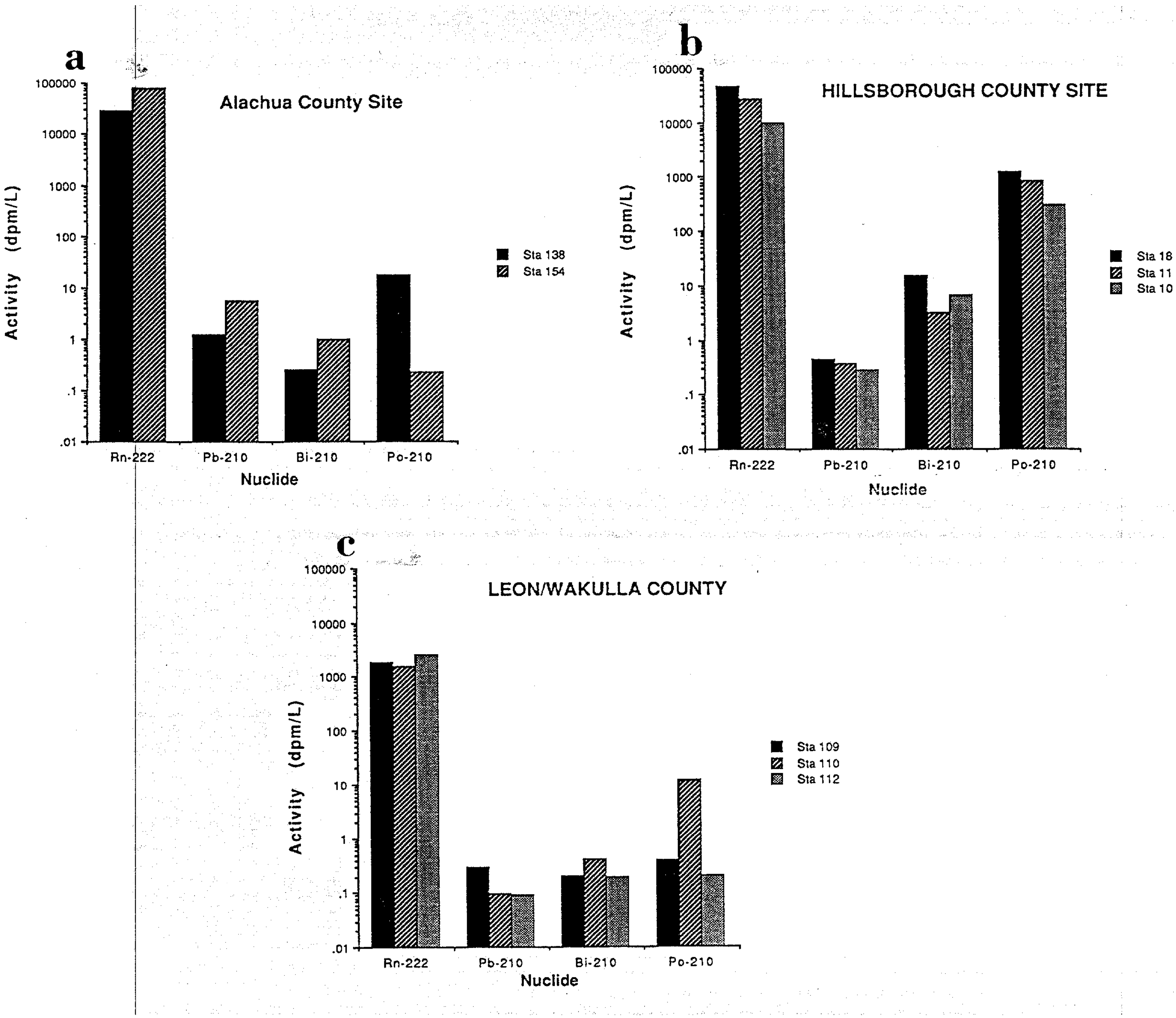


Fig. 44. Bar graph illustrating the disequilibrium relationships in the radioactive series ^{222}Rn-^{210}Pb-^{210}Bi-^{210}Po in groundwater samples from: (a) Alachua County (b) Hillsborough County; and (c) Leon/Wakulla Counties. All stations with significant excess activities of ^{210}Po are characterized by pH less than 5.0 and contain measureable sulfide.

Table 8. Radiochemical results for ^{210}Pb, ^{210}Bi, and ^{210}Po from shallow aquifers in Florida. Measurements of pH and H_2S measured in the same samples also reported.

Station No.	Sampling Date	^{210}Pb	^{210}Bi (dpm/L)	^{210}Po	pH	H_2S (µM/L)
			Leon/Wakulla County			
109	1/11/88	0.30 ± 0.03	0.21 ± 0.14	0.40 ± 0.02	6.10	0.0
110	2/5/88	0.10 ± 0.04	0.42 ± 0.04	11.80 ± 0.30	4.60	5.2
112	2/5/88	0.09 ± 0.04	0.20 ± 0.05	0.21 ± 0.04	7.15	0.0
			Alachua County			
138	5/26/88	1.24 ± 0.09	0.25 ± 0.17	16.6 ± 0.6	4.70	3.9
154	5/27/88	5.24 ± 0.14	0.97 ± 0.15	0.22 ± 0.07	5.10	0.0
			Hillsborough County			
10	6/30/88	0.16 ± 0.06	6.80 ± 0.14	374 ± 3	3.90	24.7
	7/14/88	0.46 ± 0.08	6.52 ± 0.21	238 ± 4	--	16.5
	7/28/88	0.75 ± 0.08	6.62 ± 0.11	686 ± 17	4.27	20.6
11	6/30/88	0.59 ± 0.10	3.31 ± 0.14	856 ± 15	4.90	15.7
	7/14/88	0.28 ± 0.08	3.15 ± 0.19	879 ± 20	--	17.2
	7/28/88	1.33 ± 0.07	3.86 ± 0.08	916 ± 18	4.80	14.0
18	4/15/88	0.36 ± 0.06	15.4 ± 0.3	1350 ± 15	3.70	18.4
	6/30/88	0.52 ± 0.08	15.5 ± 0.2	1320 ± 18	4.50	18.8
	7/14/88	0.48 ± 0.08	16.1 ± 0.4	1312 ± 32	--	20.6

to Pb, but a moderate excess of Po in the sulfide-bearing station and is deficient at the other well. Hillsborough County shows the largest excess of ^{210}Bi relative to ^{210}Pb (activity ratios ~10-40) as well as a spectacular excess of ^{210}Po to ^{210}Bi (activity ratios up to >200). Thus, whatever the process is that mobilizes polonium, it may effect bismuth as well but to a much lesser extent. These results confirm that the presence of high activities of ^{210}Po in shallow groundwaters is normally not associated with high activities of its predecessors, i.e., the polonium is unsupported.

During the course of this study, we collected and analyzed water samples for ^{210}Po and water quality parameters at six stations at the Alachua County test site (Fig. 45), 10 stations at the Hillsborough County test site (Figs. 46, a-b), and 2 stations at the Leon County site (Fig. 47). Examination of the time-series records of these results not only shows that polonium is much lower in the shallow aquifers of our Alachua and Leon County test sites compared to wells at the Hillsborough site, but that the polonium activities are much more variable than the radon in water results from the same wells (compare to the time-series plots for radon in these shallow aquifers: Alachua - Figs. 22 and 23; Hillsborough - Figs. 26, 27, and 28; Leon - Fig. 31).

We have compared these temporal variations with rainfall records obtained from nearby monitoring stations (Fig. 48). None of the variations in polonium concentration appear to vary in an obvious, systematic manner with rainfall. In fact, as can be seen by comparing different stations on the same time-series plot, trends in neighboring stations may occasionally be quite different. This is also true for different levels in the aquifer. For example, notice the completely different trends for ^{210}Po in the two levels at station C in Hillsborough County (Fig. 46a). The deeper 30-foot well shows a well-defined maximum during the winter of 1988-89 while the shallower, 15-foot well remains relatively low until the following 1989-90 winter and remains high into the summer.

Earlier studies sponsored by FIPR and the Florida Department of Environmental Regulation (FDER) performed by our research group have also showed that ^{210}Po, the last radioactive member of the ^{238}U decay chain, is often present in great excess over its predecessors in shallow groundwaters of west central Florida (Burnett *et al.,* 1987a, 1987b; Cowart *et al.*, 1988). The search for the explanation of this anomalous situation lead us ultimately into the field of microbiology because of our observations that high levels of ^{210}Po were invariably associated with S^{2-}, formed by sulfur bacteria (see Table 8). As a member of group 6B in the periodic classification of the elements together with sulfur, tellurium, and

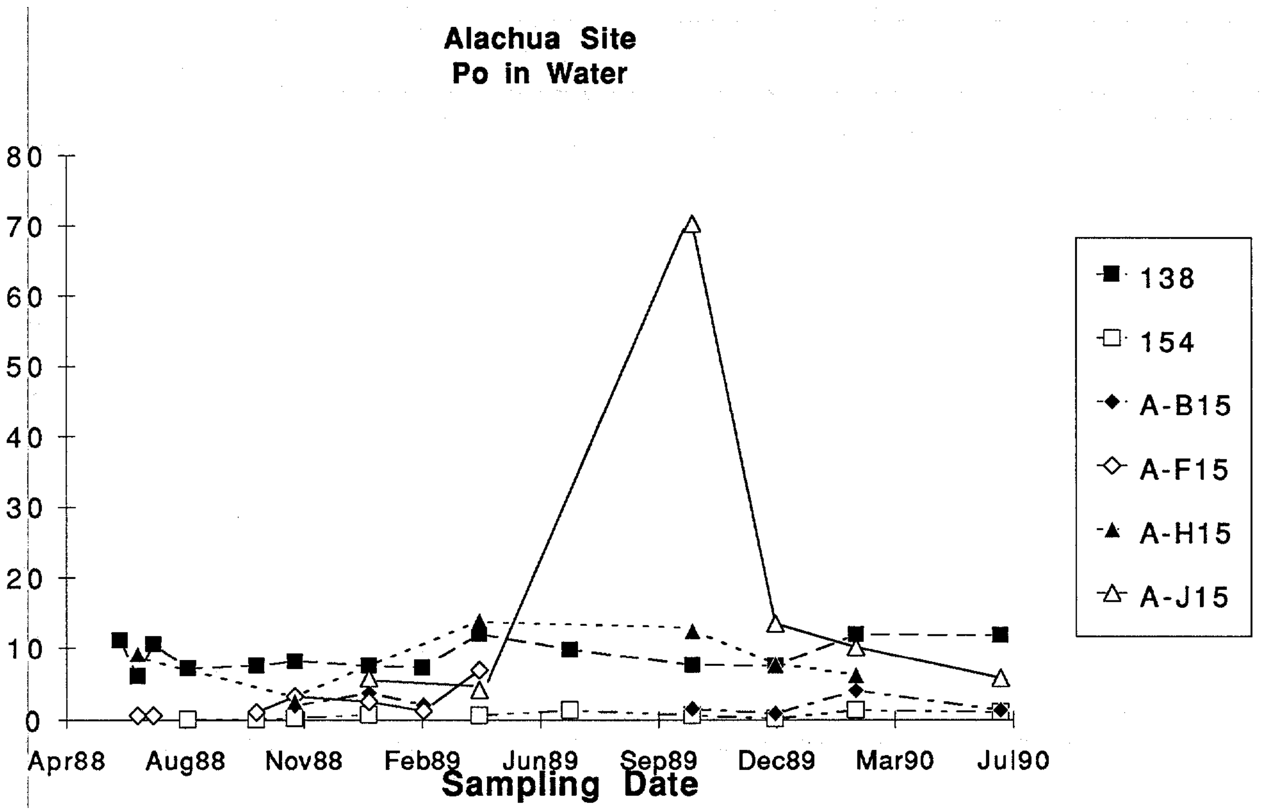
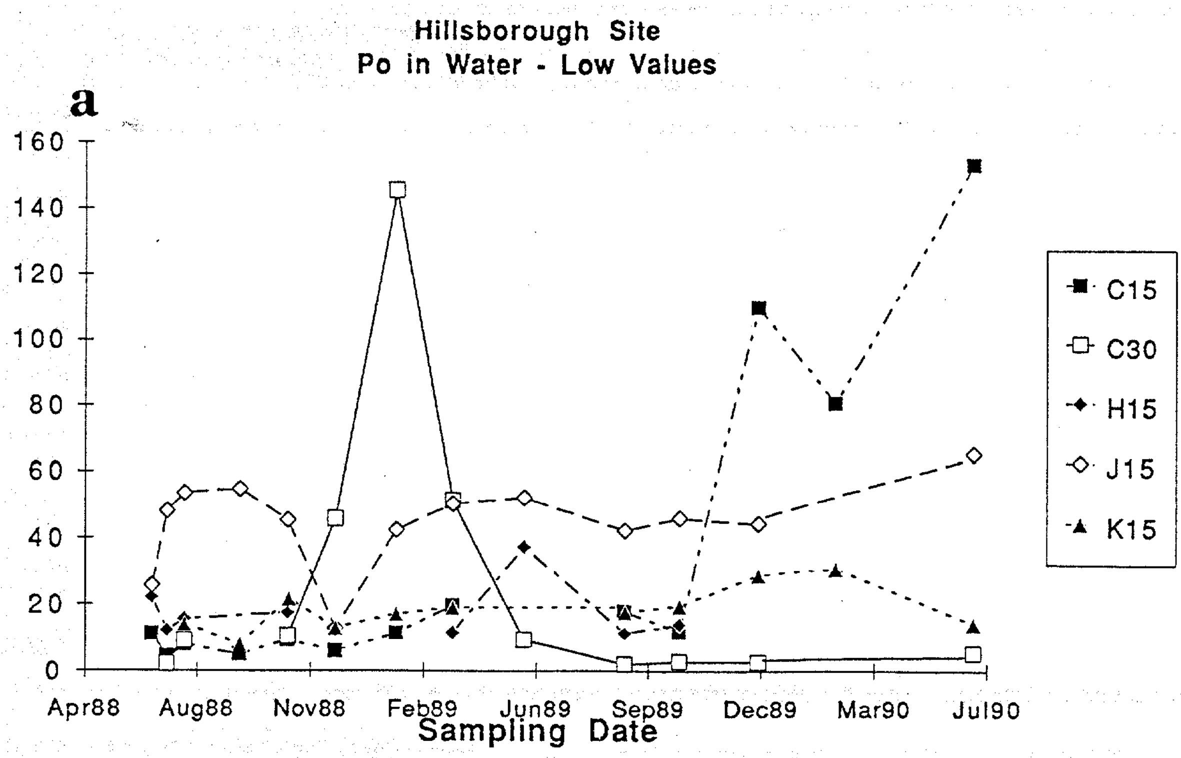


Fig. 45. Time-series plot of ^{210}Po activities (pCi/L) in shallow groundwater samples from wells at the Alachua County test site.



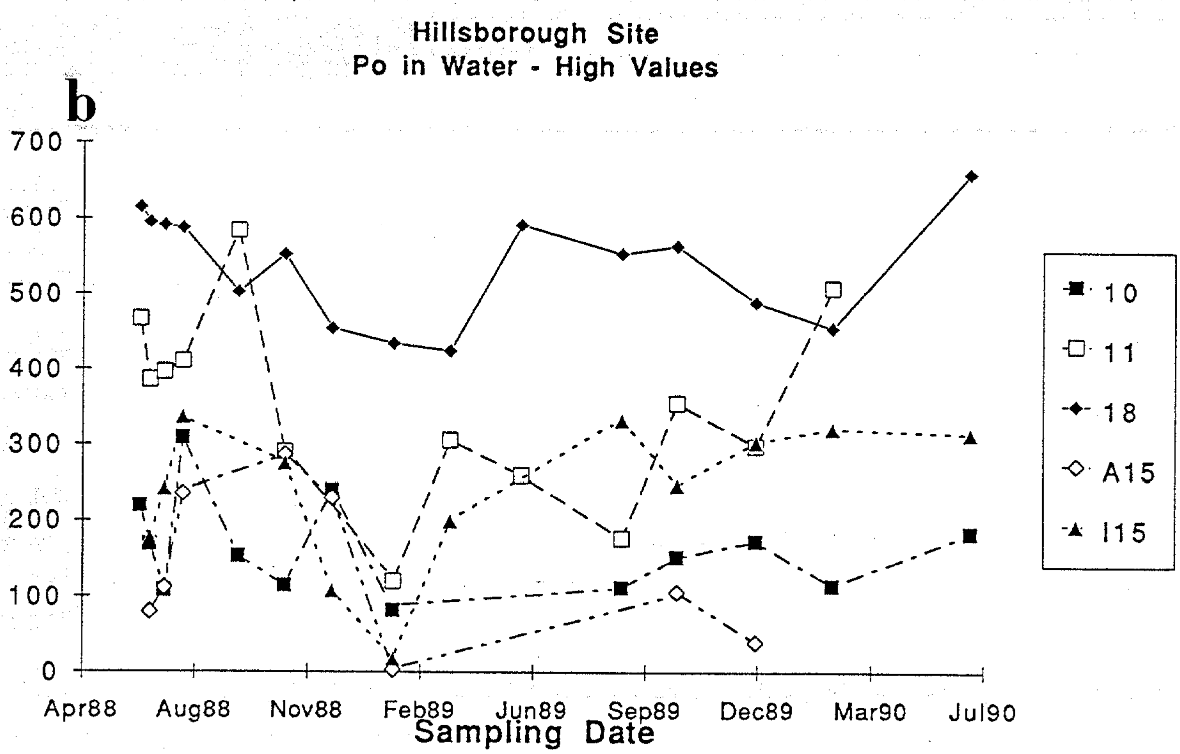


Fig. 46. Time-series plot of ^{210}Po activities (pCi/L) in shallow groundwater samples from wells at the Hillsborough County test site for: (a) low values; (b) high values. Note that wells C15 and C30 are sampling two different depths at the same location.

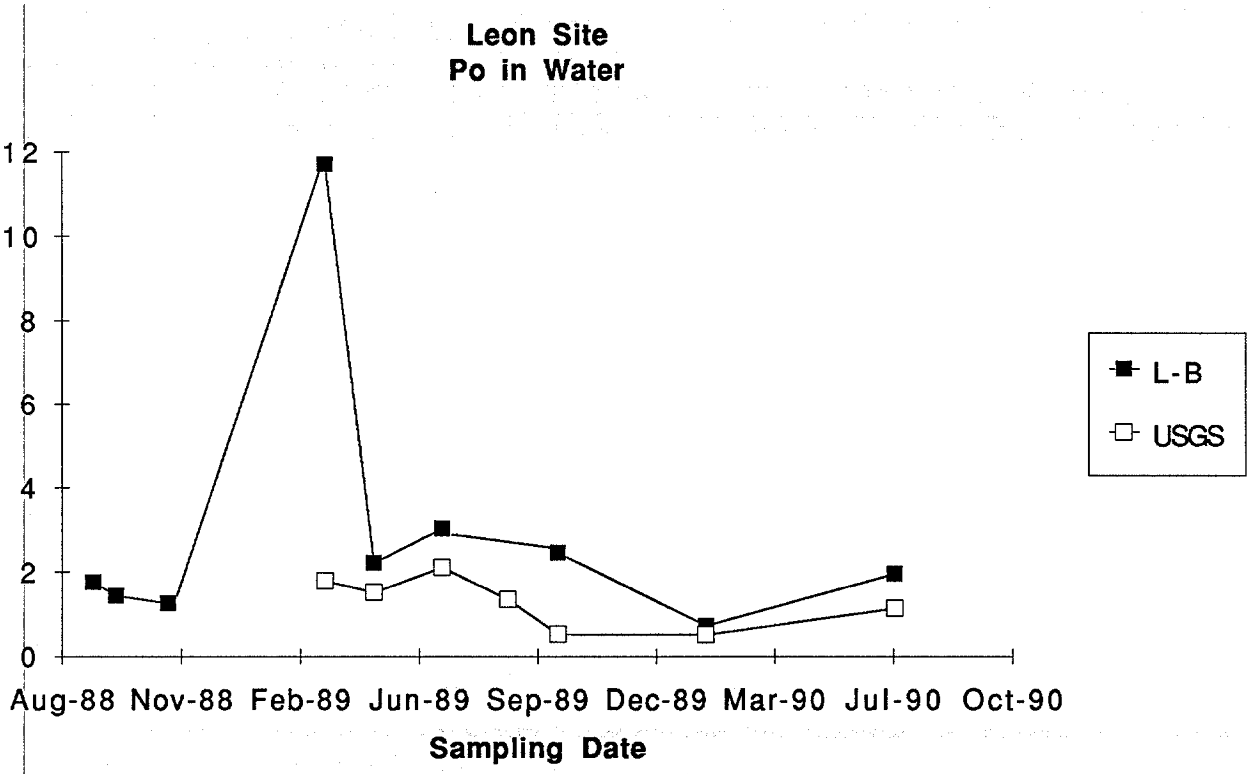


Fig. 47. Time-series plot of ^{210}Po activities (pCi/L) in groundwater samples from wells at the Leon County test site.

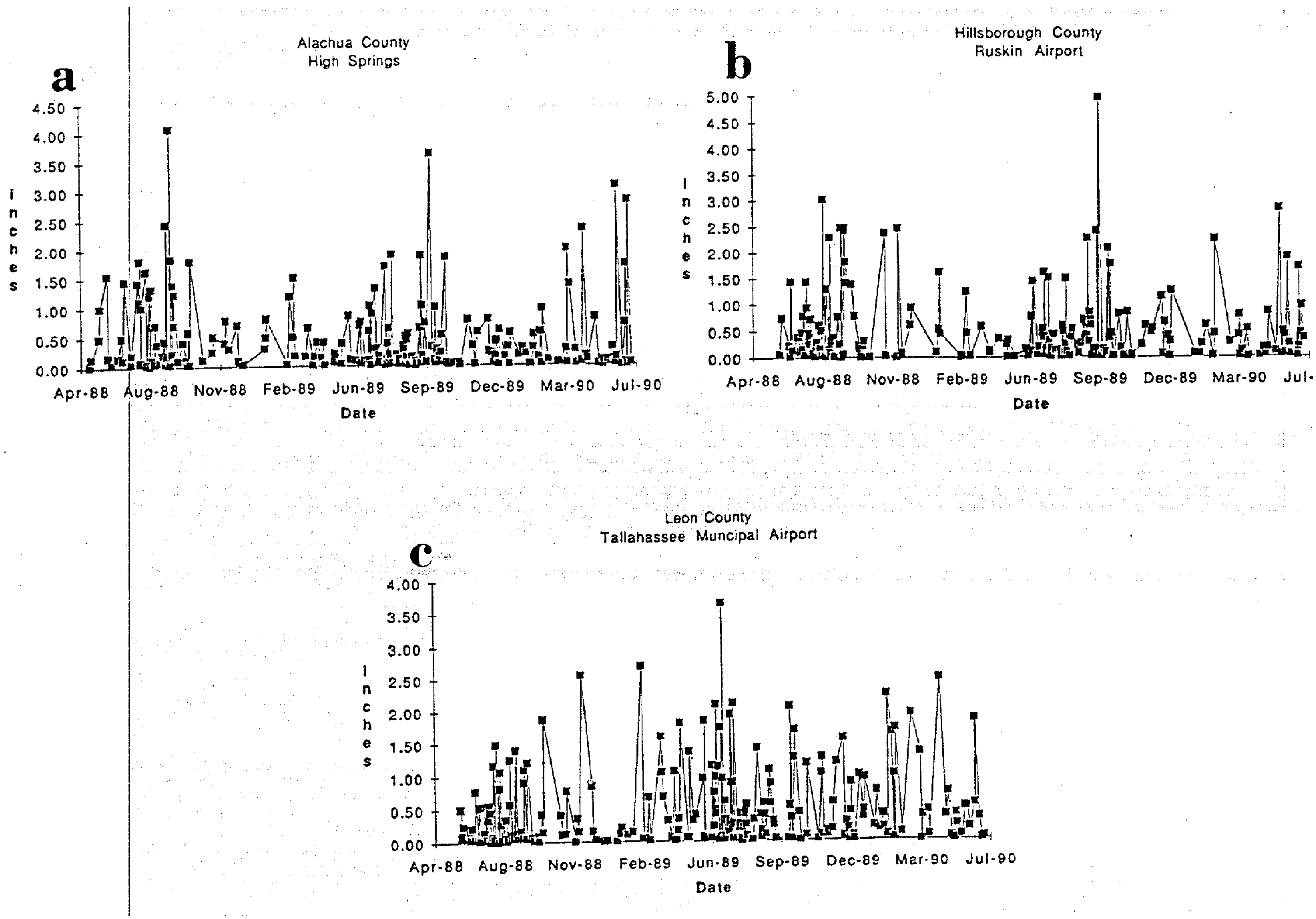


Fig. 48. Twenty-four hour rainfall records during the course of this study for: (a) High Springs, near the Alachua County test site; (b) Ruskin Airport, near the Hillsborough County test site; and (c) Tallahassee Muncipal Airport, near the Leon County test site.

selenium -- the so-called “sulfur group” -- polonium may be influenced by sulfur bacteria living in the aquifer, which encounter polonium in their search for sulfur.

An experiment, published by our group last year (Harada *et al.*, 1989) monitored both polonium and bacterial growth in a water sample taken from a shallow well at station 18 at the Hillsborough County test site which routinely contains in excess of 500 pCi/L ^{210}Po. Our experiment simultaneously monitored sulfide, soluble and particulate polonium, and bacterial growth over a period of several hours after collection of one large water sample in a collapsible plastic “cubitaner” (Fig. 49). Sulfide should decrease by the action of sulfide-oxidizing bacteria at a rate proportional to the increase of bacterial cells within the sample. Furthermore, if polonium is affected in the same manner as sulfide, there should be a corresponding decrease in soluble polonium and an increase in particulate polonium over the same time interval. Bacterial growth rates were evaluated by a “pulse labeling method” developed by LaRock *et al.* (1988). This method “pulses” subsamples with a labeled nucleic acid precursor (^{3}H-adenine) in such a way that the true growth rate of the bacterial community is determined.

Our results showed that soluble polonium displayed a drop in concentration of almost one order of magnitude over the time span (<40 hrs) during which sulfide decreased from close to 30 µM to 0. Bacterial growth, as seen by pulse labeling results, show a sharp rise during the first several hours of the experiment with a doubling time of approximately 6 hours, the same as the apparent half-life of polonium uptake during the same period. After the first 10 hours or so of the experiment, there is a change in slope of all parameters with a doubling time of about 22 hours for the bacterial growth, close to the half-life of the next segment of polonium uptake (20.7 hrs). Sometime after the 30-hour mark, when the sulfide concentration had dropped to zero and no further bacterial growth is seen, the soluble ^{210}Po remains more-or-less stable from about that time to the end of the experiment. These data show that soluble polonium is largely converted to particulate polonium over a time scale of about one day and this decrease responds to a disappearance of the water’s sulfide content and concomitant increase in bacterial cells. The apparent decrease in “total” ^{210}Po is significant and probably represents accumulation of bacterial growth on the walls of the container used in the experiment.

The most reasonable interpretation of these results is that transformation from soluble to particulate polonium is accomplished by inadvertent uptake by bacteria, perhaps in a manner resembling the metabolic transformation of sulfide to sulfur (or sulfate) by active sulfide-oxidizing bacteria. Our results clearly document the fate of dissolved polonium during a

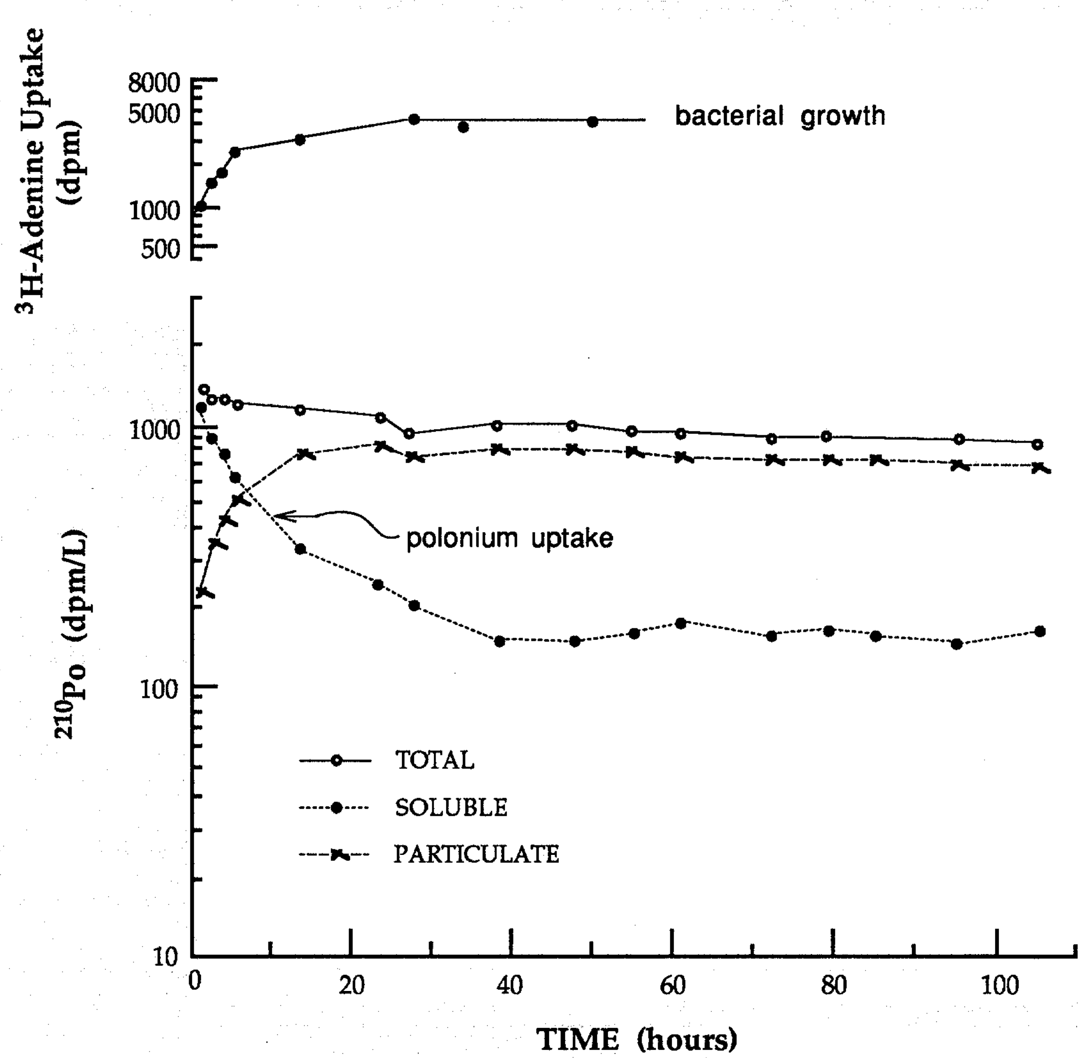


Fig. 49. Variation of bacterial growth, soluble, particulate, and total ^{210}Po with time in a well water sample from station 18, Hillsborough County test site. Bacterial growth, monitored by the rate of uptake of ^{3}H-adenine into nucleic acids, closely follows the trend of the transformation of soluble to particulate polonium observed in this experiment (from Harada *et al.*, 1989).

sulfide oxidation in groundwater. This led us to suspect that the source of the dissolved polonium in the aquifer may also be related to bacterial growth.

It is well known that sulfate reducing bacteria (SRB) may utilize solid phase sulfate as a sulfur source. Zajic (1969) reported that microbial sulfate reduction may be responsible for solubilization of gypsum and Bolze *et al.* (1974) and McCready and Krouse (1980) showed that SRB are capable of metabolizing barite ($BaSO_4$). Fedorak *et al.* (1986) demonstrated that bacteria utilizing the SO_4^{2-} of $(Ba,Ra)SO_4$ sludges, dissolved Ba^{2+} and $^{226}Ra^{2+}$ from the sludge with the concurrent production of S^{2-}.

A possible, yet admittedly tentative relationship between bacterial growth and polonium release may be seen upon examination of the relationships between ^{210}Po and bacterial activity at the same station used for our experiment (Fig. 50). Although there are few data points for bacterial growth activity, there is a strong suggestion of a relationship between polonium activity and bacterial growth at this station. None of the other parameters monitored at this station, including ^{222}Rn, display variations similar to ^{210}Po and bacterial growth. The bacterial growth rates may be related to temperature or other climatic patterns in this area. It is possible, for example, that the supply of organic matter to the aquifer microbes may vary during the year. Growth rates were actually slightly negative during a cold, very low rainfall period centered around December, 1988--a period when the ^{210}Po concentrations were also very low.

After seeing clear evidence of polonium <u>uptake</u> during the sulfide oxidation, most likely by sulfide oxidizing bacteria, we hypothesized that polonium <u>release</u> could also be controlled by bacteria. Our initial assumption was that bacteria appear to "confuse" Po with S in their metabolic processes and are able to solublize it in the reductive portion of the cycle, and ultimately precipitate it in the oxidative, or energy generating phase. Further research in our laboratory, however, has shown that while bacteria do seem to be actively involved in polonium cycling, our initial assumptions were in part incorrect. It now appears that it is the surface charge on the bacterial envelope that adsorbs polonium. For example, we have observed that if cells are killed by the addition of penicillin, the attached polonium immediately returns to solution (Burnett and LaRock, 1988).

Although further work will obviously be necessary to fully resolve the complexities of the ^{210}Po cycle in shallow aquifers, the following observations can be made: (1) ^{210}Po is often in great excess of secular equilibrium with its radioactive predecessors ^{210}Pb and ^{210}Bi by up

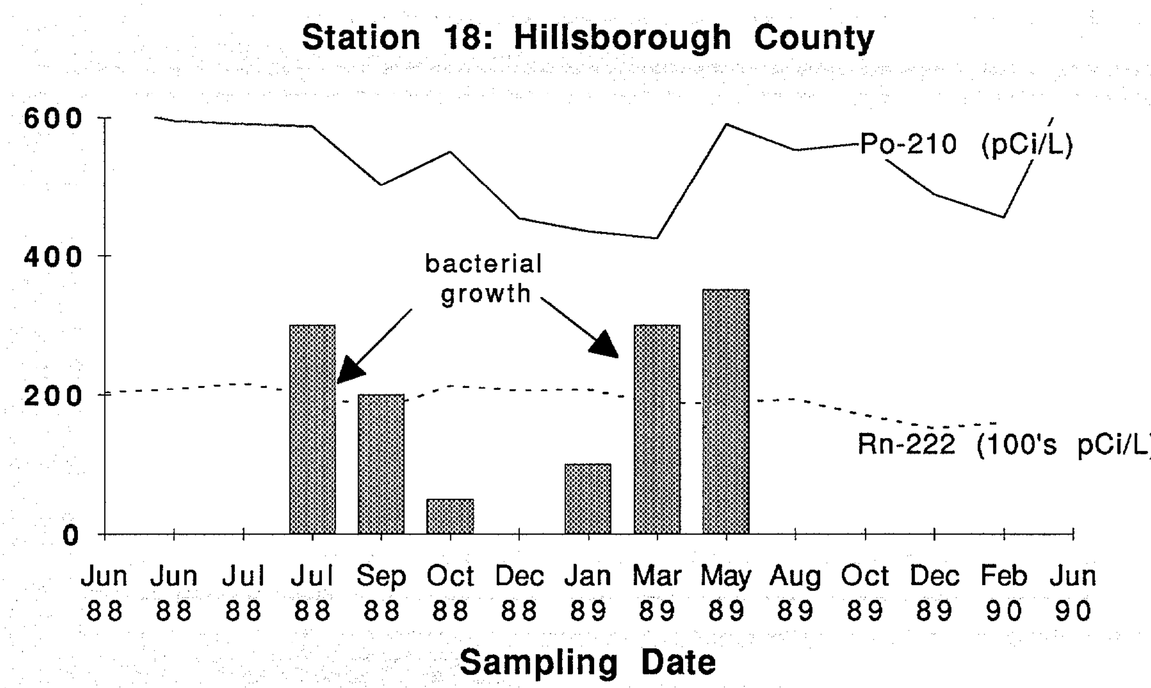


Fig. 50. Variation of ^{210}Po and ^{222}Rn activity (pCi/L) as well as relative bacterial growth rates (shown by bars) over the last two years at the same station in Hillsborough County where our uptake experiment was performed (Fig. 3-28). Radon activities have been divided by 100 in order to express them on the same scale.

to 3 orders of magnitude; (2) this disequilibrium is often accompanied by a lesser excess of ^{210}Bi over ^{210}Pb; (3) the shallow groundwaters which are significantly enriched in ^{210}Po are invariably characterized by low pH (<5.00) and contain reduced forms of sulfur; (4) most polonium in these enriched waters exist in a form which does not coprecipitate with iron hydroxide implying that it is not present as a "free" cationic species (Harada *et al.,* 1989); and (5) a conversion of soluble to particulate polonium occurs after a sample is collected over a time scale of a few days during sulfide oxidation. The last finding, together with the observation that bacterial growth occurs at the same time and approximately the same rate as polonium transformation, leads us to suspect that polonium is being "processed" by sulfur bacteria residing in these shallow aquifers.

REMOVAL OF RADON AND POLONIUM BY WATER PURIFICATION

In an effort to determine what type of water purification system is most efficient at removing radionuclides from groundwater, we designed a simple experiment to simultaneously evaluate four common types of water purification systems (Pig. 51). Four standard purification cartridges were installed in-line at an existing well (Station 18) in our test site in Hillsborough County. As previously discussed in this report, we have a considerable amount of data on this well and have shown that it is consistently high in ^{210}Po (~500 pCi/L) and ^{222}Rn (~20,000 pCi/L). The experiment was designed so that all tanks can be isolated and the well water can be cycled through any tank to evaluate its effective removal efficiency. We also installed flow meters to enable us to determine if a discernible change in removal efficiency occurred after a certain volume was passed through any of these cartridges.

Our experiment was designed so that purification tank #1 processed water through 1.5 cubic feet of 20 x 40 mesh granular activated carbon (GAC). Tank #2 contained an equal quantity of manganese greensand, tank #3 a standard water softening agent (Cullex resin), and tank #4 contained a mixed resin bed (both anion and cation exchange) for nearly complete deionization. We tested all four tanks a total of 10 times for radon removal and 8 times for polonium purification during the course of this study. Untreated water from station 18 was collected at the same time for comparison to results from water samples which passed through the purification systems. With the exception of the first two samplings, we flushed each tank out with at least 50 gallons of well water from station 18 before samples were collected for analyses. A total of approximately 500 gallons of water was processed through each of these tanks by the end of the study. Although some of the early results for radon implied that substantial uptake was occurring, this was apparently an artifact of sampling caused by

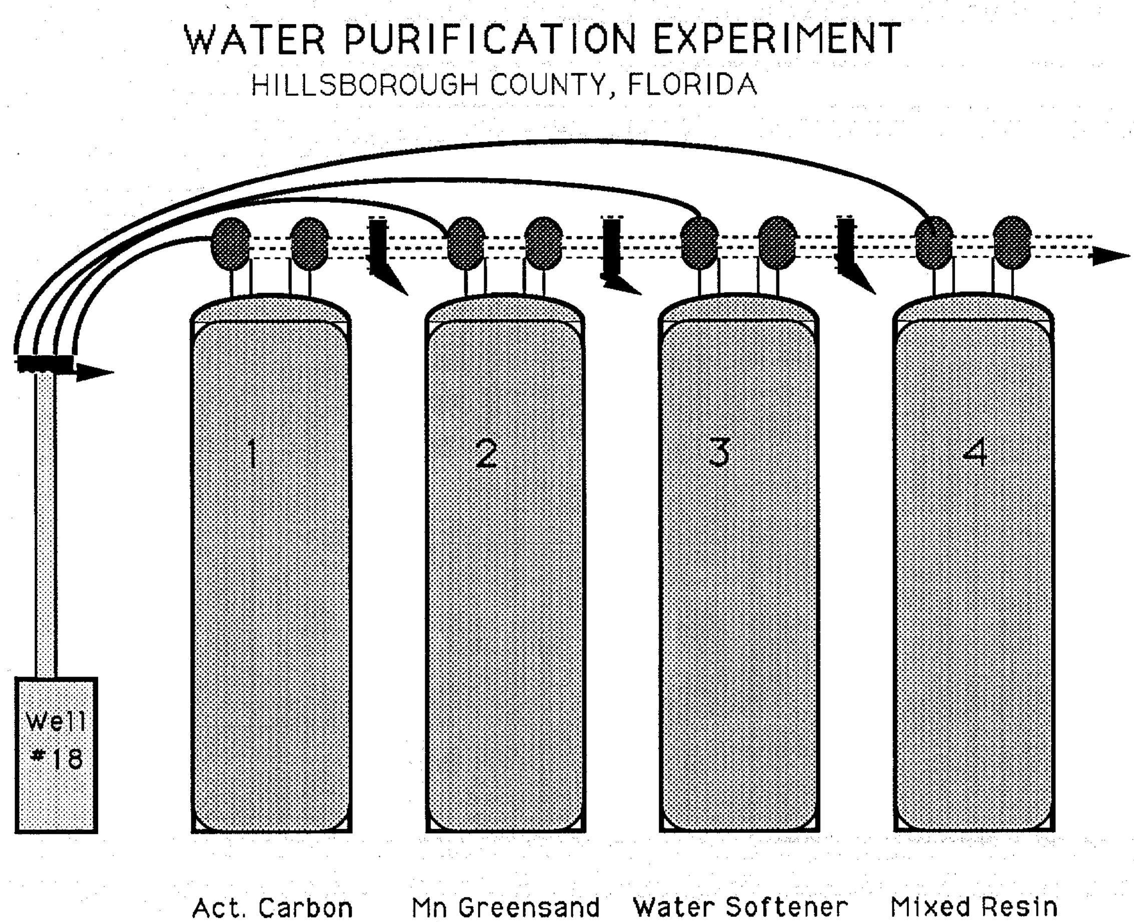


Fig. 51. Diagrammatic representation of an experiment performed to evaluate various water purification systems to assess removal of radon and polonium from shallow well water. The four filtration cartridges were filled with activated carbon, manganese greensand, a proprietary water softening agent, and a mixed resin bed.

insufficient flushing. The apparent low concentrations were a result of decay of radon inside the tanks since the last sampling. After this problem was resolved, the results became much more internally consistent. All results, for both radon and polonium, as well as for temperature, pH, and conductivity measurements, are given in tabulated form in Appendix Table A-7.

After excluding the results obtained when insufficient rinse volumes had been used, we averaged the result from each treatment system as well as the unprocessed water. The radon results (Fig. 52) clearly show that only GAC has a significant effect on radon removal. The carbon is very effective, removing greater than 99% of the initial radon. Note that the results from all three other purifiers are virtually the same with measured radon activities equivalent to 91±l% of the untreated water. This may actually imply that there is no effective radon removal by any of these 3 systems but the apparent 9% removal is simply a consequence of incomplete flushing, even when a 50-gallon rinse was used.

Our results concerning radon removal by GAC are consistent with the results reported by previous investigators including Lowry and Lowry (1988). In several other studies radon has been shown to be about 99% removed by GAC, compared to influent waters. With constant flow through a GAC bed, a steady-state condition will eventually be reached where the adsorption of radon onto the carbon is just balanced by radioactive decay. If the flow is interrupted, as in our experiment, the radon will decay and the site will be available for subsequent adsorption. Thus, the GAC bed may last almost indefinitely, especially for domestic use where flow rates are modest. In actual practice, the capacity of the GAC units would most likely be limited by adsorption of other species (metals, organics, etc.) in the influent water.

The polonium results also show that activated carbon worked most effectively although all the treatment systems demonstrated substantial polonium uptake (Fig. 53). Both the GAC and mixed resin bed had removal efficiencies of greater than 99% compared to the untreated well water. The manganese greensand also has a high removal efficiency of 98% while the water softener was somewhat lower at about 95%. None of the removal efficiencies, for either radon or polonium, varied significantly during the course of our study, even after more than 500 gallons had been processed through each of the tanks.

Although GAC systems apparently provide an effective means of removing radionuclides from domestic water supplies, a potential drawback is the buildup of gamma radiation caused

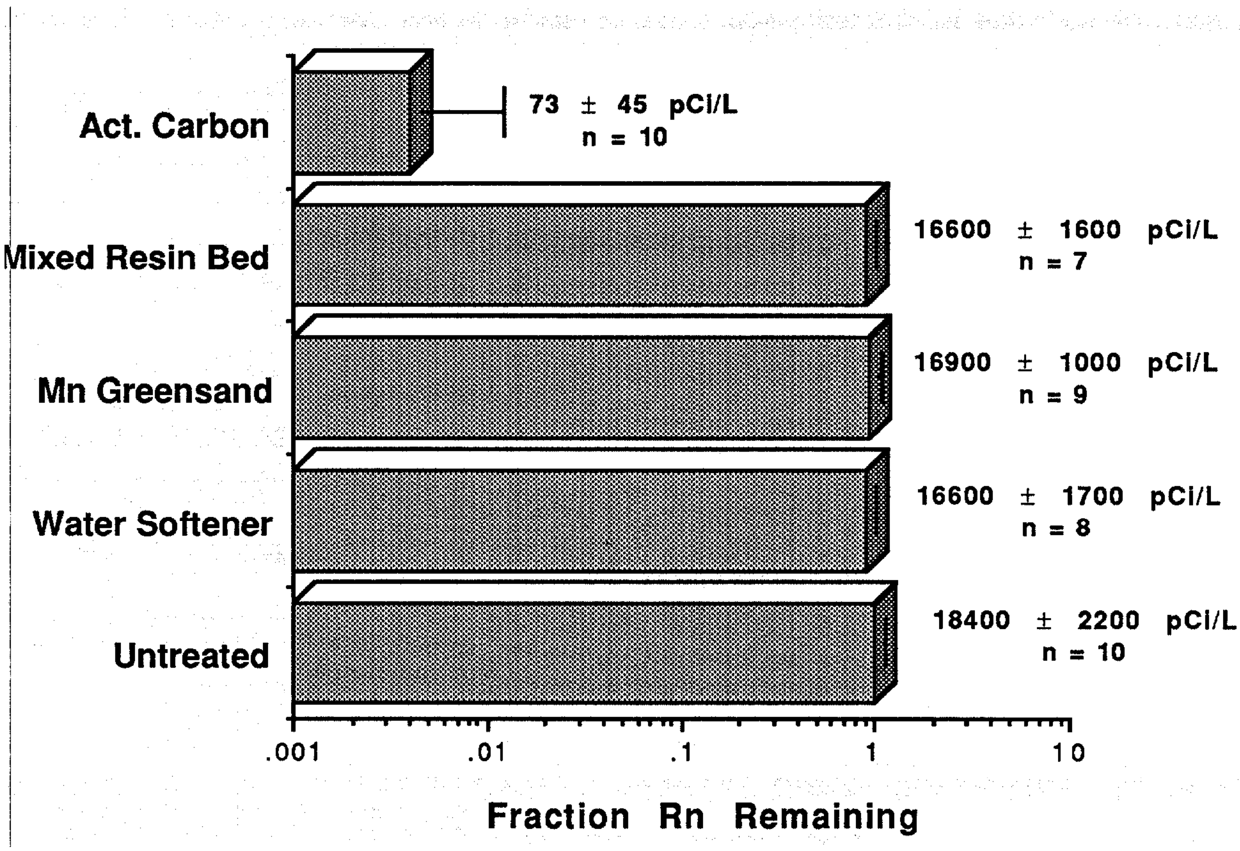


Fig. 52. Mean, standard deviation, and number of measurements of the radon concentrations in treated water compared to unprocessed water from well 18, Hillsborough County test site. The activated carbon removed over 99% of the radon present in this well water.

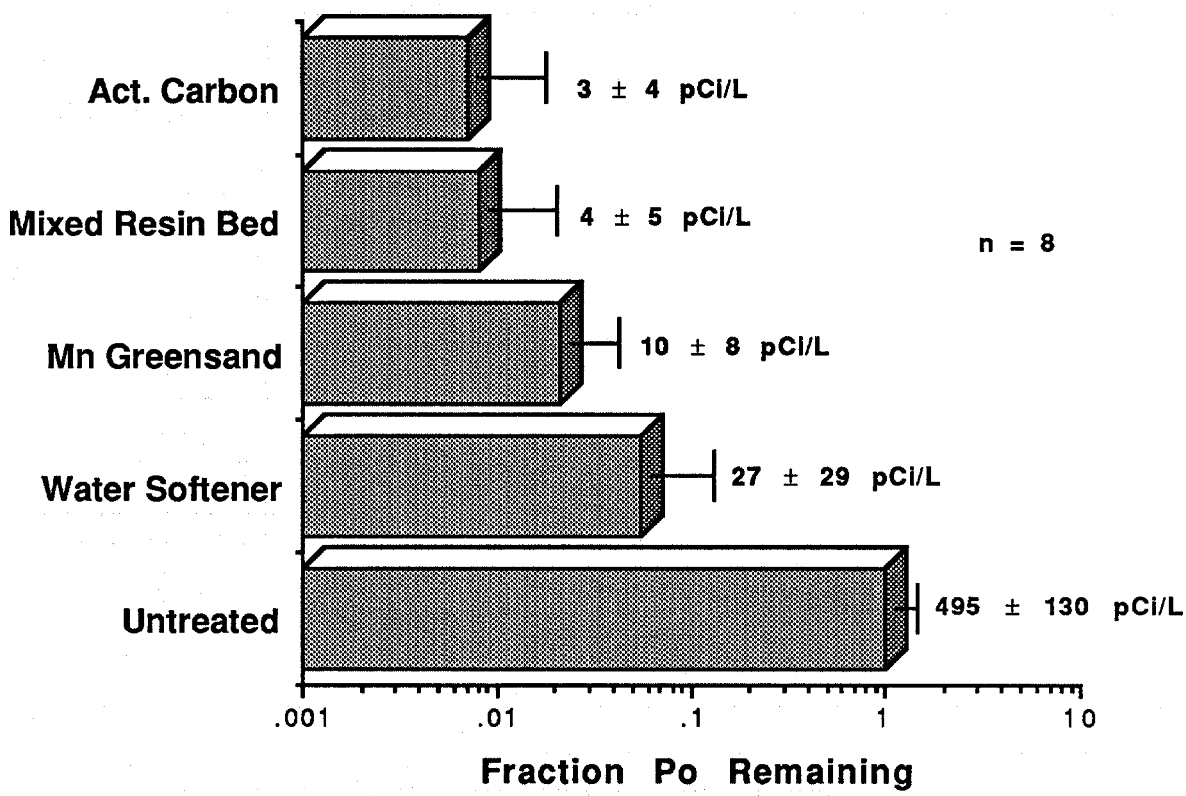


Fig. 53. Mean, standard deviation, and number of measurements of the polonium concentrations in treated water compared to unprocessed water from well 18, Hillsborough County test site. The activated carbon and mixed resin removed approximately 99% of the polonium present in this well water.

primarily by ^{214}Pb and ^{214}Bi daughters of radon. In addition, longer-lived nuclides such as ^{226}Ra and ^{238}U may be retained. Although these nuclides may be below regulatory concern in the influent groundwaters, they could become concentrated on the GAC to the point that it eventually becomes a low-level radioactive waste (Kinner *et al.*, 1990). Problems associated with gamma radiation may be handled by shielding with a water jacket or similar approach. The accumulation of long-lived radiation, however, could present some serious as well as expensive disposal problems. Thus, it is recommended to evaluate these potential problems by prior analysis of the groundwater and application of the principles outlined by Lowry and Brandow (1985) for calculating the extent of radon daughter concentration on the GAC depending upon flow rates and initial isotopic activities.

These results demonstrate that while any of the water purification systems tested may be suitable for removal of polonium from domestic water, only the GAC effectively removes <u>both</u> radon and polonium at high efficiencies. Interestingly, of the four systems evaluated for this investigation, the activated carbon unit was the <u>least</u> expensive, yet performed the best overall for removal of radon and polonium. Since activated carbon is also very useful for removal of other impurities, including organics, it seems an appropriate choice for use in areas where high radionuclide contents are suspected.

CONCLUSIONS AND RECOMMENDATIONS

The principal conclusions and recommendations from this investigation are summarized below according to subject area.

Methods:

(1) A simple, inexpensive radon flux measurement technique has been developed which is based on radon adsorption onto charcoal. This technique, calibrated by use of radium-spiked barium palmitate on a filter substrate, produced excellent agreement when compared to the more established chamber technique.

(2) Comparisons of soil radon measurements by overnight charcoal canister deployment to long-term (months) track etch measurements showed two principal features: (i) generally lower charcoal canister results, most likely the result of the radon equilibration time constituting a substantial fraction of the total deployment period; and (ii) occasional, very high radon "events" which appear only in the track etch results. The causes of the events are unclear, but their simultaneous appearance in records from neighboring stations provides convincing evidence that these periods of elevated soil radon are authentic.

(3) A new technique for electrochemical separation of the radon daughters, Pb, Bi, and Po, has been developed that substantially reduces the time required for processing natural water samples before low-level alpha or beta counting is initiated.

Assessment of Radon Potential:

(1) Radon concentrations in soils and associated radon fluxes into the atmosphere measured at 35 stations in three study areas over a two year period have shown that these parameters display considerable spatial and temporal variation. Regionally, results range by over three orders of magnitude between different stations at any one study site. Temporal trends show less variation although still significant, often amounting to more than 100% of the mean value at any one station.

(2) Radon concentrations in shallow groundwaters display considerably less variability in either time or space than radon concentrations in soils or radon fluxes. Overall,

shallow groundwater radon contents varied by about a factor of eight regionally within one study area, and were usually within about 10% at any one station.

(3) Radiochemical studies of surface soils and core samples shows that "available" radon (defined operationally as that fraction free to migrate from soil particles into water and measured *via* LSC) follows the distribution of total soil ^{226}Ra fairly closely, with most soils showing about 50% radon loss.

(4) In spite of the observed high variation in all radon parameters measured, long-term averages of radon soil concentrations, radon fluxes, and radon in associated shallow groundwater, all show the same pattern, i.e., the order of radon potential for the sites examined is as follows: Alachua>Hillsborough>Leon. Since any of these parameters, given a sufficient number of measurements, would apparently indicate the same potential, it is clearly advantageous to employ the least erratic parameter for situations when only one or a few measurements are possible.

<u>Radon Daughters in Shallow Groundwaters;</u>

(1) Radiochemical analyses of the portion of the uranium decay-series, ^{222}Rn-^{210}Pb-^{210}Bi-^{210}Po in shallow groundwaters from several stations in Florida has shown that while there is often significant disequilibrium in $^{210}Bi/^{210}Pb$, it is not nearly as great as the spectacular disequilibrium which occasionally exists in the $^{210}Po/^{210}Bi$ activity ratio. The analyses of all radon daughters confirms that ^{210}Po is largely unsupported when present in excessive amounts.

(2) Polonium-210 is present in excess of its predecessor activities only in cases where the groundwater pH is low ($\leq$5.0) and measureable sulfide is present in the aquifer waters.

(3) Time-series plots of ^{210}Po in shallow groundwater show that polonium is considerably more variable than radon concentrations within the same wells. Trends between neighboring stations, and even different levels of the aquifer at the same station, are often quite different. There are no readily discernible trends which correlate to rainfall events over the time period studied.

(4) Both experimental and field evidence suggest that polonium cycling may be related to the sulfur cycle in these shallow aquifers. Variations in bacterial growth rates at one station generally parallels the concentration of polonium in the groundwater at the same station. The variable ^{210}Po concentrations, therefore, may represent changes in the growth rates of microbes that mobilize polonium from the aquifer solids.

Removal of Radon and Polonium from Domestic Waters

(1) Activated carbon removed >99% of the ^{222}Rn present when unprocessed water was passed through a standard water purification unit containing this material. None of the other three purification agents tested (manganese greensand, a water softening agent, and a mixed deionizing bed) removed a significant amount of radon.

(2) All four purifying agents tested removed almost all ^{210}Po from the unprocessed water. Activated carbon and the mixed resin bed showed the greatest efficiencies at about 99% while the manganese greensand and water softener were both 295%. No reduction in removal efficiencies of either radon or polonium were noted after a total of greater than 500 gallons were passed through each purification cartridge.

(3) Based on the high removal efficiency for both radon and polonium, as well as its reported use for removal of other impurities and relatively low cost, it is recommended that activated carbon be used for purification of domestic water when contamination by natural uranium decay-series isotopes is suspected.

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PART V: APPENDIX

Table A-1 Results of precision tests for soil concentrations measured at 3 sites in Hillsborough County in December, 1988 and 4 sites in Alachua County in January, 1989. Averages, standard deviations and coefficients of variation shown for canisters deployed within each hole as well as for all canisters centered around one station.

Date Deployed	Location	Radon Soil Conc pCi/L	Av	sd	Cv %
		Station H-E			
12/8/88	north	177± 19			
		170± 19			
		159± 17	168	8	4
	east	165± 18			
		133± 15			
		161± 18	153	14	9
	south	139± 15			
		150± 17			
		141± 16	143	5	3
	west	153± 17			
		137± 15			
		103± 11	131	21	16
			Overall =149	19	13
		Station H-C			
12/8/88	north	80			
		754 ± 83			
		876 ± 96	784	66	8
	east	796 ± 88			
		745 ± 82			
		757 ± 83	766	22	3
	south	1122 ±123			
		975 ±107			
		1077 ±118	1058	62	6
	west	854 ± 94			
		760 ± 84			
		840 ± 92	818	41	5
			Overall =856	128	15
		Station H-D			
12/07/88	north	25 ± 3			
		24 ± 3			
		22 ± 2	24	1	5
	east	13 ± 1			
		12 ± 1			
		14 ± 2	13	1	9
	south	14 ± 2			
		11 ± 1			
		12 ± 1	13	1	10

Table A-1 Continued

Date Deployed	Location	Radon Soil Conc pCi/L	Av	sd	Cv %
	west	15 ± 2			
		18 ± 2			
		17 ± 2	17	1	9
		Overall =	16	5	29
		Station A-H			
01/09/89	north	1963 ±216			
		1644 ±181			
		2038 ±224	1882	171	9
	west	1701 ±187			
		1768 ±194			
		1976 ±217	1815	117	6
	south	1885 ±207			
		1797 ±198			
		1766 ±194	1816	50	3
	east	1957 ±215			
		1766 ±194			
		1766 ±194	1829	90	5
		Overall =	1836	119	6
		Station A-B			
01/09/89	west	57 ± 6			
		49 ± 5			
		45 ± 5	50	5	10
	south	16 ± 2			
		19 ± 2			
		19 ± 2	18	1	8
	east	20 ± 2			
		22 ± 2			
		20 ± 2	21	1	4
	north	24 ± 3			
		21 ± 2			
		21 ± 2	22	1	6
		Overall =	28	13	48
		Station A-F			
01/09/89	west	215 ± 24			
		177 ± 20			
		205 ± 23	199	16	8
	south	94 ± 10			
		118 ± 13			
		106 ± 12	106	10	9
	east	225 ± 25			
		184 ± 20			
		165 ± 18	192	25	13

Table A-1 Continued

Date Deployed	Location	Radon Soil Conc pCi/L	Av	sd	Cv %
	north	172 ± 19			
		184 ± 20			
		164 ± 18	173	8	5
		Overall =	168	40	24
		Station H-E			
01/30/89	north	232 ± 26			
		213 ± 23			
		238 ± 26	228	11	5
	east	262 ± 29			
		209 ± 23			
		226 ± 25	232	22	10
	south	165 ± 18			
		166 ± 8			
		177 ± 19	169	5	3
	west	196 ± 22			
		213 ± 23			
		207 ± 23	205	7	3
		Overall =	209	28	13
		Station H-F			
01/30/89	north	62 ± 7			
		67 ± 7			
		65 ± 7	65	2	3
	east	95 ± 11			
		105 ± 12			
		86 ± 9	95	8	8
	south	87 ± 10			
		104 ± 11			
		90 ± 10	94	8	8
	west	93 ± 10			
		96 ± 11			
		109 ± 12	99	7	7
		Overall =	88	15	17
		Station H-D			
01/30/89	north	28 ± 3			
		20 ± 2			
		16 ± 2	22	5	23
	east	10 ± 1			
		11 ± 1			
		9 ± 1	10	1	7
	south	9 ± 1			
		10 ± 1			
		9 ± 1	9	1	8

Table A-1 Continued

Date Deployed	Location	Radon Soil Conc pCi/L	Av	sd	Cv %
	west	13 ± 1			
		15 ± 2			
		14 ± 2	14	1	7
			Overall =14	6	40

Table A-2 Results of precision tests of radon flux measurements made at 2 sites in Alachua County in April, 1989. Averages, standard deviations, and coefficients of variation shown for clusters of 3 canisters deployed next to each other as well as for all canisters centered around one station.

Date Deployed	Location	Radon Flux pCi/m^2 sec	Av	sd	Cv %
		Station A-B			
04/12/89	north	0.36			
		0.56			
		0.49	0.47	0.08	17
	east	0.34			
		0.31			
		0.35	0.33	0.02	4
	south	0.24			
		0.24			
		0.22	0.23	0.01	4
	west	0.54			
		0.50			
		0.52	0.52	0.02	
		Overall=	0.39	0.12	31
		Station A-H			
04/12/89	north	12.39			
		10.99			
		10.81	11.40	0.70	6
	south	11.38			
		11.38			
		9.37	10.71	0.94	9
	east	16.93			
		17.15			
		14.7 1	16.26	1.10	7
	west	11.12			
		10.65			
		12.20	11.33	0.65	6
		Overall=	12.42	2.40	19

Table A-3 Results of radon flux and concentrations in soil gas and shallow groundwater from the Alachua County test site. Po-210 concentrations and water quality parameters are also shown.

Date	Location	Radon Flux pCi/m² sec	Radon Soil Conc pCi/L	Radon Water Conc pCi/L	Po-210 pCi/L	Temp °C	pH	Cond µS
13-Jun-88	138			17011	11.2	21.2	4.25	40
28-Jun-88	138		56	12935	6.1	22.0	4.70	42
11-Jul-88	138		50	14351	10.6	24.0	5.00	48
9-Aug-88	138		9	12551	7.2	24.2	5.28	48
6-Oct-88	138	0.33	4	13388	7.6	24.0		49
7-Nov-88	138		3	13605	8.2	23.5	4.82	45
9-Jan-89	138	0.06	8	13275	7.5	22.0	4.80	40
23-Feb-89	138	0.27	5	16056	7.2	20.0	5.20	38
12-Apr-89	138	0.20	28	9931	12.0	19.9	4.49	39
28-Jun-89	138	0.10	14	10692	9.8	23.5	6.36	40
10-Oct-89	138	0.00	3	11023	7.6	23.9	4.30	40
19-Dec-89	138	0.04	5	11565	7.5	22.8	5.20	32
25-Feb-90	138	0.12	3	10705	11.9	20.1	4.20	30
27-Jun-90	138	0.10	3	10988	11.8	23.0	4.90	36
13-Jun-88	151		77	31138		24.0	4.10	63
28-Jun-88	151		62	32710		23.9	5.40	59
11-Jul-88	151			32414		21.5	4.80	60
9-Aug-88	151		68	31032		25.9	5.72	68
6-Oct-88	151			38957		23.0		91
7-Nov-88	151			38029		21.8	4.70	59
9-Jan-89	151							
23-Feb-89	151							
12-Apr-89	151	0.53	50	33385	0.5	18.0	4.95	48
28-Jun-89	151	1.58	57	24175		23.0	5.15	69
10-Oct-89	151	0.33	80	36497		23.2	5.45	51
19-Dec-89	151	1.02	92	30553		19.5	4.60	42
25-Feb-90	151	0.67	91	28967		21.0	4.85	40
27-Jun-90	151	0.22	77	27478		25.0	4.80	50
13-Jun-88	152		183					
28-Jun-88	152		166	32962		21.0	4.70	42
11-Jul-88	152		146	36907		24.0		48
9-Aug-88	152		170	34680		22.5	5.59	48
6-Oct-88	152		92	33642		22.9		50
7-Nov-88	152	0.88	110	37386	1.0	22.9	4.60	50
9-Jan-89	152	0.72	124					
24-Feb-89	152			40779	1.3	20.1	4.71	40
12-Apr-89	152	0.85	121	30933	2.0	20.5	4.65	39
28-Jun-89	152	1.87	162	31568	2.3	23.5	5.25	41
10-Oct-89	152	0.40	99					

Table A-3 Continued

Date	Location	Radon Flux pCi/m^2 sec	Radon Soil Conc pCi/L	Radon Water Conc pCi/L	Po-210 pCi/L	Temp °C	pH	Cond µS
13-Jun-88	153							
28-Jun-88	153			19720		21.0	4.90	103
11-Jul-88	153		86	20144		22.0	4.90	102
9-Aug-88	153		90	17598		24.0	5.24	102
6-Oct-88	153		79	18045		23.0		103
7-Nov-88	153		68	18739		20.1	4.43	98
9-Jan-89	153	0.58	67	19343		27.5	4.90	107
24-Feb-89	153			23530	2.9	16.9	4.67	81
12-Apr-89	153	0.29	58	15886	0.2	19.9	4.46	88
28-Jun-89	153	0.41	63	20211	0.2	22.0	5.25	87
10-Oct-89	153	0.49	81	17463		22.2	4.45	79
19-Dec-89	153	0.77	102	16187		21.0	5.06	58
25-Feb-90	153	0.61	79	16618		19.5	5.10	62
27-Jun-90	153	0.39	80	16876		22.3	4.70	70
13-Jun-88	154		328	38612		20.5	5.30	63
28-Jun-88	154		407	38141		21.5	5.20	68
11-Jul-88	154		448	39115		23.0	5.40	68
9-Aug-88	154		454	36386	0.1	22.0	5.22	68
6-Oct-88	154		168	37087	0.1	22.9		77
7-Nov-88	154		261	40444	0.3	22.3	4.34	70
9-Jan-89	154	2.86	298	39995	0.8	22.1	5.00	65
24-Feb-89	154	6.78	379	47588		15.9	4.69	55
12-Apr-89	154	16.12	395	34463	0.6	21.0	4.80	60
28-Jun-89	154		374	33391	1.3	24.0	5.10	60
10-Oct-89	154	1.00	189	35882	0.6	23.6	4.80	58
19-Dec-89	154	63.06	1055	32477	0.2	21.5	6.00	50
25-Feb-90	154	8.01	1472	30957	1.4	21.0	4.60	47
27-Jun-90	154	3.37	705	27246	1.1	24.0	4.55	51
13-Jun-88	A-A15		219	12456		23.1	4.50	60
28-Jun-88	A-A15		144	14872	0.9	22.1	5.30	76
11-Jul-88	A-A15		62	16939	0.4	24.0	4.65	60
9-Aug-88	A-A15		139	17350		23.9	5.61	43
6-Oct-88	A-A15		85	10933		24.0		43
7-Nov-88	A-A15		109	17260	1.9	22.5	4.29	38
9-Jan-89	A-A15	0.27	175	15655	1.4	21.8	4.90	38
24-Feb-89	A-A15		104	22385		18.0	4.83	35
12-Apr-89	A-A15	0.51	94	15730	4.5	20.2	4.48	31
28-Jun-89	A-A15	1.09	92	15091	4.8	25.0	4.93	32
10-Oct-89	A-A15	0.39	102	16923		24.6	4.38	25
19-Dec-89	A-A15	0.58	168	11963		21.0	5.40	23
25-Feb-90	A-A15		160	9162		19.8	4.55	20
27-Jun-90	A-A15	1.32	159	10449		23.0	4.50	25

Table A-3 Continued

Date	Location	Radon Flux pCi/m^2 sec	Radon Soil Conc pCi/L	Radon Water Conc pCi/L	Po-210 pCi/L	Temp ^oC	pH	Cond µS
13-Jun-88	A-A25			12071		23.5	5.50	62
28-Jun-88	A-A25			32208	2.3	22.1	5.50	59
11-Jul-88	A-A25			33194	1.4	22.5	4.70	47
9-Aug-88	A-A25			34297		22.6	5.70	45
6-Oct-88	A-A25			37805		22.8		49
7-Nov-88	A-A25			36654		22.0	4.46	43
9-Jan-89	A-A25			33309		23.0	5.07	42
24-Feb-89	A-A25			30142		19.4	5.04	36
12-Apr-89	A-A25			25599		21.0	4.15	41
28-Jun-89	A-A25			30621		26.5	5.20	43
10-Oct-89	A-A25			31134		23.5	4.95	39
19-Dec-89	A-A25			29638		21.5	5.30	39
25-Feb-90	A-A25			25611		21.8	4.90	35
27-Jun-90	A-A25			30927		23.0	4.70	39
13-Jun-88	A-B15		39	27615			4.60	125
28-Jun-88	A-B15		66	37134	0.6	23.7	4.60	121
11-Jul-88	A-B15		76	36420	0.9	23.0		128
9-Aug-88	A-B15		45	37266		23.9	5.19	128
6-Oct-88	A-B15	0.26	28	37998		24.0		130
7-Nov-88	A-B15	0.35	51	36335	2.0	23.5	4.34	131
9-Jan-89	A-B15	0.36	21	37329	3.7	24.9	4.80	127
24-Feb-89	A-B15	0.43	41	43341	2.1	19.1	4.21	110
12-Apr-89	A-B15	0.33	31	30257		21.0	5.10	117
28-Jun-89	A-B15	0.36	26	31460		27.0	4.80	125
10-Oct-89	A-B15	0.49	24	32025	1.5	25.2	4.60	119
19-Dec-89	A-B15	0.09	36	33898	0.9	22.0	4.30	100
25-Feb-90	A-B15	0.19	40	32949	4.1	21.6	4.70	82
27-Jun-90	A-B15	0.46	44	30361	1.4	24.0	4.10	91
13-Jun-88	A-B25			3862		25.0	5.80	80
28-Jun-88	A-B25			35857		22.5	5.10	133
11-Jul-88	A-B25			24080	0.9	26.0		124
9-Aug-88	A-B25			20953		23.0	5.77	112
6-Oct-88	A-B25			39370		23.0		128
7-Nov-88	A-B25			25796		22.7	4.46	119
9-Jan-89	A-B25			37627		24.0	4.98	127
24-Feb-89	A-B25			27210		18.4	5.05	100
12-Apr-89	A-B25			19038	3.6	21.0	5.10	102
28-Jun-89	A-B25			22329		26.0	5.10	111
10-Oct-89	A-B25			31595		24.0	4.65	108
19-Dec-89	A-B25			29082		22.0	4.50	91
25-Feb-90	A-B25			24123		22.9	4.85	82
27-Jun-90	A-B25			26177		23.0	4.30	91

Table A-3 Continued

Date	Location	Radon Flux pCi/m^2 sec	Radon Soil Conc pCi/L	Radon Water Conc pCi/L	Po-210 pCi/L	Temp ^oC	pH	Cond µS
13-Jun-88	A-C15		347	7462	62.8	25.0	4.50	60
28-Jun-88	A-C15			40595	1.1	28.0	5.10	65
11-Jul-88	A-C15		579	53893	1.2	25.0	6.00	55
9-Aug-88	A-C15		295	56813	3.9	24.3	5.66	55
6-Oct-88	A-C15		212	66150	1.7	24.9		58
7-Nov-88	A-C15	1.42	225	42447	2.6	23.1	4.43	52
13-Jun-88	A-C25			1150	1.3	25.5	5.80	60
28-Jun-88	A-C25			8377		24.8	5.70	40
11-Jul-88	A-C25			14325	1.2	26.5	5.70	68
9-Aug-88	A-C25			16802	2.7	22.9	6.06	58
6-Oct-88	A-C25			19779		23.2		61
7-Nov-88	A-C25			19892		22.2	4.90	53
13-Jun-88	A-D25		108	1714		26.0	6.40	115
28-Jun-88	A-D25		86	28010		23.0	5.10	102
11-Jul-88	A-D25		112	27345		24.0	5.20	108
9-Aug-88	A-D25		70	25959		22.2	5.71	102
6-Oct-88	A-D25		78	29645		22.0		97
7-Nov-88	A-D25		77	29865		22.0	4.76	99
9-Jan-89	A-D25	0.81	98	31037		22.5	5.20	88
24-Feb-89	A-D25	0.64	92	35045		20.1	4.95	80
12-Apr-89	A-D25	0.79	71	23580		20.8	5.09	82
28-Jun-89	A-D25	1.83	105	26862		23.0	4.95	79
10-Oct-89	A-D25	0.44	75	25224		22.2	4.90	69
19-Dec-89	A-D25	0.90	116	24955		21.5	5.52	60
25-Feb-90	A-D25	0.58	118			21.0	5.00	55
27-Jun-90	A-D25	0.70	120	23379		22.5	4.70	59
14-Jun-88	A-E15		457					
28-Jun-88	A-E15		643	1337	1.6	25.1	5.60	250
11-Jul-88	A-E15		958	811		30.2	5.70	221
9-Aug-88	A-E15		881	1681		23.1	6.16	204
6-Oct-88	A-E15	0.18	104	1585		23.8	5.36	270
7-Nov-88	A-E15	1.29	232	3951	41.3	21.8	5.34	261
28-Jun-88	A-E25			4209		22.5	6.00	530
11-Jul-88	A-E25			678		30.0	5.60	380
9-Aug-88	A-E25			4255		24.5	6.09	430
6-Oct-88	A-E25			2990		24.5	5.50	318
7-Nov-88	A-E25			4524		19.6	5.45	268
13-Jun-88	A-F15		294	20316		22.0	6.00	115
28-Jun-88	A-F15		233	27236	0.6	23.0	5.50	78
11-Jul-88	A-F15		209	22463	0.7	25.0	5.40	93

Table A-3 Continued

Date	Location	Radon Flux pCi/m² sec	Radon Soil Conc pCi/L	Radon Water Conc pCi/L	Po-210 pCi/L	Temp °C	pH	Cond µS
9-Aug-88	A-F15		200	23869		24.4	5.50	82
6-Oct-88	A-F15	1.25	134	29943	1.1	24.3		77
7-Nov-88	A-F15	0.86	163	29560	3.3	23.0	4.55	73
9-Jan-89	A-F15	0.87	192	27815	2.5	22.3	5.09	71
24-Feb-89	A-F15	0.91	199	33828	1.3	18.3	4.79	62
12-Apr-89	A-F15	0.85	185	23707	6.9	21.0	4.80	69
28-Jun-89	A-F15	1.92	126	23458		24.8	5.20	68
10-Oct-89	A-F15	0.61	175	25774		24.2	4.70	72
19-Dec-89	A-F15	2.04	227	23946		21.5	4.96	59
25-Feb-90	A-F15	0.87	307	23071		20.3	4.75	62
27-Jun-90	A-F15	1.08	277	23414		23.0	4.90	60
13-Jun-88	A-F25			9210		21.9	6.00	140
28-Jun-88	A-F25			9225	2.1	22.8	5.40	145
11-Jul-88	A-F25			7962	0.8	24.8	5.70	120
9-Aug-88	A-F25			10398		22.7	6.03	93
6-Oct-88	A-F25			10785	0.3	22.8		89
7-Nov-88	A-F25			9896		22.0	5.12	77
9-Jan-89	A-F25			9494		23.0	5.40	78
24-Feb-89	A-F25			12535		19.4	5.20	68
12-Apr-89	A-F25			8818		19.1	5.00	71
28-Jun-89	A-F25			9048	1.9	27.5	5.45	72
10-Oct-89	A-F25			8459		23.0	5.15	71
19-Dec-89	A-F25			8079		22.0	5.60	59
25-Feb-90	A-F25			8174		21.9	5.15	60
27-Jun-90	A-F25			7036		22.0	5.20	69
13-Jun-88	A-FX15			20884		23.5	6.00	121
28-Jun-88	A-FX15			23069		23.0	5.60	93
11-Jul-88	A-FX15			25228		23.0	5.50	82
9-Aug-88	A-FX15			26862		23.9	5.49	79
6-Oct-88	A-FX15			25715		24.2		87
11-Jul-88	A-FX20			25008	1.7	26.0	6.30	82
28-Jun-88	A-FX25			15342		22.8	5.80	104
9-Aug-88	A-FX25			25576		23.8	5.54	80
6-Oct-88	A-FX25			24053		23.7		88
11-Jul-88	A-FX30			21645		27.0	5.70	105
13-Jun-88	A-G15		179	8642		20.7	4.60	138
28-Jun-88	A-G15		120	11383		23.0	5.60	130
11-Jul-88	A-G15		138	9993	0.4	25.0	5.30	130
9-Aug-88	A-G15		163	11399		24.2	5.56	130

Table A-3 Continued

Date	Location	Radon Flux pCi/m² sec	Radon Soil Conc pCi/L	Radon Water Conc pCi/L	Po-210 pCi/L	Temp °C	pH	Cond µS
6-Oct-88	A-G15		137	11599	0.8	24.1		133
7-Nov-88	A-G15	1.81	107	10965	0.7	23.9	4.70	123
9-Jan-89	A-G15	0.96	130					
24-Feb-89	A-G15	1.19	129	14907	1.0	18.7	5.04	100
12-Apr-89	A-G15	1.02	112	10742	0.9	20.9	4.15	104
28-Jun-89	A-G15	3.17	117	10269	4.8	25.5	5.90	117
10-Oct-89	A-G15	1.07	139	7769		24.3	5.25	108
19-Dec-89	A-G15	1.28	159	10066		21.5	5.35	87
25-Feb-90	A-G15		208	10696		20.6	4.95	82
27-Jun-90	A-G15	1.35	243	9625		23.9	4.90	95
14-Jun-88	A-H15		2077					
28-Jun-88	A-H15		1844	3375	9.2	25.0	6.30	247
11-Jul-88	A-H15		1937	11519		28.5	5.60	220
9-Aug-88	A-H15		1835	5821		27.0	6.46	210
6-Oct-88	A-H15	9.91	1799	2969		22.9	6.17	121
7-Nov-88	A-H15	18.63	1874	7368	2.6	17.5	5.10	108
9-Jan-89	A-H15	12.06	1882					
24-Feb-89	A-H15	1.50	97					
12-Apr-89	A-H15		1774	9566	14.0	18.9	6.10	119
28-Jun-89	A-H15	44.71	1691					
10-Oct-89	A-H15	10.77	1737	5313	12.5	23.8	5.65	104
19-Dec-89	A-H15	15.57	1821		7.8			
25-Feb-90	A-H15	11.19	2206	4175	6.3	18.0	5.45	75
28-Jun-88	A-I15		96	16750		22.0	5.10	125
11-Jul-88	A-I15		121	15560		25.0	4.70	131
9-Aug-88	A-I15		99	13170		22.9	5.70	116
6-Oct-88	A-I15	0.09	79	9062		23.1		127
7-Nov-88	A-I15	1.07	72	14693	1.0	22.2	4.82	121
9-Jan-89	A-I15	0.82	75	7190	0.9	21.1	5.56	101
24-Feb-89	A-I15		87	15692		16.1	5.26	82
12-Apr-89	A-I15	0.81	64	13352	3.5	18.6	5.40	82
28-Jun-89	A-I15	1.62	105	15607		26.0	5.19	81
10-Oct-89	A-I15	0.60	70	13547		23.8	5.00	71
19-Dec-89	A-I15	1.90	83	4321		20.9	4.50	49
25-Feb-90	A-I15	0.66	83	7569		20.2	4.65	58
27-Jun-90	A-I15	1.07	100	8979		23.0	4.80	109
9-Jan-89	A-J15	0.20	216		5.8			
23-Feb-89	A-J15		238	19649		15.5	5.80	48
12-Apr-89	A-J15	1.98	155	6120	4.1	20.8	4.90	52
28-Jun-89	A-J15	1.58	239					
10-Oct-89	A-J15	1.01	189	10301	70.3	23.8	5.20	48
19-Dec-89	A-J15	2.27	237	9006	13.5	20.7	5.67	38

Table A-3 Continued

Date	Location	Radon Flux pCi/m2 sec	Radon Soil Conc pCi/L	Radon Water Conc pCi/L	Po-210 pCi/L	Temp °C	pH	Cond µS
25-Feb-90	A-J15	1.60	253	15254	10.2	19.0	5.40	35
27-Jun-90	A-J15	1.32	276	15764	5.8	23.2	5.40	40
9-Jan-89	A-J25			2046		22.3	6.42	99
28-Jun-89	A-J25			405	3.2	26.9	5.50	75
10-Oct-89	A-J25			960		23.1	5.15	58
19-Dec-89	A-J25			282		18.5	6.11	47
25-Feb-90	A-J25			830		19.8	5.60	50
27-Jun-90	A-J25			1311		23.2	5.70	69
Summary	Average =	2.89	286	20886	5.3	22.7	5.14	87
	sd =	8.09	475	12254	10.4	2.3	0.52	62
	Minimum =	0.00	3	282	0.1	15.5	4.10	20
	Maximum =	63.1	2206	66150	70.3	30.2	6.46	530
	n =	103	172	236	96	236	216	236

Table A-4 Results of radon flux and concentrations in soil gas and shallow groundwater from the Hillsborough County test site. Po-210 concentrations and water quality parameters are also shown.

Date	Location	Radon Flux pCi/m² sec	Radon Soil Conc pCi/L	Radon Water Conc pCi/L	Po-210 pCi/L	Temp °C	pH	Cond µS
19-Jun-88	10		14	3988	219	24.0	3.60	150
28-Jun-88	10			4352	169	25.2	3.90	153
11-Jul-88	10			4437	107	25.0		111
27-Jul-88	10		18	4403	309	24.8	4.27	119
14-Sep-88	10		4	4074	153	25.2	4.32	148
26-Oct-88	10		41	3987	114	25.0	4.20	167
7-Dec-88	10		47	4434	240	21.2	3.91	132
30-Jan-89	10			4751	82	22.0	3.90	140
21-Mar-89	10	0.50	37	3405		23.2	3.65	160
23-May-89	10	0.57	20					
21-Aug-89	10	1.02	28	3752	112	26.5	4.05	179
9-Oct-89	10	0.55	22	3852	152	25.4	3.85	172
18-Dec-89	10	0.91	59	3391	173	23.2	3.90	146
24-Feb-90	10	0.76	38	3305	114	23.0	3.90	147
26-Jun-90	10	1.17	57	2718	184	25.8	3.90	158
19-Jun-88	11			12093	467	23.5	4.20	190
28-Jun-88	11			11746	385	25.5	4.90	180
11-Jul-88	11			12439	396	23.5		182
27-Jul-88	11			13119	411	25.8	4.80	198
14-Sep-88	11			11674	583	26.0	4.78	194
26-Oct-88	11		16	12059	290	24.5	4.21	327
7-Dec-88	11		13	12272				
30-Jan-89	11			12309	120	21.6	4.22	162
21-Mar-89	11	0.05	2	11045	306	24.0	4.35	179
23-May-89	11	0.09	4	10066	260	25.9	4.40	186
21-Aug-89	11	0.12	4	10621	177	26.9	4.45	202
9-Oct-89	11		2	11310	356	26.5	4.20	203
18-Dec-89	11	0.11	3	8593	298	24.0	4.30	171
24-Feb-90	11	0.19	5	9885	508	24.0	4.40	180
26-Jun-90	11	0.19	5					
19-Jun-88	18		13	20376	615	24.0	3.80	39
28-Jun-88	18			20851	595	25.1	4.50	41
11-Jul-88	18			21617	591	24.5		39
27-Jul-88	18		1	20023	587	25.3	4.94	40
14-Sep-88	18			18002	502	28.8		52
26-Oct-88	18			21327	551	22.7	3.88	40
7-Dec-88	18			20607	454	21.8	4.26	39
30-Jan-89	18	0.28	11	20759	435	20.4	4.44	35
21-Mar-89	18	0.06	5	18696	424	24.5	4.30	38

Table A-4 Continued

Date	Location	Radon Flux pCi/m^2 sec	Radon Soil Conc pCi/L	Radon Water Conc pCi/L	Po-210 pCi/L	Temp °C	pH	Cond µS
23-May-89	18		9	18891	591	27.0	4.60	39
21-Aug-89	18	0.16	6	19376	553	25.8	4.35	35
9-Oct-89	18	0.17	9	17099	563	25.8	4.10	34
18-Dec-89	18	0.16	27	15212	489	23.5	3.80	30
24-Feb-90	18	0.16		16072	455	22.5	4.30	30
26-Jun-90	18	0.06	1	15246	659			
20-Jun-88	H-A15		14					
28-Jun-88	H-A15		17	5565	80	30.0	5.10	215
11-Jul-88	H-A15		9	3111	112	27.2		108
27-Jul-88	H-A15		6	4668	236	26.4	4.91	91
14-Sep-88	H-A15			4221		25.2	4.90	81
26-Oct-88	H-A15		2	3377	287	24.8	4.15	78
7-Dec-88	H-A15		2	4080	230	24.7	4.34	69
30-Jan-89	H-A15	0.04	1	3617	3	22.9	4.67	75
21-Mar-89	H-A15	0.04	2	3202		24.5	4.90	92
23-May-89	H-A15		1	1997		27.5	5.60	90
21-Aug-89	H-A15	0.22	2			28.0	4.90	119
9-Oct-89	H-A15	0.10	1	1281	106	27.5	4.80	140
18-Dec-89	H-A15	0.05	3	953	39	24.0	4.60	119
24-Feb-90	H-A15	0.22	4			23.5	4.95	227
26-Jun-90	H-A15	0.20	3	818		26.5	4.90	125
28-Jun-88	H-A30			21346	248	29.0	5.00	319
11-Jul-88	H-A30			19154	160	26.1		312
27-Jul-88	H-A30			21379	274	25.5	5.36	290
14-Sep-88	H-A30			22040		24.2	5.18	260
26-Oct-88	H-A30			20306	315	24.6	4.66	190
7-Dec-88	H-A30			21953		22.7	4.60	176
30-Jan-89	H-A30			24377	81	23.9	4.64	240
21-Mar-89	H-A30			19849		24.8	4.70	262
23-May-89	H-A30			18977		26.1	4.50	270
21-Aug-89	H-A30			19851		25.5	4.50	252
9-Oct-89	H-A30			19092		25.3	4.40	256
18-Dec-89	H-A30			16677		24.1	4.00	231
24-Feb-90	H-A30			21467		25.1	4.45	252
26-Jun-90	H-A30			11023		26.0	4.70	241
19-Jun-88	H-B15							
28-Jun-88	H-B15		4	8093		28.3	4.40	210
11-Jul-88	H-B15		10	11918	99	28.0	4.50	82
27-Jul-88	H-B15		2	10317	88	29.3	5.11	90
14-Sep-88	H-B15			3988	90	25.0	5.18	77
26-Oct-88	H-B15		16	11449	96	25.1	4.29	71

Table A-4 Continued

Date	Location	Radon Flux pCi/m^2 sec	Radon Soil Conc pCi/L	Radon Water Conc pCi/L	Po-210 pCi/L	Temp ^{o}C	pH	Cond µS
7-Dec-88	H-B15		15	10961		24.5	4.50	72
30-Jan-89	H-B15	0.12	10	8668	38	23.7	4.42	71
21-Mar-89	H-B15	0.25	11	11186		24.6	4.35	66
23-May-89	H-B15	0.20	10	9928		24.0	4.70	790
21-Aug-89	H-B15	0.24	10	3046		30.8	4.40	82
9-Oct-89	H-B15	0.34	7	4505		26.9	4.25	69
18-Dec-89	H-B15	0.51	9	5615		23.5	3.95	69
24-Feb-90	H-B15	0.27	7	7494		23.0	4.50	55
26-Jun-90	H-B15	0.37	11	2841		25.4	4.23	47
28-Jun-88	H-B30			19422		26.5	4.70	119
11-Jul-88	H-B30			17049		28.0	5.80	141
27-Jul-88	H-B30			13326	278	25.3	5.21	
14-Sep-88	H-B30			15621		24.5	5.15	58
26-Oct-88	H-B30			11301	270	24.5	4.65	55
7-Dec-88	H-B30			14845		24.1	4.45	54
30-Jan-89	H-B30			14910	327	23.2	4.45	47
21-Mar-89	H-B30			15955	494	25.0	4.65	52
23-May-89	H-B30			11985	273	24.0	4.40	510
21-Aug-89	H-B30			15741		26.5	4.25	51
9-Oct-89	H-B30			20412		26.0	4.50	55
18-Dec-89	H-B30			17898		24.0	4.70	50
24-Feb-90	H-B30			15592		23.9	4.60	48
26-Jun-90	H-B30			14370		26.0	4.40	49
11-Jul-88	H-BX15			3982		26.9	6.60	268
27-Jul-88	H-BX15			5245	10	25.3	5.53	125
14-Sep-88	H-BX15			6190		24.0	4.88	52
26-Oct-88	H-BX15			3945		25.1	4.75	95
27-Jul-88	H-BX20			6635	22	25.1	5.01	78
27-Jul-88	H-BX25			6535	32	24.9	5.33	82
28-Jun-88	H-BX30			7434		30.0	5.10	121
11-Jul-88	H-BX30			2838		26.5	7.20	399
27-Jul-88	H-BX30			6631	46	25.1	5.36	83
14-Sep-88	H-BX30			6477		23.6	5.04	59
26-Oct-88	H-BX30			5222		24.7	4.53	115
19-Jun-88	H-C15		915					
28-Jun-88	H-C15		984	21168	11	30.0	5.10	119
11-Jul-88	H-C15		1267	26099	5	26.1	4.60	86
27-Jul-88	H-C15		565	28212	8	24.2	5.10	70

Table A-4 Continued

Date	Location	Radon Flux pCi/m^2 sec	Radon Soil Conc pCi/L	Radon Water Conc pCi/L	Po-210 pCi/L	Temp °C	pH	Cond µS
14-Sep-88	H-C15		383	31109	5	24.2	4.92	73
26-Oct-88	H-C15		228	32300	9	24.7	4.60	84
7-Dec-88	H-C15	4.95	754	30088	6	23.6	4.65	97
30-Jan-89	H-C15	6.28	1496	32838	11	22.3	4.64	91
21-Mar-89	H-C15	7.89	784	27839	20	23.1	4.05	89
23-May-89	H-C15	9.45	1061	27577		25.0	4.20	70
21-Aug-89	H-C15	9.51	1287	27840	18	26.5	4.60	62
9-Oct-89	H-C15	7.03	1123	26976	12	25.2	4.20	63
18-Dec-89	H-C15	8.72	1638	38206	110	23.1	4.00	61
24-Feb-90	H-C15	7.48	1871	32015	81	23.0	4.00	50
26-Jun-90	H-C15	8.05	1487	21188	153	25.0	4.30	49
28-Jun-88	H-C30			7547		31.5	5.60	229
11-Jul-88	H-C30			6989	2	27.4	5.80	192
27-Jul-88	H-C30			7609	9	26.0	6.11	145
14-Sep-88	H-C30			1163		25.0	6.30	152
26-Oct-88	H-C30			3216	10	25.0	6.15	153
7-Dec-88	H-C30			2632	46	23.8	6.13	148
30-Jan-89	H-C30			2845	145	23.4	6.07	154
21-Mar-89	H-C30			3103	51	24.4	5.70	158
23-May-89	H-C30			3000	9	25.0	5.60	165
21-Aug-89	H-C30			4336	2	28.0	5.30	148
9-Oct-89	H-C30			1498	3	24.1	4.70	142
18-Dec-89	H-C30			1777	3	22.5	5.70	136
24-Feb-90	H-C30			2014		23.2	5.20	12
26-Jun-90	H-C30			1831	5	25.0	5.20	147
20-Jun-88	H-D15		18					
28-Jun-88	H-D15		47	8100	27	27.1	4.90	318
11-Jul-88	H-D15		21	9673		27.5		232
27-Jul-88	H-D15		2	8127	184	26.0	5.18	241
14-Sep-88	H-D15		1	6860		25.2	5.04	242
26-Oct-88	H-D15		12	7617	180	26.5	5.02	247
7-Dec-88	H-D15		18	7712		23.5	4.41	241
30-Jan-89	H-D15	0.35	10	6287	237	23.9	4.90	229
21-Mar-89	H-D15	0.14	14	4667		23.8	4.60	255
23-May-89	H-D15	0.20	9	3772		26.3	4.20	305
21-Aug-89	H-D15	0.33	12	4958		26.2	4.79	254
9-Oct-89	H-D15	0.17	9	3244		27.2	4.45	272
18-Dec-89	H-D15	0.45	18	2930		14.4	3.95	260
24-Feb-90	H-D15	0.73	16	3555	116	25.0	4.50	260
26-Jun-90	H-D15	0.48	17	4363		28.0	4.50	300

Table A-4 Continued

Date	Location	Radon Flux pCi/m2 sec	Radon Soil Conc pCi/L	Radon Water Conc pCi/L	Po-210 pCi/L	Temp °C	pH	Cond µS
28-Jun-88	H-D30			18919		26.3	4.10	165
11-Jul-88	H-D30			22237	29	26.0		178
27-Jul-88	H-D30			21268	38	24.8	4.46	168
14-Sep-88	H-D30			21867		24.5	4.33	162
26-Oct-88	H-D30			23281	26	25.3	4.30	163
7-Dec-88	H-D30			22329		22.1	3.63	148
30-Jan-89	H-D30			23516	27	24.0	4.00	138
21-Mar-89	H-D30			19127	55	25.2	3.90	138
23-May-89	H-D30			18122		25.6	3.90	120
21-Aug-89	H-D30			20432		25.0	4.30	132
9-Oct-89	H-D30			17959		25.2	3.75	132
18-Dec-89	H-D30			20741		24.0	3.30	132
24-Feb-90	H-D30			17506		25.1	3.80	135
27-Jun-90	H-D30			18404		26.0	5.90	149
20-Jun-88	H-E15		177					
28-Jun-88	H-E15		366	4057		28.0	4.70	182
11-Jul-88	H-E15		361	4029		27.7	5.40	166
27-Jul-88	H-E15		161	6970	25	25.2	5.58	108
14-Sep-88	H-E15		35	8020		24.8	5.28	99
26-Oct-88	H-E15		104	7191	14	26.0	5.34	112
7-Dec-88	H-E15		153	4526		24.7	5.10	98
30-Jan-89	H-E15	2.57	204	4988	9	22.2	5.05	101
21-Mar-89	H-E15	1.54	165	3589		23.8	6.10	111
23-May-89	H-E15	2.30	160	4172		25.0	5.60	120
21-Aug-89	H-E15	1.98	229	3560		27.2	4.60	98
9-Oct-89	H-E15	1.39	133	2482		25.7	4.10	92
18-Dec-89	H-E15	1.05	255	4133		23.1	4.50	78
24-Feb-90	H-E15	0.89	267	4789		21.9	3.90	87
26-Jun-90	H-E15		284	4491		25.8	4.00	79
28-Jun-88	H-E30			17714		29.2	4.60	261
11-Jul-88	H-E30			21088		27.5	5.00	169
27-Jul-88	H-E30			22468	994	25.0	5.48	162
14-Sep-88	H-E30			17972		24.8	5.51	161
26-Oct-88	H-E30			22634	341	25.8	5.21	149
7-Dec-88	H-E30			22309		25.3	5.00	154
30-Jan-89	H-E30			25848		24.1	4.95	151
21-Mar-89	H-E30			21947	241	24.6	5.20	143
23-May-89	H-E30			20204		24.8	4.51	147
21-Aug-89	H-E30			20543		27.0	4.60	138
9-Oct-89	H-E30			19347		24.5	4.20	129
18-Dec-89	H-E30			23145		23.3	4.33	121
24-Feb-90	H-E30			20251		23.1	4.10	106

Table A-4 Continued

Date	Location	Radon Flux pCi/m2 sec	Radon Soil Conc pCi/L	Radon Water Conc pCi/L	Po-210 pCi/L	Temp °C	pH	Cond µS
26-Jun-90	H-E30			21453		25.0	4.50	111
20-Jun-88	H-F15		109					
28-Jun-88	H-F15		210	4715		32.4	5.30	38
11-Jul-88	H-F15			5357		38.0	5.80	570
27-Jul-88	H-F15		55	6306		28.2	6.25	320
14-Sep-88	H-F15		26	1471		25.0	6.43	140
26-Oct-88	H-F15		76	2573		27.5	5.40	152
7-Dec-88	H-F15		131	7174		24.8	4.67	155
30-Jan-89	H-F15	2.27	62	4938	30	21.8	4.76	120
21-Mar-89	H-F15	0.71	70	7302	14	23.5	4.30	125
23-May-89	H-F15	0.73	78	6221		27.0	4.70	95
21-Aug-89	H-F15	1.27	171	5774		27.0	4.80	112
9-Oct-89	H-F15	0.78	89	7258		27.0	4.20	105
18-Dec-89	H-F15	1.86	164	6938		23.0	4.00	110
24-Feb-90	H-F15	1.25	149	6320		21.5	3.85	100
26-Jun-90	H-F15		168	7394		27.0	4.10	120
28-Jun-88	H-F30			7564	53	25.0	4.80	119
11-Jul-88	H-F30			6923		25.0	5.60	142
27-Jul-88	H-F30			7662	79	25.1	5.66	102
14-Sep-88	H-F30			7455		24.0	5.60	115
26-Oct-88	H-F30			6402	51	25.8	5.64	108
7-Dec-88	H-F30			7153	75	25.5	5.05	92
30-Jan-89	H-F30			7289		22.7	5.16	78
21-Mar-89	H-F30			6755		24.8	4.64	88
23-May-89	H-F30			6325		25.5	5.20	95
21-Aug-89	H-F30			6752		26.5	4.90	83
9-Oct-89	H-F30			5841		24.8	4.65	88
18-Dec-89	H-F30			5261		24.0	5.70	74
24-Feb-90	H-F30			5126		24.0	4.20	70
26-Jun-90	H-F30			6089		25.0	4.60	81
20-Jun-88	H-G15		350					
29-Jun-88	H-G15		858					
11-Jul-88	H-G15		452	23539		27.0	5.30	133
27-Jul-88	H-G15		251	23022	23	25.0	5.07	109
14-Sep-88	H-G15		92	20446		25.2	4.64	132
26-Oct-88	H-G15		501	20468	9	27.5	4.65	122
7-Dec-88	H-G15		460	20140		27.0	4.38	112
30-Jan-89	H-G15	0.95	391	22648	33	22.2	4.45	105
21-Mar-89	H-G15	1.88	240	19374	16	22.6	3.80	102
23-May-89	H-G15	2.57	307	15433		25.0	4.40	108
21-Aug-89	H-G15	2.39	330	20375		27.0	4.48	98

Table A-4 Continued

Date	Location	Radon Flux pCi/m^2 sec	Radon Soil Conc pCi/L	Radon Water Conc pCi/L	Po-210 pCi/L	Temp ^oC	pH	Cond µS
9-Oct-89	H-G15		264	22252		27.1	4.00	93
18-Dec-89	H-G15	2.17	373	20098		24.1	3.00	90
24-Feb-90	H-G15		611	21281		24.0	4.05	90
26-Jun-90	H-G15		698	21024		25.0	4.00	91
11-Jul-88	H-G30			14671		24.8	5.40	188
27-Jul-88	H-G30			13154	273	25.2	5.67	110
14-Sep-88	H-G30			13637		24.0	5.41	78
26-Oct-88	H-G30			13481	271	25.3	5.10	72
7-Dec-88	H-G30			13551	175	25.0	4.96	70
30-Jan-89	H-G30			14327		24.0	4.98	68
21-Mar-89	H-G30			11677	260	24.0	4.40	70
23-May-89	H-G30			11315		25.0	5.00	75
21-Aug-89	H-G30			12447		25.2	4.80	65
9-Oct-89	H-G30			9755		25.2	4.40	63
18-Dec-89	H-G30			10168		24.0	4.25	58
24-Feb-90	H-G30			11012		25.0	4.70	64
26-Jun-90	H-G30			8854		25.0	4.70	62
20-Jun-88	H-H15		341					
28-Jun-88	H-H15		671	21571	22	24.0	3.90	78
11-Jul-88	H-H15			22426	12	24.0	4.40	102
27-Jul-88	H-H15		33	24478	16	24.6	4.82	85
26-Oct-88	H-H15			23088	18	24.6	5.00	84
7-Dec-88	H-H15		8					
30-Jan-89	H-H15	0.62	25					
21-Mar-89	H-H15	0.71	103	20213	12	22.0	4.38	81
23-May-89	H-H15	2.01	499	16753	37	25.5	4.20	87
21-Aug-89	H-H15	2.18	149	20129	11	25.1	4.70	79
9-Oct-89	H-H15	1.58	52	19586	14	25.8	4.35	78
18-Dec-89	H-H15	0.78						
24-Feb-90	H-H15	0.46						
28-Jun-88	H-H30			27839		24.0	5.20	144
11-Jul-88	H-H30			29299	25	26.5	5.80	135
27-Jul-88	H-H30			35834	35	23.8	6.11	129
26-Oct-88	H-H30			36261	18	24.6	6.03	119
21-Mar-89	H-H30			29553		22.8	5.60	125
23-May-89	H-H30			23352		24.0	5.80	151
21-Aug-89	H-H30			28028		24.5	5.60	132
9-Oct-89	H-H30			22708		24.7	5.10	152
20-Jun-88	H-I15		111					
28-Jun-88	H-I15			10344	178	25.0	4.10	128

Table A-4 Continued

Date	Location	Radon Flux pCi/m² sec	Radon Soil Conc pCi/L	Radon Water Conc pCi/L	Po-210 pCi/L	Temp °C	pH	Cond µS
11-Jul-88	H-I15		75	11580	243	27.0	4.10	123
27-Jul-88	H-I15		2	11279	337	26.3	4.61	118
14-Sep-88	H-I15		11	11540		26.0	4.49	123
26-Oct-88	H-I15	0.58	65	10690	275	26.5	4.37	120
7-Dec-88	H-I15	0.21	61	10231	107	26.2	4.11	121
30-Jan-89	H-I15	1.08	70	12174	18	24.0	4.25	112
21-Mar-89	H-I15	0.77	79	10409	200	23.5	3.70	125
23-May-89	H-I15		123	9136		25.5	4.00	139
21-Aug-89	H-I15		109	9880	333	26.5	4.15	119
9-Oct-89	H-I15		111	9310	248	26.2	3.75	112
18-Dec-89	H-I15	0.46	108	9481	303	29.0	4.30	110
24-Feb-90	H-I15	0.68	92	9901	322	24.0	3.60	104
26-Jun-90	H-I15		135	9402	314	26.0	3.60	108
20-Jun-88	H-J15		199					
28-Jun-88	H-J15		394	32633	26	23.9	3.90	38
11-Jul-88	H-J15		341	33184	48	25.5	4.20	34
27-Jul-88	H-J15		43	36334	53	24.5	5.00	37
14-Sep-88	H-J15		53	35692	55	24.9	4.97	41
26-Oct-88	H-J15	0.83	121	35063	45	25.2	4.85	31
7-Dec-88	H-J15		234	35160	13	24.5	4.91	30
30-Jan-89	H-J15	1.14	166	38172	42	24.1	4.43	27
21-Mar-89	H-J15		164	31468	50	23.5	4.10	28
23-May-89	H-J15	3.21	233	30980	52	23.9	4.60	300
21-Aug-89	H-J15		223	31825	42	26.0	4.90	29
9-Oct-89	H-J15	1.32	207	31764	46	25.5	4.20	27
18-Dec-89	H-J15	1.89	238	30256	44	23.0	4.50	27
24-Feb-90	H-J15	1.61	230	33467		22.5	4.00	22
26-Jun-90	H-J15	1.07	171	33473	65	24.0	4.30	
20-Jun-88	H-K15		45					
28-Jun-88	H-K15		41	6524		25.3	5.30	115
11-Jul-88	H-K15		53	6244		26.5	4.60	100
27-Jul-88	H-K15		28	7074	14	26.0	5.53	68
14-Sep-88	H-K15		13	3257	8	26.2	5.40	62
27-Oct-88	H-K15	0.14	12	4809	22	26.2	4.84	50
7-Dec-88	H-K15		19	5049	13	24.5	4.65	45
30-Jan-89	H-K15	0.20	21	6489	17	22.4	4.23	50
21-Mar-89	H-K15	0.17	15	5179	19	27.0	4.00	58
23-May-89	H-K15	0.22	35	6207		24.5	5.20	400
21-Aug-89	H-K15		23	7140	18	28.0	4.35	68
9-Oct-89	H-K15		17	6338	20	26.5	3.90	70
18-Dec-89	H-K15	0.24	35	7758	29	22.2	3.99	61
24-Feb-90	H-K15	0.19	47	7332	31	20.9	3.80	43
26-Jun-90	H-K15	0.73	120	7393	14	25.0	4.00	43

Table A-4 Continued

Date	Location	Radon Flux pCi/m^2 sec	Radon Soil Conc pCi/L	Radon Water Conc pCi/L	Po-210 pCi/L	Temp ^oC	pH	Cond µS
Summary	Average =	1.41	186	13453	163	25.1	4.68	128
	sd =	2.18	324	9178	184	1.9	0.63	87
	Minimum =	0.04	1	818	2	14.4	3.00	12
	Maximum =	9.51	1871	38206	994	38.0	7.20	790
	n =	98	184	304	169	303	296	302

Table A-5. Results of radon flux and concentrations in soil gas and shallow groundwater from the Leon County test site. Po-210 concentrations and water quality parameters are also shown.

Date	Location	Radon Flux pCi/m^2 sec	Radon Soil Conc pCi/L	Radon Water Conc pCi/L	Po-210 pCi/L	Temp °C	pH	Cond µS
18-Aug-88	L-A		30					
19-Aug-88	L-A		30					
2-Sep-88	L-A							
20-Sep-88	L-A		36					
3-Nov-88	L-A		25					
18-Jan-89	L-A	0.23	29					
16-Mar-89	L-A	0.22	26					
26-Apr-89	L-A	0.19	86					
22-Jun-89	L-A	0.26	56					
17-Aug-89	L-A	0.22	42		0.4	24.0	5.00	38
28-Sep-89	L-A	0.32	36					
31-Jan-90	L-A		52		1.8	18.5	4.30	29
9-Jul-90	L-A	0.27	27					
18-Aug-88	L-B		46					
19-Aug-88	L-B		46					
2-Sep-88	L-B		62	98	1.8	21.2	4.54	23
21-Sep-88	L-B		43	171	1.4	21.9	5.28	22
4-Nov-88	L-B			160	1.3	21.9	4.80	18
19-Jan-89	L-B	0.53	30	<50		21.7	4.40	19
16-Mar-89	L-B	0.46	50	<50	11.7	19.0	4.30	19
26-Apr-89	L-B	0.20	48	<50	2.2	21.0	4.60	19
22-Jun-89	L-B	1.00	78	53	3.0	21.8	6.50	20
17-Aug-89	L-B	0.35	43	71		22.5	5.00	20
28-Sep-89	L-B	0.47	40	169	2.5	22.5	4.40	39
31-Jan-90	L-B	0.43	53	132	0.7	18.2	3.82	20
9-Jul-90	L-B	0.35	46	103	2.0	21.9	4.40	12
18-Aug-88	L-C		32					
19-Aug-88	L-C		27					
2-Sep-88	L-C		37					
20-Sep-88	L-C		30					
3-Nov-88	L-C	0.08	23					
18-Jan-89	L-C	0.14	26					
16-Mar-89	L-C	0.17	32					
26-Apr-89	L-C	0.16	32					
22-Jun-89	L-C	0.15	12					
17-Aug-89	L-C	0.23	15					
28-Sep-89	L-C	0.22	28					
31-Jan-90	L-C	0.22	31					

Table A-5 Continued

Date	Location	Radon Flux pCi/m^2 sec	Radon Soil Conc pCi/L	Radon Water Conc pCi/L	Po-210 pCi/L	Temp °C	pH	Cond µS
9-Jul-90	L-C	0.13	19					
18-Aug-88	L-D		34					
19-Aug-88	L-D		36					
2-Sep-88	L-D		32					
20-Sep-88	L-D		25					
3-Nov-88	L-D	0.29	31					
18-Jan-89	L-D	0.38	26					
16-Mar-89	L-D	0.28	28					
26-Apr-89	L-D	0.33	31					
22-Jun-89	L-D	0.50	54					
17-Aug-89	L-D	0.25	52					
28-Sep-89	L-D	0.30	44					
31-Jan-90	L-D	0.48	80					
9-Jul-90	L-D	0.33	27					
18-Aug-88	L-E		31					
19-Aug-88	L-E		30					
2-Sep-88	L-E		41	315		22.5	4.95	38
21-Sep-88	L-E		43	247		25.1	5.79	40
4-Nov-88	L-E	0.20	43	105	18.7	23.9	4.69	38
18-Jan-89	L-E	0.25	34					
16-Mar-89	L-E	0.21	38					
26-Apr-89	L-E	0.18	58					
22-Jun-89	L-E	0.24	55					
17-Aug-89	L-E	0.28	47	101	3.5	25.5	5.20	21
28-Sep-89	L-E	0.44	31	177		23.0	6.20	20
31-Jan-90	L-E	0.31	56					
9-Jul-90	L-E	0.23	35	177	4.6	25.5	6.4	25
2-Sep-88	USGS							
21-Sep-88	USGS							
4-Nov-88	USGS			465		23.0	4.94	52
18-Jan-89	USGS	0.23	18					
16-Mar-89	USGS			336	1.8	21.8	5.38	50
26-Apr-89	USGS	0.29	31	280	1.5	20.8	5.40	39
22-Jun-89	USGS	0.29	52	291	2.1	22.0		49
17-Aug-89	USGS	0.29	34	292	1.3	22.2	5.00	40
28-Sep-89	USGS	0.21	26	353	0.5	22.5	5.00	38
31-Jan-90	USGS	0.30	33	377	0.5	20.1	4.31	31
9-Jul-90	USGS	0.29	29	324	1.1	22.0	5.00	28

Table A-5 Continued

Date	Location	Radon Flux pCi/m^2 sec	Radon Soil Conc pCi/L	Radon Water Conc pCi/L	Po-210 pCi/L	Temp ^oC	pH	Cond µS
Summary:	Average =	0.29	38	194	3.1	22.1	4.98	29
	sd =	0.14	14	125	4.3	1.8	0.67	11
	Minimum =	0.08	12	<50	0.4	18.2	3.82	12
	Maximum =	1.00	86	465	18.7	25.5	6.50	52
	n =	49	70	25	21	27	26	27

Table A-6 Radiochemical analyses of soil from cores and surface samples collected from each of the three study sites. Cores were recovered during establishment of monitor wells at stations A-C, H-B, and L-D. Surface soil samples were collected from the same stations where soil radon and flux measurements were made.

Depth (ft) or Site	Pb-210 (dpm/g)	Ra-226 (dpm/g)	U-238 (dpm/g)	Ac-228 (dpm/g)	Tl-208 (dpm/g)
		Alachua Core Profile (A-C)			
1.0	2.1 ± 1.9	2.4 ± 0.2	6.3 ± 1.8		0.1 ± 0.1
3.0	3.0 ± 1.1	2.4 ± 0.2	1.9 ± 0.4	2.0 ± 0.4	
5.0	11.2 ± 1.8	9.1 ± 0.5			1.4 ± 0.2
7.0	5.5 ± 1.8	5.3 ± 0.4	0.4 ± 0.2	1.2 ± 0.5	
9.0	14.0 ± 2.6	12.4 ± 0.8	14.8 ± 2.3		
11.0	16.2 ± 1.8	14.0 ± 0.5	15.5 ± 1.2	2.3 ± 0.6	
13.0	56.2 ± 2.7	49.1 ± 1.2	74.9 ± 3.1		
15.0	50.1 ± 2.5	42.6 ± 0.9	51.7 ± 2.4	3.0 ± 0.8	
17.0	48.5 ± 2.2	44.5 ± 0.8	56.4 ± 2.2	3.9 ± 0.8	
19.0	33.1 ± 3.6	34.7 ± 1.6	29.2 ± 2.9		0.3 ± 0.1
21.0	57.9 ± 2.8	48.3 ± 1.1	57.9 ± 2.7	4.8 ± 1.1	1.0 ± 0.2
23.0	45.5 ± 2.3	46.9 ± 0.9	54.0 ± 2.6	1.9 ± 0.6	2.5 ± 0.3
25.0	5.5 ± 1.5	4.4 ± 0.3	3.9 ± 1.0	3.6 ± 0.7	0.7 ± 0.1
27.0	17.6 ± 1.7	17.7 ± 0.6	18.9 ± 1.6		0.3 ± 0.1
29.0	20.4 ± 2.8	16.3 ± 0.7	9.9 ± 1.4		
		Hillsborough Core Profile (H-B)			
1.0		1.2 ± 0.3	2.7 ± 0.5		0.6 ± 0.1
3.0	0.8 ± 0.4	0.8 ± 0.2	1.0 ± 0.3		0.6 ± 0.1
5.0	1.9 ± 0.7				
7.0	0.6 ± 0.3	0.7 ± 0.2	0.9 ± 0.3		
9.0					
11.0	12.5 ± 1.7	12.3 ± 0.6	15.1 ± 1.8		
13.0	13.2 ± 1.0	12.9 ± 0.4	20.3 ± 1.1	4.8 ± 0.1	0.7 ± 0.1
15.0	10.4 ± 1.9	8.7 ± 0.5	8.9 ± 1.4	0.2 ± 0.1	
17.0	7.4 ± 1.1	6.5 ± 0.4	15.2 ± 1.1		
19.0	3.5 ± 0.4	4.4 ± 0.2	9.6 ± 0.6		
21.0	76.2 ± 3.4	70.6 ± 1.8	89.6 ± 3.4		
23.0	27.3 ± 2.1	30.4 ± 0.9	29.3 ± 2.3		
25.0	152.0 ±10.8	154.0 ± 4.9	125.3 ± 9.9		
27.0	39.8 ± 3.0	44.8 ± 1.4	38.3 ± 3.0		
29.0	14.1 ± 1.7	16.2 ± 0.7	14.7 ± 1.8	2.2 ± 0.6	0.3 ± 0.1
		Leon Core Profile (L-D)			
2.0	3.6 ± 1.3	0.7 ± 0.1	1.0 ± 0.5	1.2 ± 0.4	0.4 ± 0.1
4.0		0.5 ± 0.2	2.9 ± 0.8	0.4 ± 0.3	0.8 ± 0.1
6.0		0.8 ± 0.2	0.7 ± 0.3	0.3 ± 0.2	0.5 ± 0.1
9.0		0.7 ± 0.2	0.7 ± 0.3	0.8 ± 0.2	0.6 ± 0.1
11.0		0.5 ± 0.3	0.1 ± 0.2	0.0 ± 0.2	0.7 ± 0.1

Table A-6. Continued

Depth (ft) or Site	Pb-210 (dpm/g)	Ra-226 (dpm/g)	U-238 (dpm/g)	Ac-228 (dpm/g)	Tl-208 (dpm/g)
13.0					
18.0		0.8 ± 0.2	0.4 ± 0.2		
25.0		1.5 ± 0.3	3.2 ± 1.0	0.4 ± 0.3	1.1 ± 0.2
27.0	1.8 ± 0.6	0.4 ± 0.1			
32.0	0.6 ± 0.4	2.0 ± 0.4	0.2 ± 0.1		
37.0		0.4 ± 0.2		0.7 ± 0.3	0.7 ± 0.1
39.0		0.8 ± 0.2	0.5 ± 0.4		0.4 ± 0.2
41.0	0.6 ± 0.3	1.8 ± 0.2	1.9 ± 0.3	1.6 ± 0.2	
		Alachua Surface Soil			
A-A	±	1.3 ± 0.2	0.6 ± 0.4	0.2 ± 0.3	0.8 ± 0.2
A-B	0.9 ± 0.5	1.5 ± 0.2	2.4 ± 0.9		0.7 ± 0.2
A-C	0.1 ± 0.2	1.5 ± 0.2		1.2 ± 0.4	0.9 ± 0.2
A-D	0.6 ± 0.4		0.9 ± 0.5		0.9 ± 0.2
A-E	0.2 ± 0.2	0.6 ± 0.1		1.3 ± 0.4	0.7 ± 0.1
A-F	1.1 ± 0.6	2.2 ± 0.3	2.0 ± 1.0	0.4 ± 0.3	0.7 ± 0.1
A-G		0.9 ± 0.2	2.3 ± 0.6	0.9 ± 0.3	0.7 ± 0.1
A-H	2.2 ± 0.8	5.2 ± 0.4	7.4 ± 1.1	0.7 ± 0.3	0.6 ± 0.1
138	0.7 ± 0.3		2.0 ± 0.6		0.6 ± 0.1
151		1.3 ± 0.3	1.1 ± 0.4	0.3 ± 0.3	0.7 ± 0.1
152	2.3 ± 0.9	0.8 ± 0.1	0.8 ± 0.4	1.7 ± 0.4	0.1 ± 0.1
154	1.0 ± 0.8	1.3 ± 0.2	0.8 ± 0.3		0.2 ± 0.1
		Hillsborough Surface Soil			
H-C	2.2 ± 1.1	2.4 ± 0.2	2.8 ± 0.6	1.3 ± 0.4	0.3 ± 0.1
H-D	2.6 ± 0.9	0.5 ± 0.1	0.3 ± 0.1	1.9 ± 0.4	
H-E	1.8 ± 0.9	0.6 ± 0.1	1.1 ± 0.5	1.6 ± 0.4	0.2 ± 0.1
H-F		0.3 ± 0.1	1.5 ± 0.9	1.9 ± 0.6	0.1 ± 0.1
H-H	5.3 ± 1.0	2.8 ± 0.2			0.3 ± 0.7
H-G	2.4 ± 0.9	1.7 ± 0.2			0.3 ± 0.1
H-I		0.5 ± 0.1	1.3 ± 0.4	1.1 ± 0.3	
H-J	1.5 ± 1.0	2.4 ± 0.2		1.8 ± 0.4	
H-K	1.3 ± 0.5	0.7 ± 0.1			0.2 ± 0.1
10	0.7 ± 0.7	0.8 ± 0.1	0.9 ± 0.3		0.2 ± 0.1
18	1.9 ± 0.8	1.0 ± 0.2	0.2 ± 0.1		0.4 ± 0.1
		Leon Surface Soil			
L-A		1.4 ± 0.3	1.6 ± 0.6		0.6 ± 0.1
L-B		0.4 ± 0.1	3.7 ± 0.7	0.6 ± 0.3	0.7 ± 0.1
L-C		0.3 ± 0.1	0.5 ± 0.3		0.6 ± 0.1

Table A-7 Results for ^{210}Po, ^{222}Rn, temperature, pH and conductivity for untreated well water from station 18, Hillsborough County test site, before and after treatment by four different water purification systems.

Date	Total Po-210 (pCi/L)	Rn-222 (pCi/L)	Temp (°C)	pH	Cond (µS)
		Untreated			
14-Sep-88	502.3 ± 13.3	18002 ± 122	28.8	5.86	52
26-Oct-88	551.4 ± 6.9	21327 ± 307	21.0	3.88	40
7-Dec-88	453.7 ± 8.3	20607 ± 704	21.8	4.26	39
30-Jan-89	434.5 ± 2.1	20759 ±1772	20.4	4.44	35
21-Mar-89	424.3 ± 4.6	18696 ± 211	24.5	4.30	38
22-Aug-89	553.0 ± 5.5	19376 ± 102	25.8	4.35	35
9-Oct-89	563.2 ± 5.0	17099 ± 178	25.8	4.10	34
18-Dec-89	489.1 ± 4.8	15212 ± 148	23.5	3.80	30
3-Apr-94	220.2 ± 1.7	17432 ± 175			
27-Jun-94	658.9 ± 5.4	15240 ± 182	25.0	4.30	42
		Activated Carbon			
14-Sep-88	1.0 ± 0.1	96 ± 10	29.0		470
26-Oct-88	0.3 ± 0.1	<50 ±	21.0	7.64	461
7-Dec-88		179 ± 208	23.0	6.82	220
30-Jan-89		<50 ±	22.2	6.20	218
21-Mar-89	6.0 ± 0.3	<50 ±	24.5	5.40	228
22-Aug-89	3.3 ± 0.3	<50 ±	25.8	6.00	170
9-Oct-89	13.2 ± 2.0	<50 ±	26.0	5.00	170
18-Dec-89	1.5 ± 0.1	<50 ±	23.0	5.00	132
3-Apr-94	1.2 ± 0.0	<50 ±			
27-Jun-94	1.5 ± 0.1	120 ± 12	25.0	5.50	106
		Mixed Bed Deionizing Resin			
14-Sep-88	1.2 ± 0.1	150 ± 11	28.3		0
26-Oct-88	0.2 ± 0.0	19019 ± 134			
7-Dec-88		8822 ± 148	23.0	5.40	0
30-Jan-89		3969 ± 160	17.5	6.70	0
21-Mar-89	16.0 ± 0.3	16519 ± 269	24.6	3.40	0
22-Aug-89	3.7 ± 0.3	17873 ± 102	25.8	4.70	0
9-Oct-89	4.9 ± 0.3	15883 ± 110	25.8	5.40	0
18-Dec-89	1.5 ± 0.2	14952 ± 224	23.0	5.15	0
3-Apr-94	1.6 ± 0.1	17148 ± 185			
27-Jun-94	3.4 ± 0.1	14535 ± 346	25.0	4.50	0
		Manganese Greensand			
14-Sep-88	2.0 ± 0.2	6176 ± 814	28.0	8.00	321
26-Oct-88	7.1 ± 0.3	17392 ± 107	21.2	6.85	268
7-Dec-88		15294 ± 218	23.2	6.68	228
30-Jan-89		16944 ± 62	21.3	6.33	220
21-Mar-89	1.0 ± 0.0	17911 ± 221	25.0	6.20	195
22-Aug-89	22.3 ± 0.0	17855 ± 173	25.8	5.60	192

Table A-7 Continued

Date	Total Po-210 (pCi/L)	Rn-222 (pCi/L)	Temp (°C)	pH	Cond (µS)
9-Oct-89	12.9 ± 0.4	17720 ± 98	25.8	5.30	160
18-Dec-89	21.2 ± 0.4	15193 ± 201	23.0	5.20	142
3-Apr-94	5.3 ± 0.1	17096 ± 436			
27-Jun-94	10.0 ± 0.2	16884 ± 565	25.2	5.60	160
		Water Softener			
14-Sep-88	3.3 ± 0.2	<50	29.0		222
26-Oct-88	55.6 ± 1.2	19628 ± 232	24.3	5.54	100
7-Dec-88		14998 ± 144	23.0	5.42	80
30-Jan-89		9522 ± 158	17.6	5.10	72
21-Mar-89	18.3 ± 0.4	17393 ± 446	24.5	5.50	75
22-Aug-89	14.5 ± 0.4	17730 ± 185	25.8	5.60	72
9-Oct-89	7.5 ± 0.3	16955 ± 282	25.8	5.35	68
18-Dec-89	22.2 ± 0.4	14531 ± 416	23.1	5.00	55
3-Apr-94	10.0 ± 0.2	16884 ± 565			
27-Jun-94	88.3 ± 1.1	15051 ± 368	25.0	5.30	52