

INFLUENCE OF GEOLOGY ON RADON IN GROUND WATER  
SUPPLIES OF THE NEW JERSEY HIGHLANDS

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## ABSTRACT

Ground water radon concentrations were determined in three types of Middle Proterozoic rocks in the New Jersey Highlands. The rock types (hornblende granite, quartz-oligoclase gneiss, and pyroxene granite) were selected because of their suspected uranium contents (high, low, and low, respectively). It was hypothesized that high ground water radon concentrations might be associated with uranium-bearing rock units. Radon concentrations in 154 wells ranged from 36 pCi/L to 24,000 pCi/L (picocuries per liter) with a geometric mean and a median of 1600 pCi/L. Radon levels were greater than 300 pCi/L (USEPA's proposed MCL for radon in drinking water) in 90% of the wells. None of the rock units studied had ground water radon levels consistently low enough to be regarded as a low priority for testing. Local mineralogy and structure were found to influence ground water radon concentrations. In highly deformed rock units, such as those in the New Jersey Highlands, there is considerable heterogeneity. Migmatites, alaskites and pegmatites which may not appear on a geologic quadrangle map due to their small size or because they are not exposed can affect radioactivity on a local scale.

## ACKNOWLEDGEMENTS

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## EXECUTIVE SUMMARY

Existing data on human exposure to high radon-222 concentrations in indoor air have prompted concern regarding radon sources in homes. The U. S. Environmental Protection Agency (USEPA) has estimated that radon in indoor air causes 21,000 lung cancer deaths each year in the United States. While the primary radon source is believed to be the rock and soil surrounding and underlying the building foundation, well water can also be a significant source. The USEPA is in the process of setting a Maximum Contaminant Level (MCL) for radon in drinking water.

High ground water radon concentrations have been found in parts of New England that are geologically similar to the New Jersey Highlands. The similarities prompted the New Jersey Department of Environmental Protection and Energy's (NJDEPE) Division of Science and Research (DSR), New Jersey Geological Survey (NJGS), and Princeton University (PU) to investigate ground water radon concentrations within crystalline rocks of the New Jersey Highlands (Figures 1 and 2, in text).

Radon is formed from the radioactive decay of radium. Both are members of the uranium decay series (Figure 3). The concentration and distribution of the uranium in the rock helps to determine the availability of uranium, radium, and radon for dissolution in and transport by ground water.

The Highlands is a geologic province with elevated (that is, above average) crustal rock uranium concentrations. Because radon is part of the uranium decay series, it was hypothesized that high ground water radon concentrations might be associated with uranium-bearing rock units. Information on uranium occurrence in the New Jersey Highlands is available from several sources, described in the body of the report.

The objectives of this research project were to (1) study the influence of geology on ground water radon concentration, (2) collect data about radon occurrence in ground waters of the Highlands and (3) determine if it is possible to predict areas at risk of having elevated ground water radon concentrations. This information could aid NJDEPE in developing a comprehensive, cost-effective monitoring program for radon in ground water. In particular, this study focused on determining the variability and content of radon in ground water for several rock types in the New Jersey Highlands.

Three types of Middle Proterozoic rocks were studied in this work: hornblende granite, quartz-oligoclase gneiss, and pyroxene granite. These three rock types were selected because of their suspected uranium contents (high, low, and low, respectively). For each rock unit, two discrete portions of the unit found at different locations were sampled (Figure 2). Well selection was based primarily on spatial distribution and well accessibility. In addition, all accessible public community water supply wells located in targeted rock units were sampled.

The ground water sampling method used was developed by the USGS for sampling radon. Samples were taken as close to the well head as possible, before water entered the house's pipes or any home water treatment system. Flow rate was monitored and the amount withdrawn was estimated. The pH, temperature, dissolved oxygen concentration, and specific conductivity were continually monitored, and generally stabilized after 30 minutes to an hour of pumping. Stabilization was assumed to indicate that standing water had been pumped from the well and fresh ground water could be sampled. If stabilization did not occur, researchers collected the water sample after an hour of pumping. Samples were delivered to Princeton University's Ocean Tracers Laboratory (OTL) at the end of the field day, and counted within 48 hours, using a modified version of the Lucas cell scintillation technique.

A variety of quality assurance/quality control measures were incorporated. Blanks were run on empty sample bottles and found to be negligible relative to the activity of the samples. Dilutions of radium-226 standards were run every two weeks on each of the Lucas cells used. Duplicate field samples were taken at 31 of the 154 wells. As an additional quality assurance measure, 20 split samples were collected and analyzed using both OTL's Lucas cell method and the liquid scintillation method of the NJDEPE's Bureau of Radiation and Inorganic Analytical Services. There appeared to be no systematic differences between the two methods.

In total, 154 wells were sampled in or near the rock units. The location of each well was entered into NJDEPE's Geographic Information System (GIS). Two types of statistical analyses were conducted: descriptive statistics (e.g., frequency distributions, medians, geometric means, maxima and minima) and linear regression modeling.

Radon concentrations for all wells sampled ranged from 36 pCi/L to 24,000 pCi/L. The geometric mean and the median were both 1600 pCi/L (Figure 9). Ninety percent of the wells sampled in this study had radon levels greater than 300 pCi/L, which USEPA has proposed as the MCL for radon in drinking water.

Ground water radon concentrations of three crystalline rock units in the New Jersey Highlands were characterized. Different rock units had significantly different ground water radon concentrations, although there was overlap among all units (Table 1). With one exception, the trend for each unit was as expected from geochemical information on uranium content of the respective units that was reviewed prior to the testing. Units of the same rock type generally had similar ground water radon concentrations. However, in the Hamburg quartz-oligoclase gneiss unit, subsequently found to contain microperthite alaskite veins and seams (which have elevated uranium content) the values were higher than expected.

Wells located within 320 feet of a unit contact were associated with a small but statistically significant increase in ground water radon levels within each rock unit. It is not known whether this statistical effect is due to an underlying physical cause. In several rock units, shallower wells were associated with higher radon levels than deeper wells, but this association was not seen consistently throughout all units.

Local mineralogy and structure were found to influence ground water radon concentrations. In highly deformed rock units, such as those in the Highlands, there is considerable heterogeneity in the rock units. Migmatites, alaskites and pegmatites which may not appear on a geologic quadrangle map (due to their small size or because they are not exposed) can affect radioactivity on a local scale. Low uranium concentration rock at the surface may overlies different, higher uranium concentration rock. This could cause a high ground water radon concentration in a well drilled through uranium-poor rock at the surface which draws water from a deeper, uranium-rich rock. Similarly, a high ground water radon concentration could occur if a well drew water from a uranium-rich fault zone, located at depth but having no surface expression.

This study complements a number of other recently completed studies investigating radon levels in ground water supplies in New Jersey. Taken together, results from the various studies provide a consistent picture of the occurrence and geographical distribution of radon in the state's ground water. The highest ground water radon concentrations in New Jersey are generally found in the Highlands (NJDEPE 1989). Levels as high as several hundred thousand picocuries per liter were measured in wells in the Highlands (NJDEPE 1988). However, data from the southern Piedmont show that, while average ground water radon concentrations are generally lower than those in the Highlands, wells with high levels (between 10,000 and 100,000 pCi/L) do occasionally occur (Zapczka

and Szabo 1987). The highest level found to date in the Coastal Plain is 2,200 pCi/L (Kozinski and others 1991).

This research shows that geologic models of uranium occurrence can help guide the use of limited resources in identifying areas with elevated ground water radon concentrations. Certain rocks known to be uraniferous are associated with elevated levels of radon in ground water. However, if only uranium occurrence data are used as a search criterion, then areas of high ground water radon concentrations may be overlooked. Also, there is always a possibility that uraniferous zones could remain undetected when an area is surveyed. Thus, reports of high levels of radon in air or water can provide important data that spurs mineralogical and structural investigation in an area.

An important aspect of this project was investigating whether it was possible, based on geology and well sampling, to rank areas most critical for ground water radon sampling in the New Jersey Highlands. While on a statewide scale, it is clear that there are areas of higher and lower ground water radon concentrations, this research suggests that it is difficult to predict locally where high ground water radon concentrations may occur. In addition, even the low uranium rock units studied had many wells with ground water radon concentrations higher than the USEPA's proposed MCL.

This research suggests that when the USEPA promulgates the radon in drinking water MCL, even if the final MCL is ten times higher than proposed MCL, many of the wells sampled in this study, and indeed in northwestern New Jersey, will exceed the MCL. In July 1991, the USEPA proposed an MCL of 300 pCi/L. Ninety percent of the wells sampled in this study had ground water radon concentrations greater than 300 pCi/L. Additional research and policy development may be needed to enable NJDEPE to provide guidance to both public water supply operators and private well owners regarding radon in water testing and remediation.

## 1. Introduction

Existing data on human exposure to high radon<sup>1</sup> concentrations in indoor air have prompted concern regarding radon sources in homes. The U. S. Environmental Protection Agency (USEPA) estimates that radon in indoor air causes 21,000 lung cancer deaths each year in the United States (Schmidt and others 1990). While the primary radon source is believed to be the rock and soil surrounding and underlying the building foundation (Nazaroff and others 1987), it has been shown that well water can also be a significant source (Hess and others 1983). The USEPA is in the process of setting a Maximum Contaminant Level for radon in drinking water (USEPA 1986; USEPA 1991).

Extremely high ground water radon concentrations have been found in parts of New England that are geologically similar to the New Jersey Highlands. The similarities prompted the New Jersey Department of Environmental Protection and Energy's (NJDEPE) Division of Science and Research (DSR), New Jersey Geological Survey (NJGS), and Princeton University (PU) to investigate ground water radon concentrations within crystalline rocks of the New Jersey Highlands (Figures 1 and 2).

Radon is formed from the radioactive decay of radium. Both are members of the uranium decay series (Figure 3). The concentration and distribution of the uranium in the rock helps to determine the availability of uranium, radium, and radon for transport by and dissolution into ground water.

Geochemical processes occurring during rock formation and subsequent deformation may significantly affect the distribution of uranium in rock (Rich and others 1977). Volkert (1987a) has found that uranium distribution was more prevalent in rocks enriched

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<sup>1</sup>Throughout this report, radon is understood to refer to the isotope <sup>222</sup>Rn; uranium is <sup>238</sup>U; and radium is <sup>226</sup>Ra.

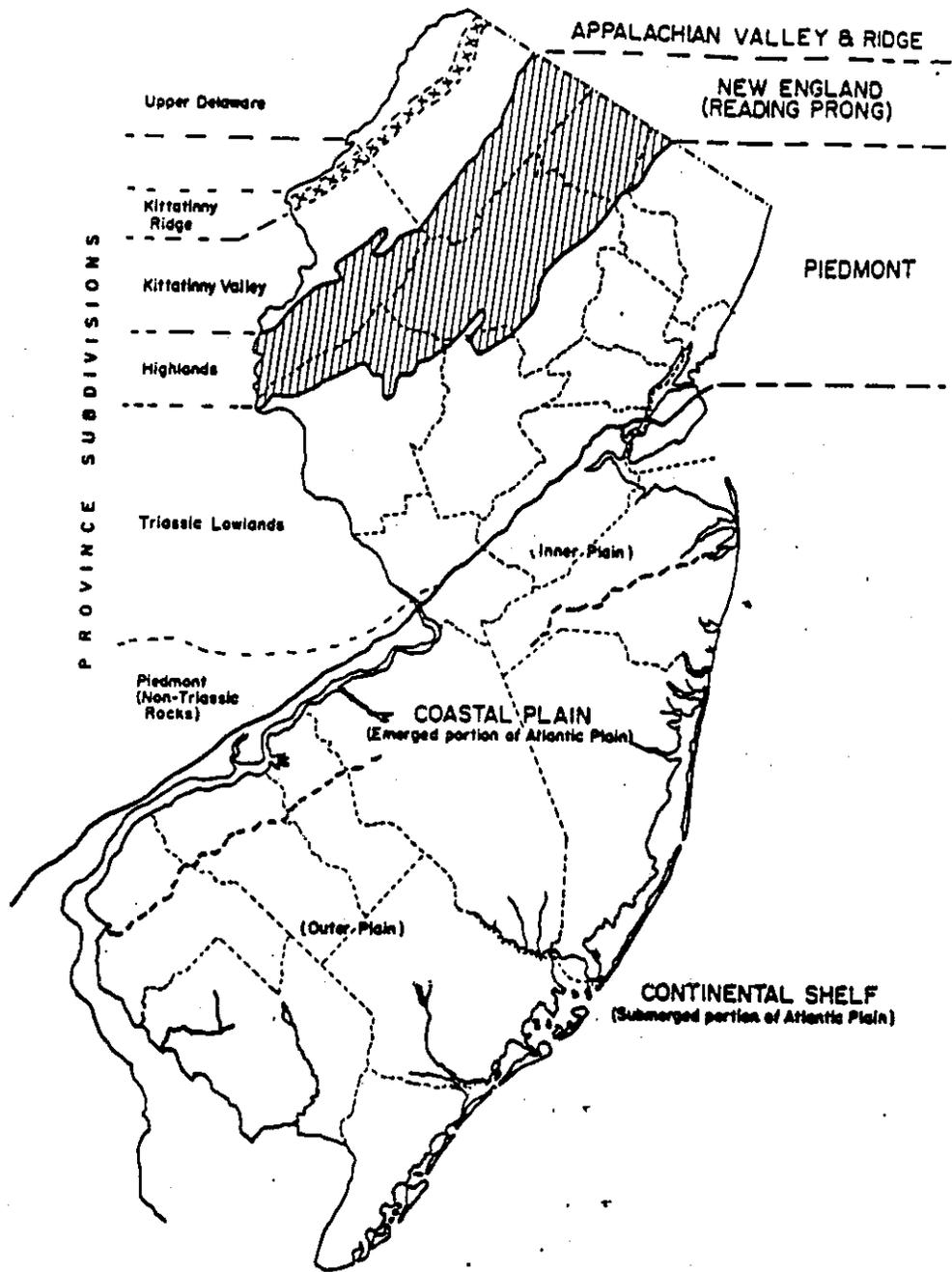


Figure 1. Physiographic provinces of New Jersey.

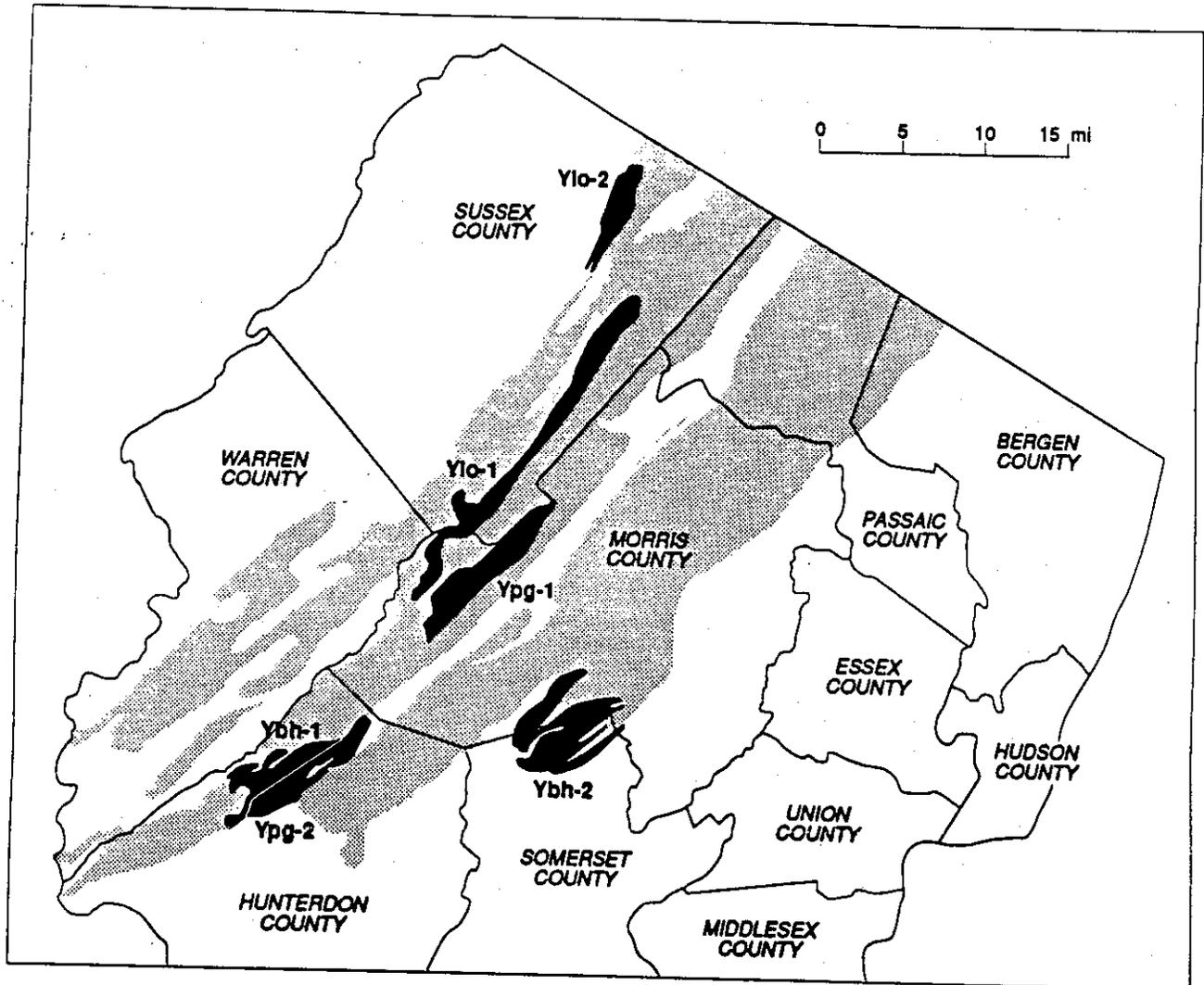


Figure 2. Shading indicates crystalline rocks of the New Jersey Highlands. Black areas indicate rock units studied: Ybh-1 = High Bridge hornblende granite; Ypg-2 = High Bridge pyroxene granite; Ybh-2 = Bernardsville hornblende granite; Ylo-1 = Stanhope quartz-oligoclase gneiss; Ypg-1 = Stanhope pyroxene granite; Ylo-2 = Hamburg quartz-oligoclase gneiss. Data source: Bedrock geology coverage in the NJDEPE GIS.

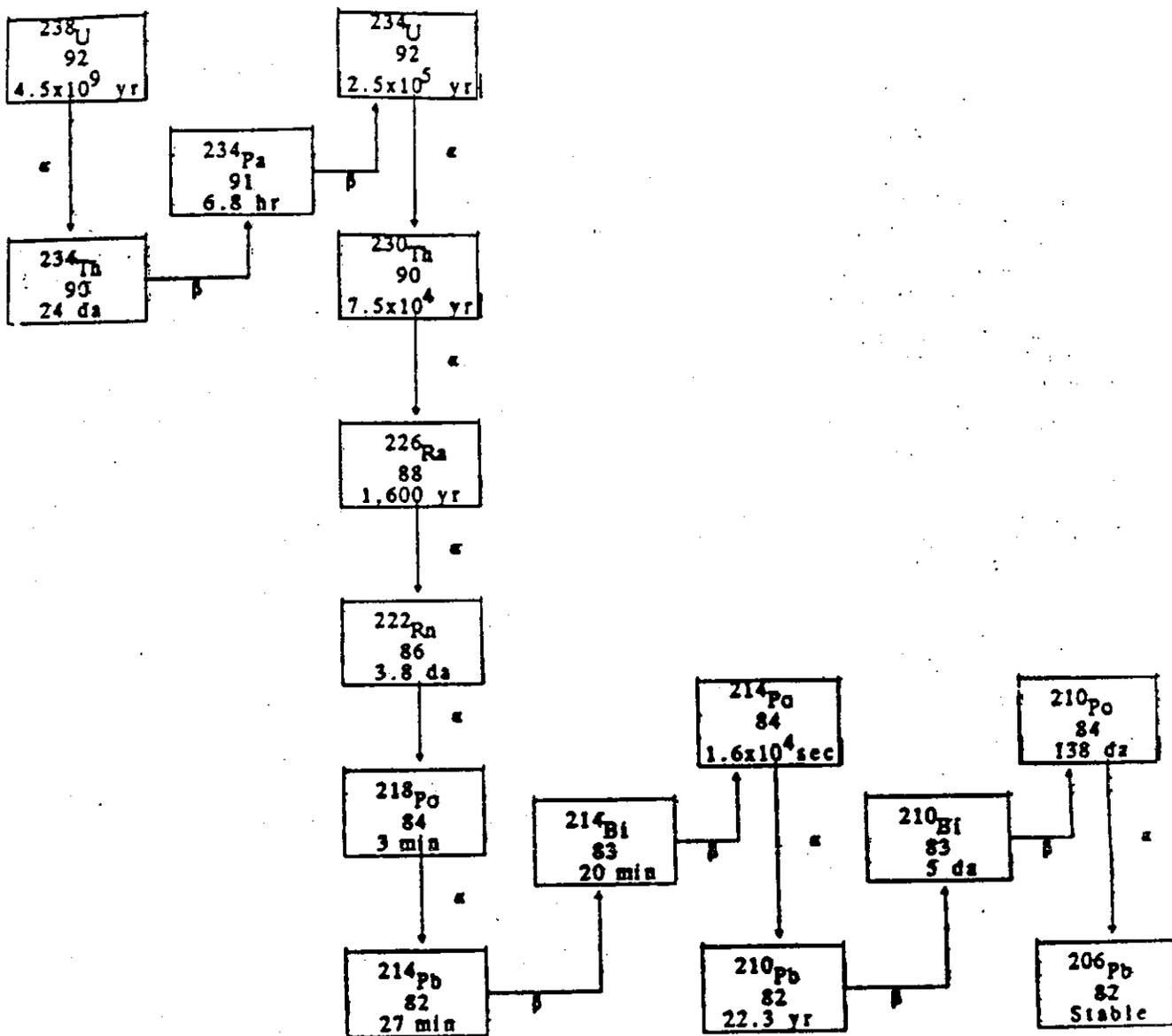


Figure 3. Uranium decay series.

in potassium and with high  $K_2O$  to  $Na_2O$  ratios. Rock chemistry is primarily controlled by chemical processes and pressure and temperature changes during rock formation and in non-granitic rocks by the relict chemistry of the protolith, that is, chemistry of the original rock that has persisted into the present rock in spite of metamorphism. Uranium occurrence in rocks is influenced by these processes (Durrance 1986). In addition, the presence of other trace elements can affect the availability of uranium and its decay products for transport by ground water. Uranium may be concentrated along faults in at least two possible ways. First, faults may be conduits for uranium-rich hydrothermal fluids. Alternately, uranium-bearing minerals may recrystallize along faults during shearing (Gunderson 1988).

Besides the occurrence of uranium in rocks, other factors such as well depth, well yield, and ground water chemistry may influence ground water radon concentrations (Brutsaert and others 1981). Ground water chemistry can be an important influence on radioactive disequilibrium between uranium and radium. The differing solubility and transport of these two elements in ground water can influence concentrations of radon in ground water (Wathen 1987).

The Highlands is a geologic province known to have elevated (that is, above average) crustal rock uranium concentrations. Because radon is part of the uranium decay series, it was hypothesized that high ground water radon concentrations might be associated with uranium-bearing rock units.

Uranium occurrence of rock units of the New Jersey Highlands has been documented in numerous studies over several decades. New Jersey Geological Survey Open-File Report 83-5, Radioactive mineral occurrences in New Jersey, by C. Bell provides referenced locational and descriptive data on more than 100 documented occurrences of radioactive minerals in northern New Jersey, of

which over 50 are of uranium, or uranium + thorium and/or rare earth elements. One of these studies, the National Uranium Resources Evaluation program (NURE) (Popper and Martin 1982) compiled aerial radiometric data showing Bismuth-214 anomalies, indicative of elevated uranium occurrences in the New Jersey Highlands and Piedmont.

This study complements a number of other recently completed research and monitoring studies investigating ground water radon concentrations in various parts of New Jersey. Two studies, the Confirmatory Monitoring Program (Cahill 1987; NJDEPE 1988) and Statewide Study of Radon by Camp Dresser & McKee (NJDEPE 1989) included wells in the crystalline rocks of the New Jersey Highlands, as well as in other rocks and physiographic provinces. Both studies included wells only at homes known to have radon in air screening levels above 4 pCi/L. The U.S. Geological Survey and NJDEPE are studying ground water radionuclide content in the Piedmont Province (Szabo and Zapecza 1987; Zapecza and Szabo 1987) and in the Outer Coastal Plain (Kozinski and others 1991). The New Jersey Geological Survey is gathering data on water quality in the Proterozoic rocks of the New Jersey Highlands including data on gross alpha in ground water samples (M. Cerfes, personal communication).

Objectives of this research project are to (1) study the influence of geology on concentrations of radon in ground water, (2) collect data about radon occurrence in ground waters of the New Jersey Highlands, and (3) determine if it is possible to predict areas at risk of having elevated concentrations of radon in ground water. This information should aid NJDEPE in developing a comprehensive, cost-effective monitoring program for radon in ground water.

In particular, this study focuses on determining the variability and content of radon in ground water for several rock

units in the New Jersey Highlands. This report describes the rock units selected for study, the sampling program, the distribution of radon concentrations, observations on the influence of mineralogy and structure on the radon concentrations, and statistical modeling done to interpret the effects of geological parameters on the radon concentrations. Implications of our research conclusions for State policy regarding radon testing of well water are also discussed.

## 2. Geology

### A. General Setting--The New Jersey Highlands

The New Jersey Highlands is a massif of Middle Proterozoic-age rocks containing faulted inliers of Paleozoic rocks that extends from eastern Pennsylvania, across northern New Jersey into southern New York State. In New Jersey it is bounded on the northwest by slightly metamorphosed Paleozoic sedimentary rocks in the Kittatiny Valley and on the southeast by Mesozoic rocks of the Newark basin (Figure 1).

Three types of Middle Proterozoic rocks were studied in this work: hornblende granite, quartz-oligoclase gneiss, and pyroxene granite. The hornblende granite was chosen for its known elevated uranium levels. The quartz-oligoclase gneiss was chosen for contrast for its low uranium levels. The pyroxene granite was chosen based on predictions that its uranium levels would be intermediate between the hornblende granite and quartz-oligoclase gneiss. The preliminary evaluation of uranium content, rock type and location was based on the most accurate mapping available at the time of the study and through discussions with New Jersey Geological Survey geologists Richard Volkert (1987b) and Karl Muessig (1987).

The hornblende granite unit studied (Ybh-1, Ybh-2) is part of the Byram Intrusive Suite (Drake, 1984), a group of rocks that are

thought to have originated from the crystallization of a melt, with some migmatization, replacement and assimilation of country rocks (Drake 1969). The source rock for the magma is not known.

The quartz-oligoclase gneiss unit studied (Ylo-1, Ylo-2) is part of the Losee Metamorphic Suite (Drake 1984), the result of partial melting of Proterozoic metadacite in a granulite facies environment during the Grenville orogeny (Puffer and Volkert 1991).

The pyroxene granite unit studied (Ypg-1, Ypg-2) is part of the Lake Hopatcong Intrusive Suite (Drake and Volkert 1991). This rock differs from those in the Byram Intrusive Suite by having mesoperthite as the primary feldspar (Drake 1969). Its relative age and relationship to the Byram Intrusive Suite, including the hornblende granite, is unknown (Volkert 1988).

These Middle Proterozoic rocks were deformed and faulted during the Grenville, Taconic and Alleghenian orogenies, at approximately 1 billion years ago, 450 million years ago (Ma) and 300 Ma, respectively. These rocks were again faulted during rift formation in the early Mesozoic era (200 Ma). These different episodes of deformation probably contributed to the distribution of uranium in rocks of the New Jersey Highlands.

#### B. Description of Units and Sampled Areas

For each rock unit, two discrete portions of the unit found at different locations were sampled.

##### High Bridge Hornblende Granite (Ybh-1)

The High Bridge hornblende granite (Ybh-1), in the High Bridge and Califon quadrangles, is composed primarily of quartz, feldspar, hornblende, some pyroxene and accessory magnetite/ilmenite, zircon and radioactive minerals of the thorite-thorogummite group and of the uranothorite group (Markewicz 1967; Figure 4). Interspersed

throughout this unit are smaller rock bodies of migmatite, amphibolite, alaskite and pegmatite (Markewicz 1967). Pods of these pegmatites and alaskites contain abundant radioactive elements while the amphibolites are relatively low in radioactive constituents (Muessig and others 1989).

#### High Bridge Pyroxene Granite (Ypg-2)

This unit (Ypg-2), in the High Bridge and Califon quadrangles, is a medium- to coarse-grained, gray to buff or white-weathering, greenish-gray, massive, gneissoid to indistinctly foliated granite composed of mesoperthite to microantiperthite, quartz, oligoclase, and clinopyroxene (Volkert 1988) (Figure 4). The pyroxene granite is suspected to contain less uranium than the hornblende granite.

The Longwood Valley Fault (Volkert 1989c; unpublished data), a high-angle (near vertical) fault striking northeast-southwest, runs through the hornblende granite and the pyroxene granite units, in some places dividing the two units (Figure 4). Uranium has been hypothesized to be concentrated along this fault (Gunderson 1988) and elevated gamma-radiation levels have been documented in the fault (Uptegrove).

#### Bernardsville Hornblende Granite (Ybh-2)

This unit (Ybh-2), in the Bernardsville (Volkert unpublished data), Gladstone (Houghton and Volkert 1990), Chester (Volkert and others 1990), and Mendham (Volkert, 1988) quadrangles, is a medium- to coarse-grained pink to buff, gneissoid to indistinctly foliated granite and sparse granite gneiss composed principally of microcline, quartz, oligoclase and hornblende, with small bodies of pegmatite and amphibolite occurring within the unit (Figure 5). As in the High Bridge hornblende granite (Muessig and others 1989), the pegmatites are apt to include radioactive minerals whereas the amphibolites are relatively low in radioactive constituents.

The Bernardsville hornblende granite is bounded sharply on the

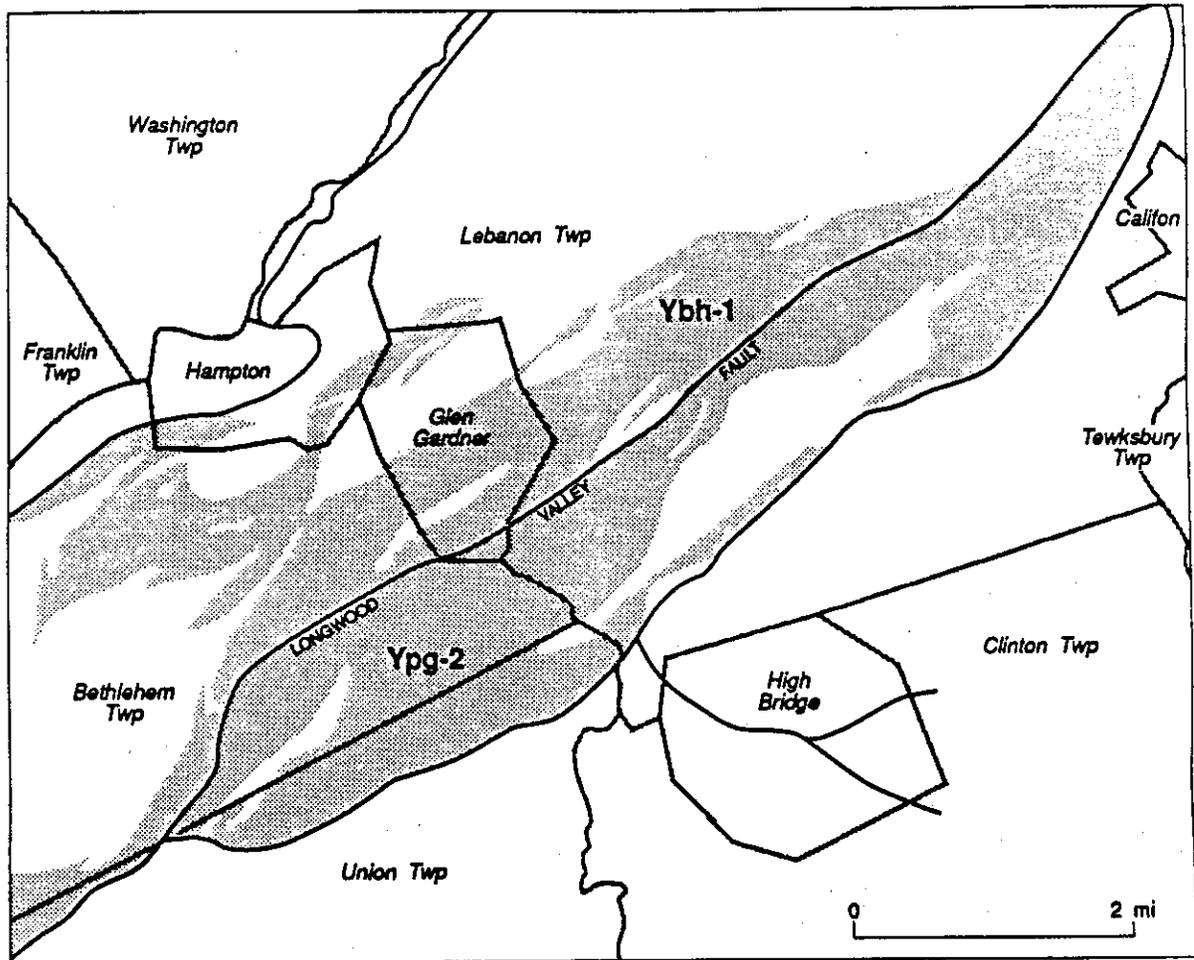


Figure 4. Shading indicates rock units studied. Ybh-1 = High Bridge hornblende granite; Ypg-2 = High Bridge pyroxene granite. The Longwood Valley Fault (Volkert 1989c; unpublished data) (1) divides the units. Data source: Markewicz (1967) and Volkert (unpublished data).

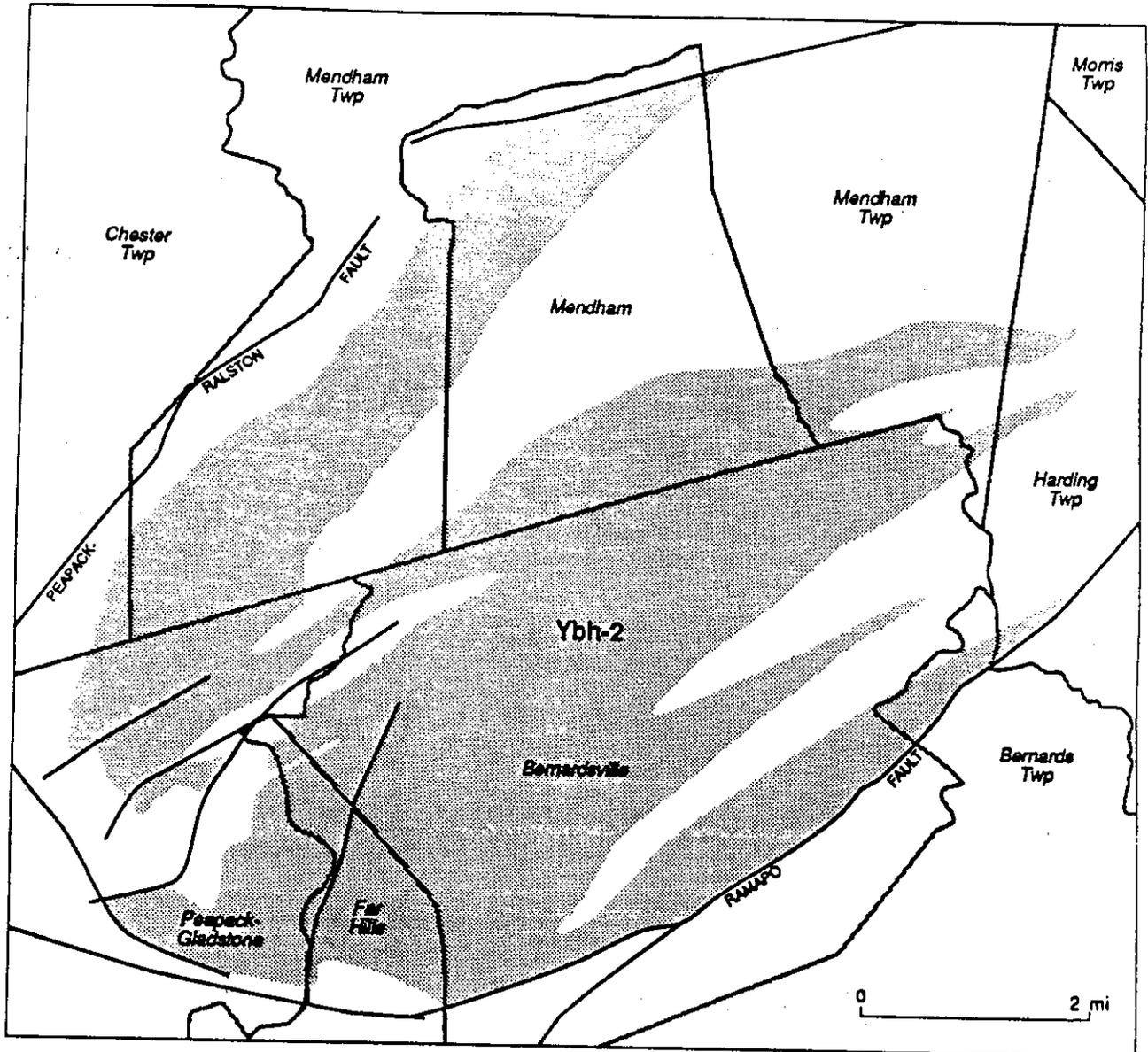


Figure 5. Shading indicates Bernardsville hornblende granite (Ybh-2). Data source: Volkert (unpublished data); Volkert 1988; Houghton and Volkert 1990; Volkert and others 1990.

southeast by the high-angle, southeast-dipping Ramapo Fault (Volkert unpublished data; Houghton and Volkert 1990). On the northwest it is bounded by the southeast-dipping Peapack-Ralston Fault (Houghton and Volkert 1990; Volkert and others 1990). These faults, as well as smaller associated faults may contain relatively high amounts of radioactive minerals (Houghton and Volkert 1990).

#### Stanhope Quartz-Oligoclase Gneiss (Ylo-1)

This unit (Ylo-1), in the Franklin (Baker and Buddington 1970), Stanhope (Volkert and others 1989), and Tranquility (Volkert unpublished data) quadrangles, is a medium-fine- to medium-coarse-grained, white to light-greenish-gray, poorly foliated gneiss composed of quartz and oligoclase with minor biotite, garnet, chlorite, epidote and hornblende (Figures 6 and 7). Throughout the unit, local layers of amphibolite commonly occur.

As can be seen in Figure 6, several major northeast-southwest-trending faults dominate the geology in the Stanhope area and border the unit on the northwest margins (Volkert and others 1989). In the left-central section of the map area (Figure 6), the gently southeast dipping Musconetcong Thrust Fault is cut off by the steeply southeast dipping Kennedy's Fault (Volkert and others, 1989), which also forms part of the unit contact. In the area surrounding the northern half of this unit (Figure 7), there are also major northeast-southwest-trending faults. The Zero, East and Vernon Faults border this unit on the northwest and southeast (Buddington and Baker 1961), but there are no faults documented within this unit in the Franklin quadrangle.

#### Stanhope Pyroxene Granite (Ypg-1)

This unit (Ypg-1), in the Stanhope (Volkert and others 1989) and Chester (Volkert and others 1990) quadrangles, is a medium- to medium-coarse grained, buff to greenish-gray, gneissoid to indistinctly foliated granite composed dominantly of sodium-rich alkali feldspar, quartz and clinopyroxene (Figure 6). This unit is

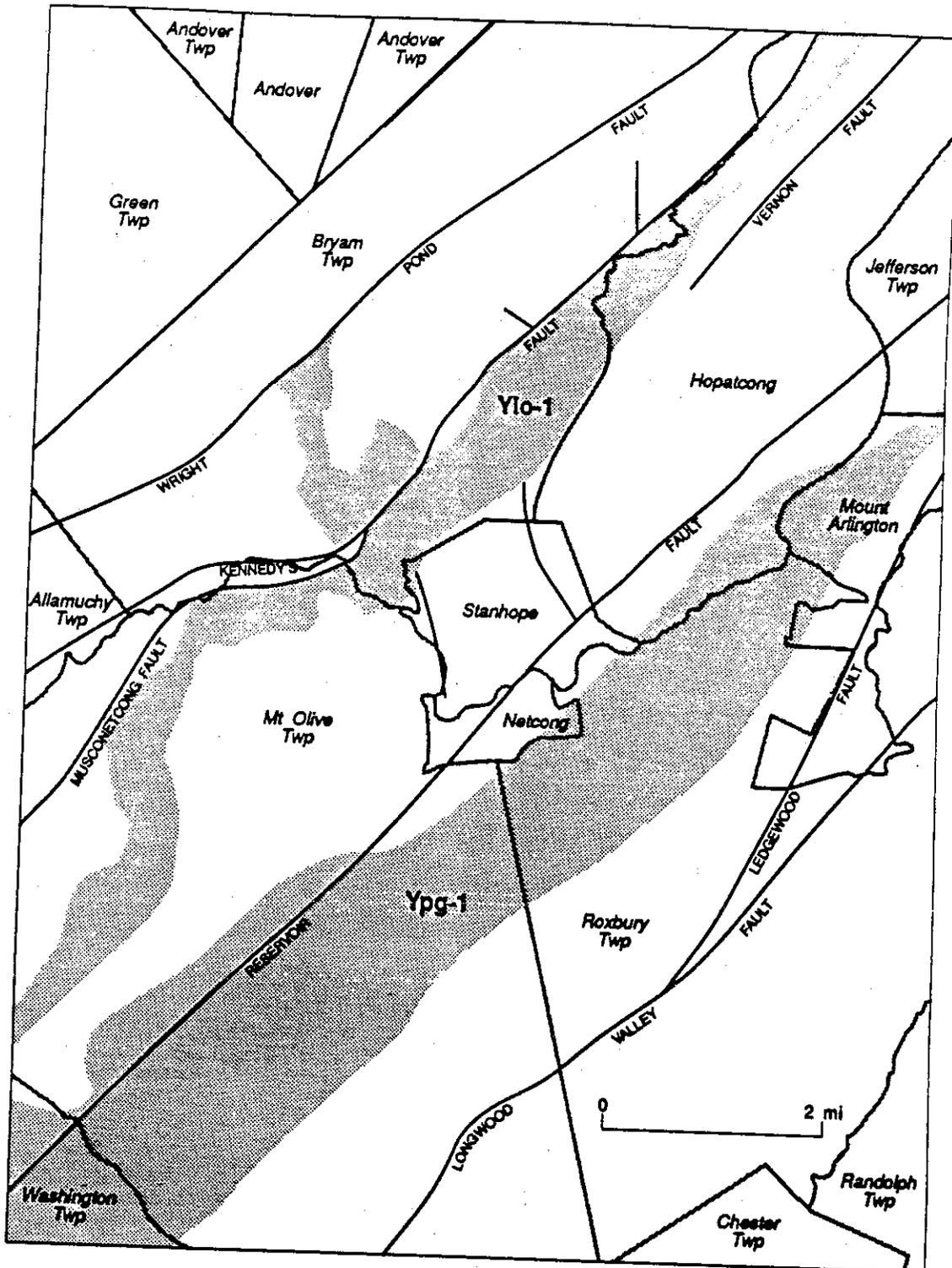


Figure 6. Shading indicates rock units studied. Ylo-1 = southern part of the Stanhope quartz-oligoclase gneiss; Ypg-1 = Stanhope pyroxene granite. Data source: Bedrock geology coverage in the NJDEPE GIS, and Volkert and others (1989).

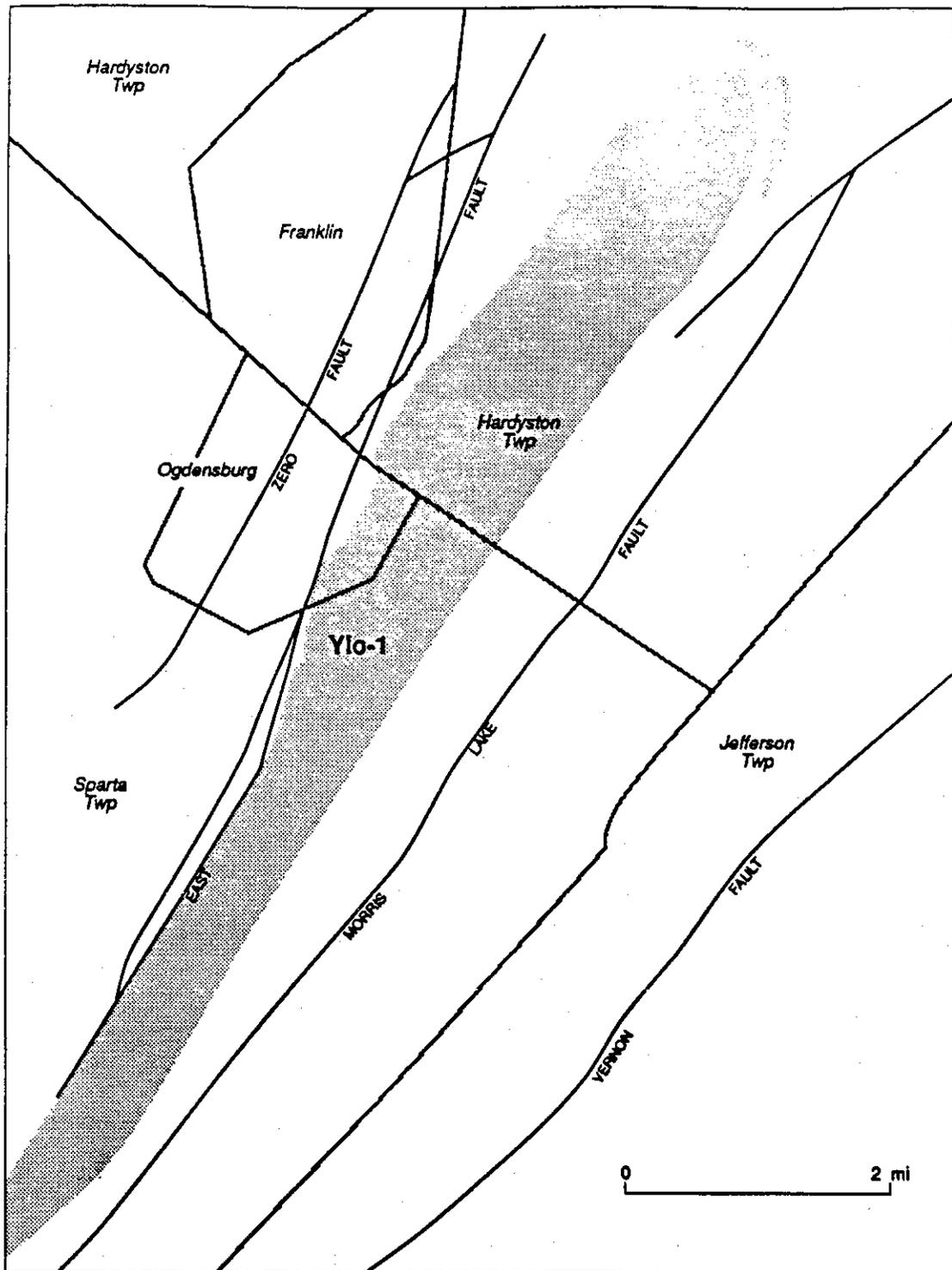


Figure 7. Shading indicates northern part of the Stanhope quartz-oligoclase gneiss (Ylo-1). Data source: Buddington and Baker (1961).

found in close association with quartz syenite and syenite at some locations (Volkert and others 1989). The Stanhope pyroxene granite is exposed in the Byram Cove Synform and bounded or cut by two high angle faults: the Vernon and Reservoir Faults (Volkert and others 1989).

Hamburg Quartz-Oligoclase Gneiss (Ylo-2)

This unit (Ylo-2), in the Hamburg quadrangle, is white to greenish-gray, medium- to coarse-grained and contains oligoclase and quartz with trace amounts of potassium feldspar (Hague and others 1956) (Figure 8). It characteristically contains aggregates of chlorite and/or epidote that impart a greenish color to fresh surfaces. It commonly contains local bands or pods of amphibolite. In the area shown on the map, it weathers to a smooth, chalky white to light-gray surface (Hague and others 1956).

The Hamburg quartz-oligoclase gneiss is bounded on the east by folded Precambrian amphibolites and gneissic units and the high-angle normal Pochuck Fault (Hague and others 1956). The low-angle Deckertown Thrust Fault is thought to be the contact of this unit at a depth of 2000 to 5000 feet below the land surface (Canace 1988). The unit is bounded on the west by lower Paleozoic quartzite and carbonates of the Valley and Ridge Province (Figure 1). The traces of the Deckertown Thrust and the Crooked Swamp Fault border the unit on the west (Canace 1988).

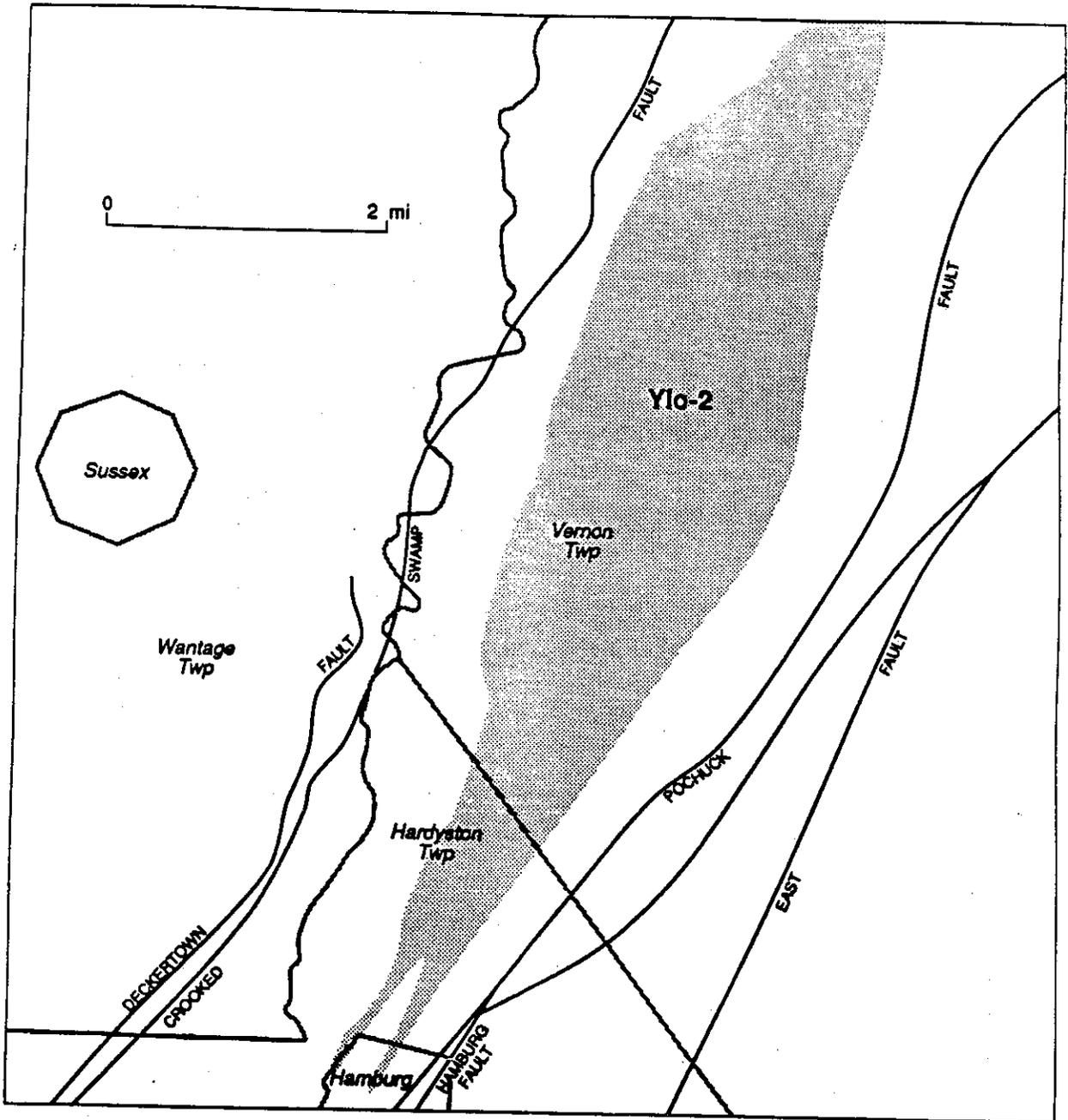


Figure 8. Shading indicates Hamburg quartz-oligoclase gneiss (Ylo-2). Data source: Hague and others (1956) and Canace (1988).

### 3. Methods

#### A. Well Selection

Wells within the rock units were identified using the NJDEPE Bureau of Water Allocation well records. Criteria used to select wells were: well depth (greater than 100 feet); depth of rock below the casing (greater than 50 feet); well location; and well owner cooperation. An attempt was made to sample wells spatially distributed throughout the rock units. The availability of wells for sampling was restricted in rural areas because wells tend to be far apart, in towns because most people get water from public drinking water supplies, and because some areas are undeveloped. Mailing addresses of the well owners were obtained from county tax offices. Property owners received letters explaining the study and requesting permission to sample their well water (Appendix A). In addition, all accessible public community water supply wells in the rock units of interest were sampled.

#### B. Sampling

The ground water sampling method used in this study, developed by the USGS for sampling radon (Szabo and Zapecza 1987), is summarized as follows. Samples were taken as close to the well head as possible, before water entered the house water pipes or any home water treatment systems. Water flow rate was monitored and the total amount withdrawn was estimated. The pH, temperature, dissolved oxygen concentration, and specific conductivity were continually monitored, and generally stabilized after 30 minutes to an hour of pumping the well. Stabilization was assumed to indicate that standing water had been pumped from the well and fresh ground water could be sampled. If stabilization did not occur, researchers collected the water sample after an hour. To avoid turbulent flow and degassing of radon, the water was pumped slowly (approximately 0.3 liters per minute) into the sample bottle.

Approximately 1/2 liter was collected in glass bottles fitted with an air-tight stopper and clamp assembly (Anderson 1983). Samples were delivered to Princeton University's Ocean Tracers Laboratory (OTL) at the end of the field day, and counted within 48 hours.

### C. Radon Analysis

Radon activity in a water sample was determined using a modified version of the Lucas cell scintillation technique (Key 1983). The Lucas cell method is being considered by USEPA for inclusion in the upcoming revision of the National Primary Drinking Water Regulations (USEPA 1986 and USEPA 1991). Radon was purged from the water samples and quantitatively transferred into scintillation cells. Decays of radon and its progeny were counted. Back calculations were made to account for radioactive decay after transfer into the counting cells, and for radon decay between sample collection and analysis (Key 1983). The effect of interference due to typical radium concentrations in the ground water samples was calculated and found to be minor (Appendix B).

The individual radon concentrations were identified with a particular well, owner, and address by the bottle number and collection time, which in turn were assigned a random code number. To ensure the confidentiality of the owner's test results, all data used for analysis and appearing in reports are solely identified by this code number. Results of the individual tests were mailed to the well owners. A sample letter for reporting results is included in Appendix A.

### D. Quality Assurance/Quality Control

A variety of quality assurance/quality control measures were taken for this project. Blanks were run on empty sample bottles and found to be negligible relative to the activity of the samples. Dilutions of radium-226 standards were run every two weeks on each

of the Lucas cells used in this study. The efficiency determined from these runs included the effects of the entire laboratory procedure. The error reported with individual datum was the uncertainty obtained by propagating the errors associated with counting, efficiency, background and blank for an individual run. If the calculated error was less than 5% of the activity, then the reported error was given as 5% of the measured sample activity.

Of the 154 wells sampled 31 (24%) included duplicate field samples. A table with the results of duplicate measurements is included as Appendix C. The average difference between the duplicates is 8.7%. The average error in excess of the analytical uncertainty is attributable to sample collection, transport, storage, natural variability, occasional analytical outliers which are not represented in the analytical error, and drifting cell efficiencies not being entirely compensated. For reporting the data outside of the laboratory, a precision of 10% at the one sigma level is justified by these duplicate measurements (i.e., about 67% of the duplicate results are within 10% of each other).

As an additional quality assurance measure, 20 split samples were collected and analyzed using both OTL's Lucas cell method and the liquid scintillation method of the NJDEPE's Bureau of Radiation and Inorganic Analytical Services, formerly the Bureau of Environmental Laboratories (Parsa 1986). The liquid scintillation method is also being considered by the USEPA for inclusion in the upcoming revision of the National Primary Drinking Water Regulations (USEPA 1986, USEPA 1991). Results of the split samples are given in Appendix D. There appear to be no systematic differences between the two methods.

One reason the Lucas cell method was used in this project was concern that the liquid scintillation method might be unable to determine quantitatively the radon concentrations for some of the low level samples we expected to encounter. In practice, the

liquid scintillation method's minimum detectable concentration of 30 pCi/L (at time of analysis) seems sufficient. The liquid scintillation method is less labor intensive than the Lucas cell method, and is thus likely to be preferred for determination of radon in water concentrations for drinking water applications.

#### E. Data Analysis

The location of each well was plotted on a USGS topographic quadrangle. These locations were later digitized using the ARC/INFO software of NJDEPE's Geographic Information System (GIS). Maps of well locations were overlaid with geologic maps to obtain: well distance from the unit contact; well distance from the nearest mapped fault; and to confirm that the well was actually in the targeted unit's expression at the surface. Geological information, field measurements, and radon concentrations for each well were entered into a Lotus database. This database was then translated into SAS for statistical analysis and ARC/INFO for geographical analysis. The geographical analysis was limited to a qualitative examination of the radon concentration spatial distribution and whether there were coincidences of anomalous radon concentrations with certain geologic features.

The data were analyzed using both descriptive statistics and linear regression models. Descriptive statistics (e.g. frequency distributions, medians, geometric means, maxima and minima) were used to look at differences in radon concentrations between geologic units. In addition, notched box plots and an Analysis of Variance, followed by Tukey's Studentized Range Test (a multiple comparison procedure) were used to determine whether measured radon distributions differed by rock unit and whether the measured distributions were similar in the same units in the different sampling areas. The 22 wells outside the units were excluded from the all statistical analyses, except for statistics describing the radon distribution of all wells sampled. Before analyses were

performed, the natural logarithms of the radon concentrations were taken, to reflect the approximate lognormal nature of the distribution of concentrations measured.

Linear regression models were used to investigate causes of variability within and between units. Assumptions made and tested were that the radon concentration could be influenced by: 1) the well's location in a specific unit, 2) the well's depth, relative to other wells in that unit, 3) the well's proximity to faults and 4) the well's proximity to the unit contact. Other parameters, such as pH, specific conductance and dissolved oxygen were not included in the analysis due to missing values for many wells. This analysis identified the model with the fewest adjustable parameters (degrees of freedom) that best described the observed data, as indicated by the coefficient of determination,  $r^2$ .

Two models were applied to the data (Appendix E). The only difference in the two models was in the treatment of the variable, well depth. The first model, called the groupings model, classified wells into one of several depth categories within each rock unit. The second model, called the continuum model, treated well depth as a continuous variable within each unit.

#### 4. Results

##### A. Radon Distribution

Ground water radon concentrations were measured in 154 wells. Appendix F includes the field and laboratory results for all analyses performed. Radon concentrations for all wells range from 36 pCi/L to 24,000 pCi/L. The geometric mean and the median for all 154 wells are both 1600 pCi/L. The distribution cannot be distinguished from lognormal. A radon frequency distribution for all wells sampled is shown in Figure 9.

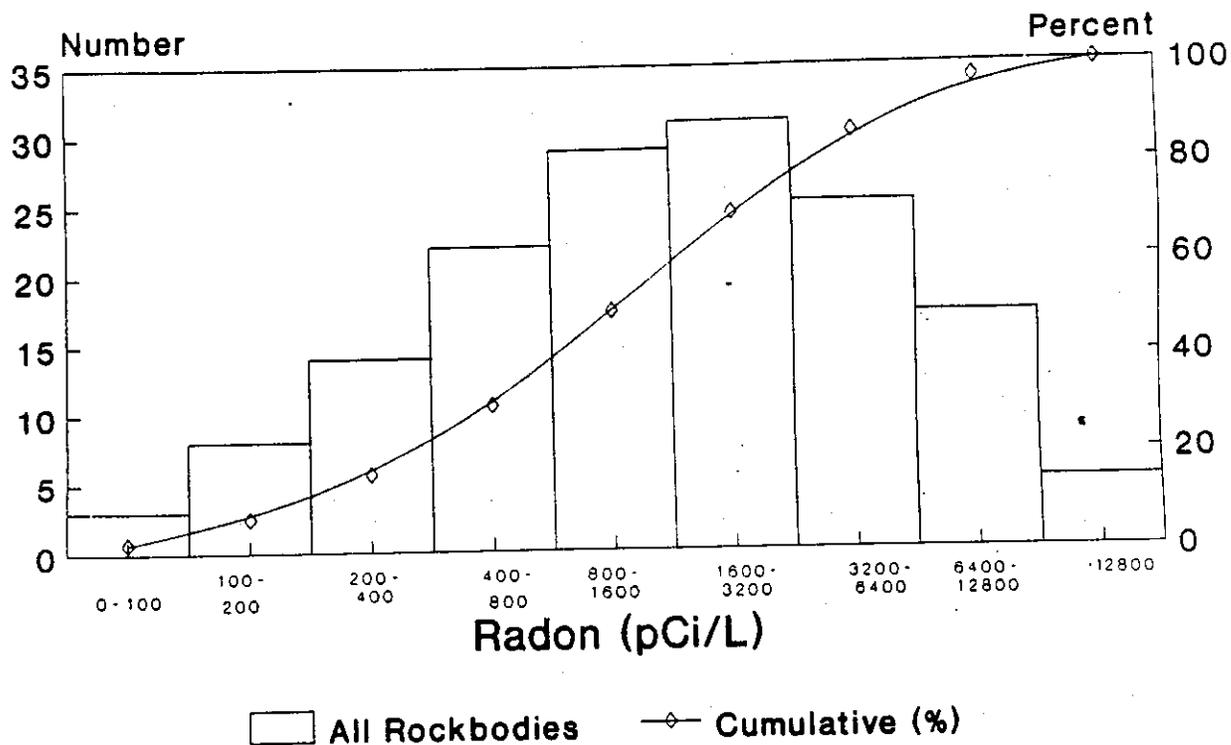


Figure 9. Frequency distribution of radon concentrations in all wells sampled (154). Note that the radon scale is nonlinear.

Table 1. Descriptive statistics, by rock unit (radon levels are in pCi/L).

Unit <sup>a</sup>	N	Percent <sup>b</sup>	Geometric Mean	Median	Minimum	Maximum
Ybh-1	10	7.5	3,000	3,700	470	24,000
Ybh-2	29	22.0	2,400	3,000	130	21,000
Ylo-1	24	18.2	810	880	150	7,000
Ylo-2	35	26.5	3,700	3,900	870	14,000
Ypg-1	22	16.7	510	620	36	3,800
Ypg-2	12	9.1	960	1,100	330	3,100

- a. Ybh-1 = High Bridge hornblende, Ybh-2 = Bernardsville hornblende granite; Ylo-1 = Stanhope quartz-oligoclase gneiss, Ylo-2 = Hamburg quartz-oligoclase gneiss; Ypg-1 = Stanhope pyroxene granite, Ypg-2 = High Bridge pyroxene granite.
- b. Of the 132 wells in the units studied.

Table 1 shows the geometric mean, median, and range of ground water radon concentrations for the 132 wells sampled in the six selected locations. Figure 10 shows notched box plots of the radon concentrations measured at the six locations. Results for Tukey's Studentized Range Test are shown in Table 2, with minor differences from the notched box plots occurring in some comparisons. For example, using Tukey's test, radon concentrations in the High Bridge hornblende granite (Ybh-1) and Bernardsville hornblende granite (Ybh-2) units are significantly different from those in the Stanhope quartz-oligoclase gneiss (Ylo-1) and Stanhope pyroxene granite (Ypg-1) units. Figures 11-15 show spatial distributions of radon concentrations within the rock bodies.

Of the six locations studied, the Hamburg quartz-oligoclase gneiss (Ylo-2) had the highest mean (3,700 pCi/L) and median (3,900 pCi/L) ground water radon concentration (Table 1). The distribution of wells and the occurrence of radon concentrations greater than 1000 pCi/L appears fairly uniform throughout the unit (Figure 15). The notched box plots and Tukey's Studentized Range Test indicate that the Hamburg quartz-oligoclase gneiss was not

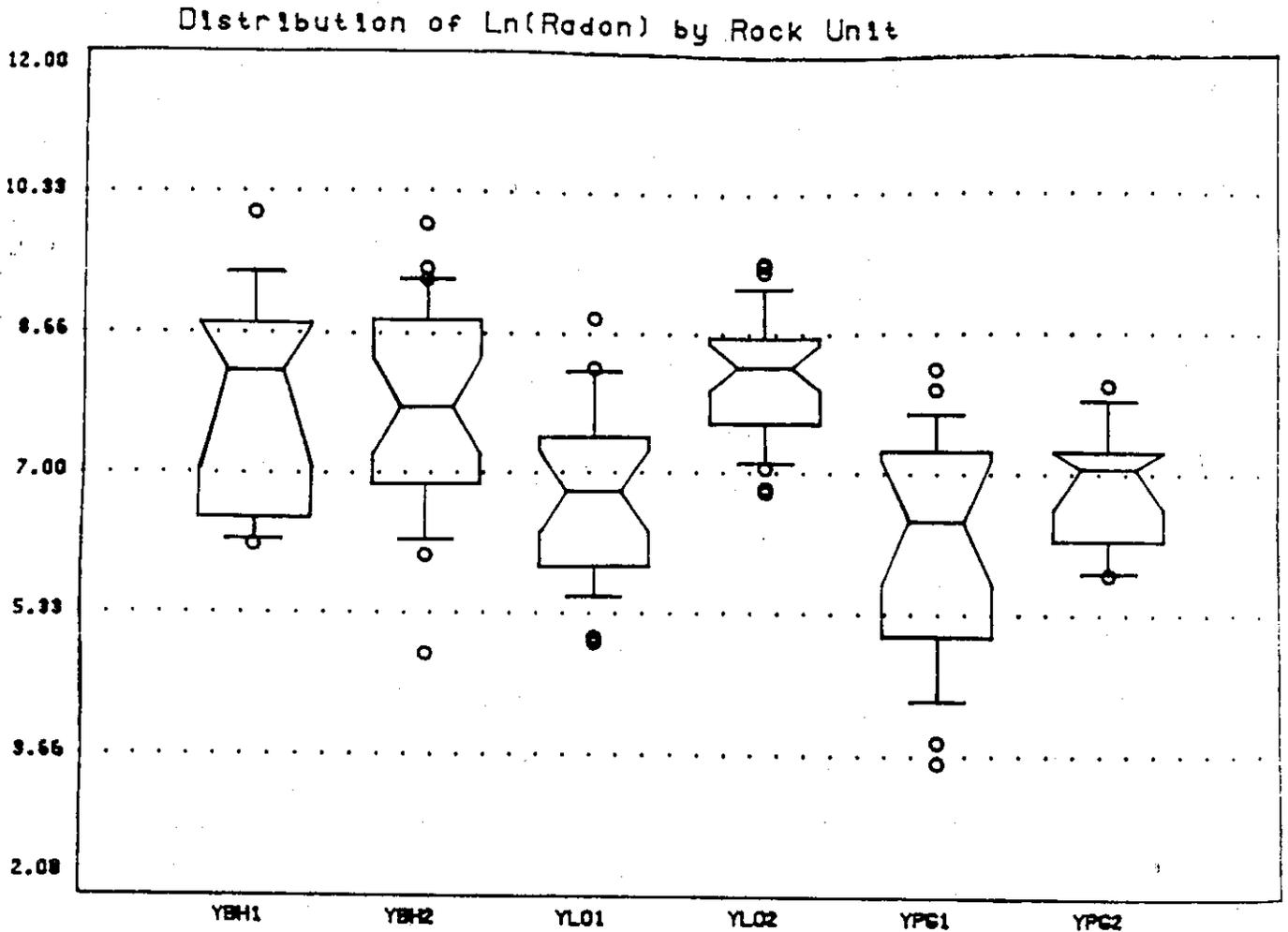


Figure 10. Distributions of the natural logarithm of the radon concentrations measured in the six rock units (notched box plots). The line at the waist is the median, and the notches begin at the median  $\pm 1.57 \times$  (interquartile range/ $\sqrt{N}$ ), where  $N$  is the number of measurements in each rock unit. The box covers the data between the 25th and 75th percentiles. The horizontal lines represent the 90th and 10th percentiles, and the circles represent values falling outside these percentiles. If the notches of two boxes do not overlap, then the distributions can be considered significantly different at the 95% confidence level without controlling for multiple comparisons.

Table 2. Units having ground water radon distributions with geometric means significantly different at the 95% confidence level, according to Tukey's Studentized Range Test, are shown by a "+". Note that this table is symmetric about its diagonal from upper left to lower right.

	Ybh-1	Ybh-2	Ylo-1	Ylo-2	Ypg-1	Ypg-2
Ybh-1			+		+	
Ybh-2			+		+	
Ylo-1	+	+		+		
Ylo-2			+		+	+
Ypg-1	+	+		+		
Ypg-2				+		

significantly different from either of the hornblende granite units (Ybh-1 and Ybh-2; Figure 10 and Table 2). The notched box plots also show ground water radon concentrations in the Hamburg quartz-oligoclase gneiss are significantly more elevated at the 95% confidence level than in the Stanhope quartz-oligoclase gneiss (Ylo-1) and both pyroxene granite units (Ypg-1 and Ypg-2; Table 2). Thus, of the three rock types studied, only the quartz-oligoclase gneiss shows significantly different ground water radon concentrations at the two locations (Table 2).

The High Bridge hornblende granite (Ybh-1) and the Bernardsville hornblende granite (Ybh-2) had the two highest ground water radon concentrations of 24,000 pCi/L and 21,000 pCi/L respectively (Table 1). Neither the notched box plots nor Tukey's Studentized Range Test found the two hornblende granite units to have significantly different radon concentrations from each other (Figure 10, Table 2). Although the spatial distribution of radon concentrations in these units does not initially appear to have a significant pattern, it was found that in the High Bridge

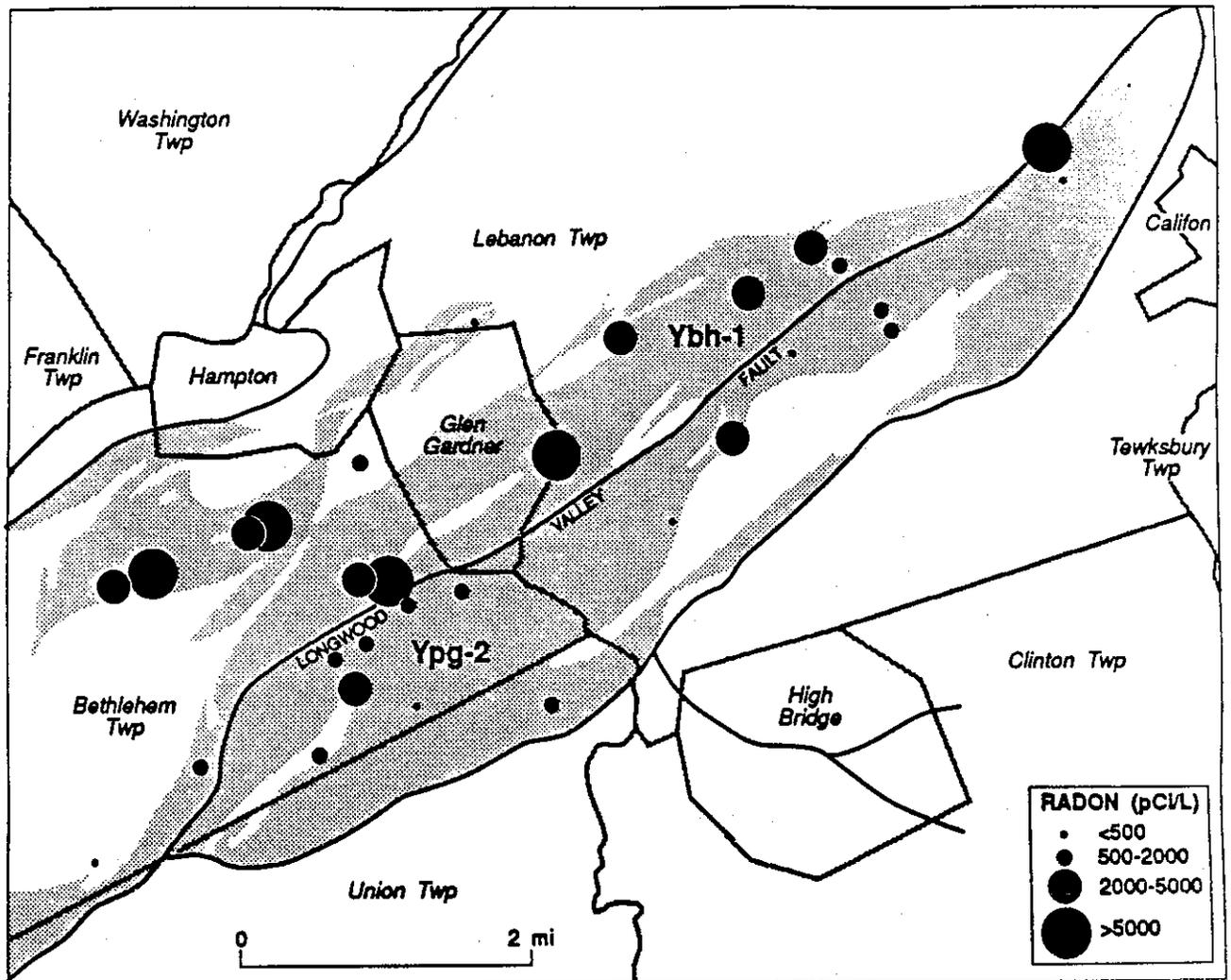


Figure 11. Results of radon sampling in the High Bridge hornblende granite (Ybh-1) and pyroxene granite (Ypg-2). The Longwood Valley Fault divides the units.

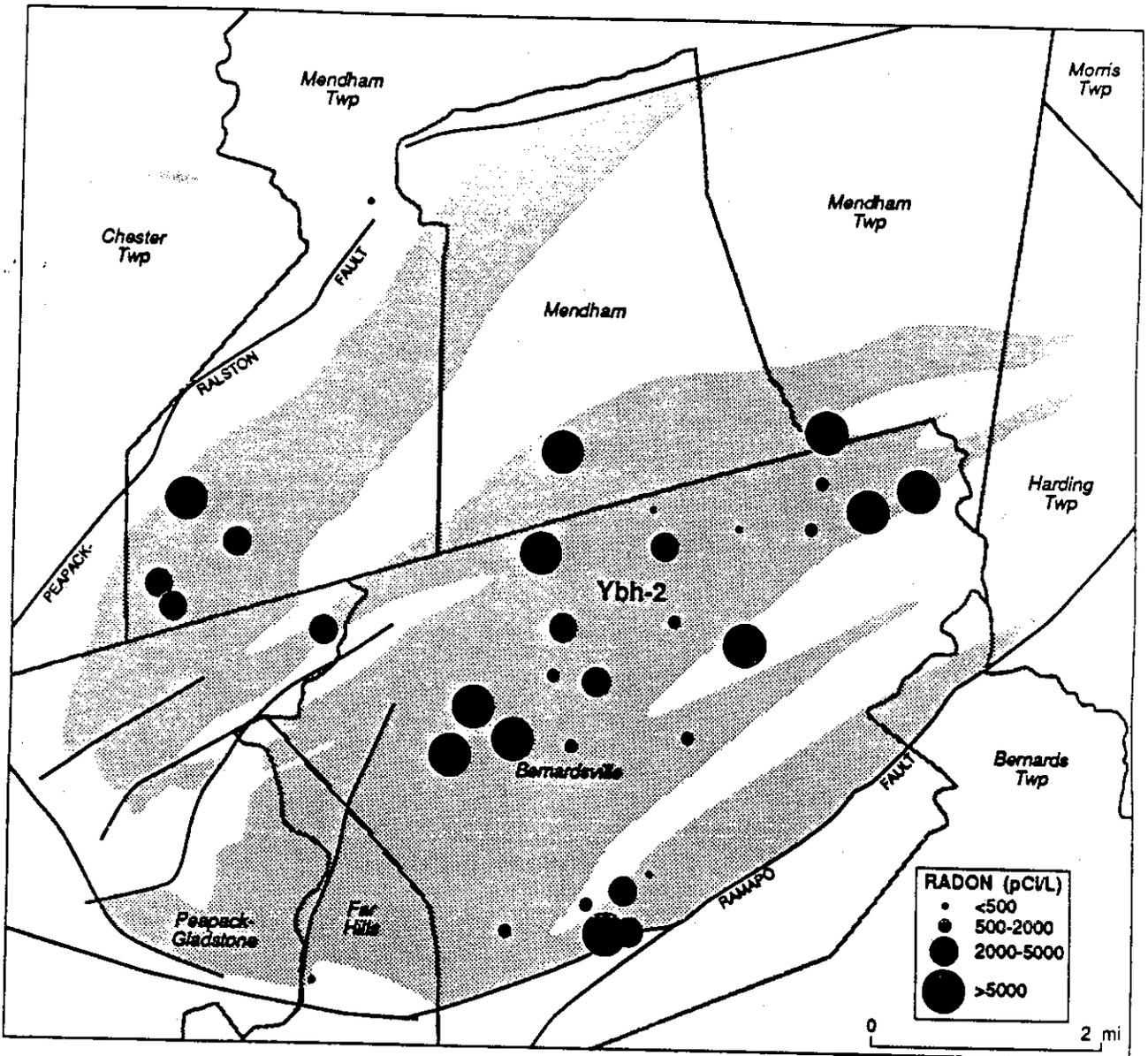


Figure 12. Results of radon sampling in the Bernardsville hornblende granite (Ybh-2).

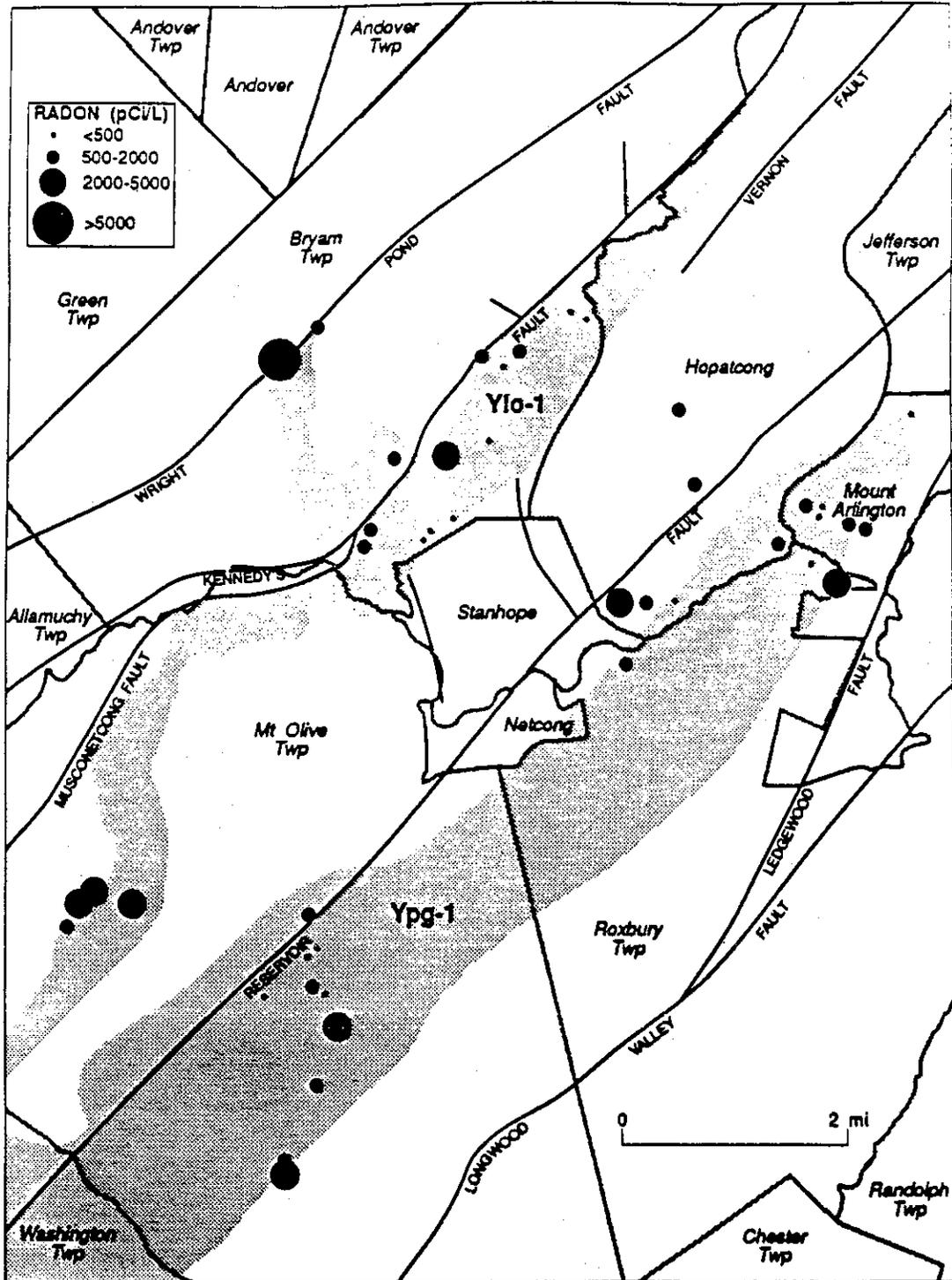


Figure 13. Results of radon sampling in the southern part of the Stanhope quartz-oligoclase gneiss (Ylo-1) and the Stanhope pyroxene granite (Ypg-1).

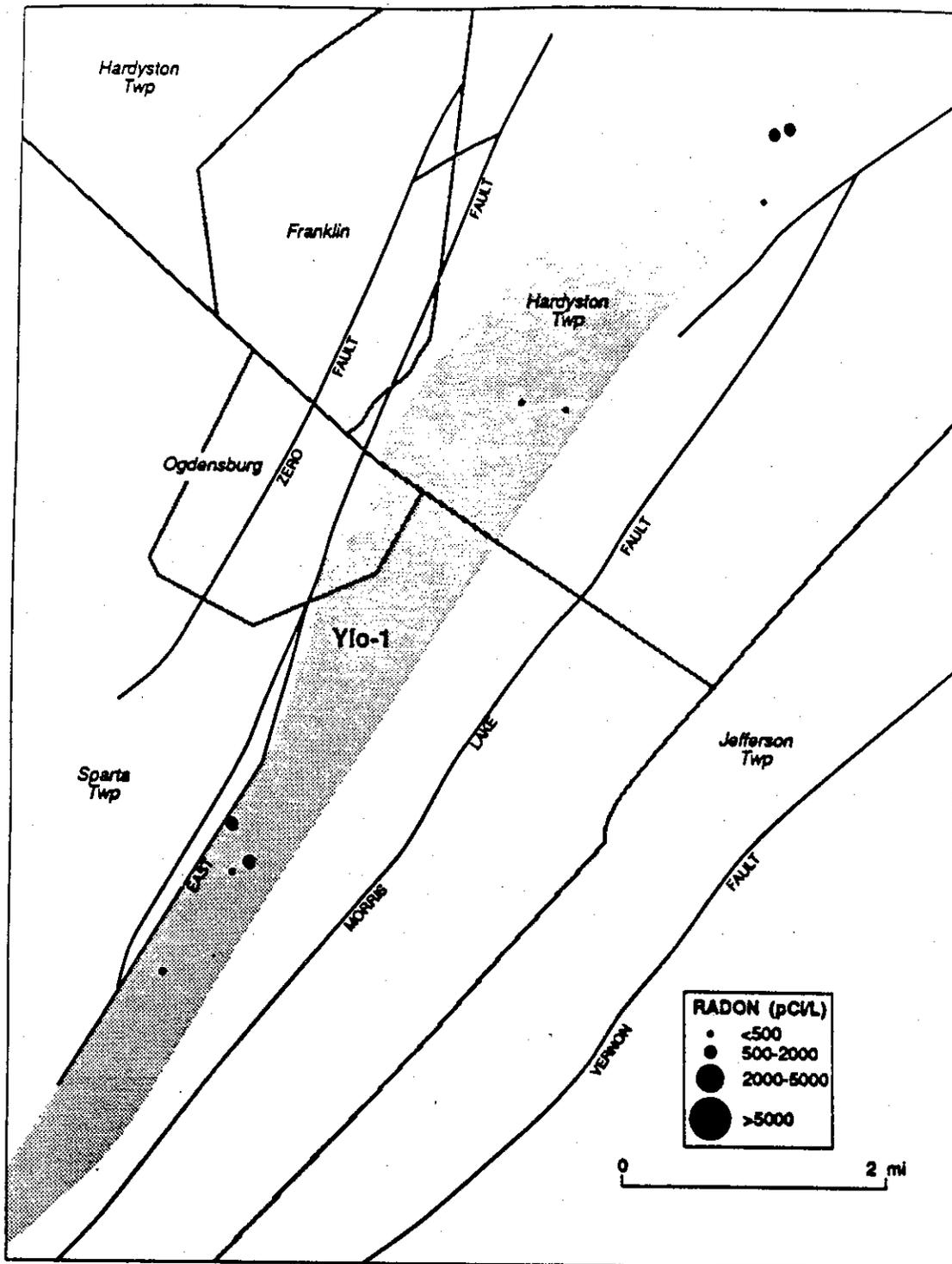


Figure 14. Results of radon sampling in the northern part of the Stanhope quartz-oligoclase gneiss (Ylo-1).

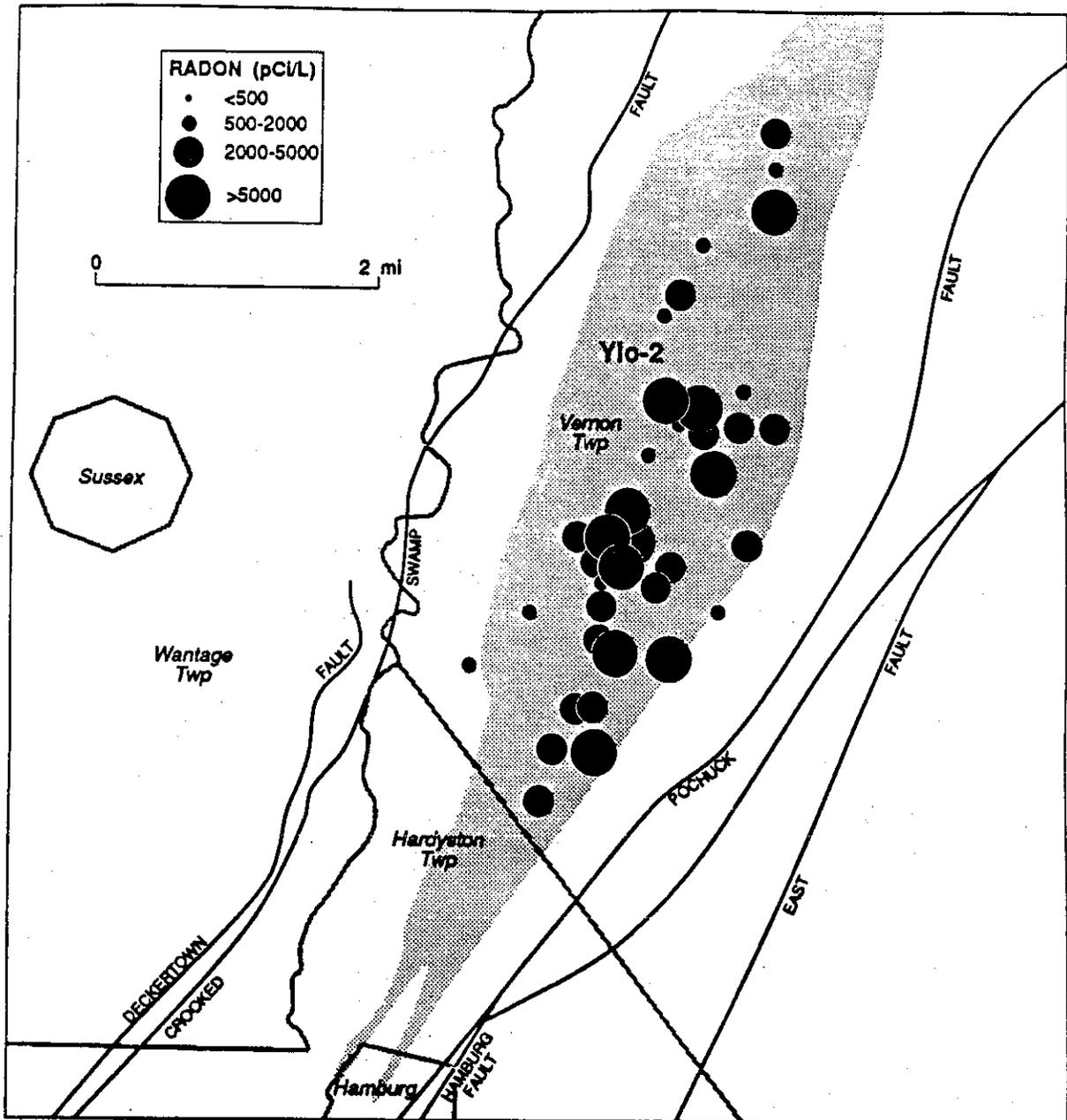


Figure 15. Results of radon sampling in the Hamburg quartz-oligoclase gneiss (Ylo-2).

hornblende granite the two highest concentrations (17,000 and 24,000 pCi/L) occur in association with migmatite and pegmatite pods (Figure 11; Markewicz 1967).

In the Bernardsville hornblende granite (Ybh-2) ground water radon concentrations greater than 5000 pCi/L tend to occur near unit boundaries or in a cluster of higher values in the center of the unit (Figure 12). The highest concentration of 21,000 pCi/L occurs in the center of the unit. A concentration of 12,000 pCi/L occurs in an outcrop of quartz-oligoclase gneiss adjoining the eastern section of the Bernardsville unit (Figure 12).

The units with the lowest mean ground water radon concentrations were the Stanhope pyroxene granite (Ypg-1) (geometric mean: 510 pCi/L), the Stanhope quartz-oligoclase gneiss (Ylo-1) (geometric mean: 810 pCi/L), and the High Bridge pyroxene granite (Ypg-2) (geometric mean: 960 pCi/L; Table 1). The distribution of radon concentrations in the Stanhope area (Ylo-1 and Ypg-1), although skewed by availability of wells, does not appear to have any distinctive pattern (Figures 13 and 14). The distribution of radon concentrations in the High Bridge pyroxene granite (Ypg-2) is also fairly uniform, though it is noteworthy that the two concentrations greater than 5,000 pCi/L occur at the unit boundaries.

These data suggest that not all rock units with different mineralogies have significantly different ground water radon concentrations. In the High Bridge area the two units studied, hornblende granite (Ybh-1) and pyroxene granite (Ypg-2), have different mineralogies, but neither the notched box plots nor Tukey's Studentized Range Test showed that these units had significantly different ground water radon concentration distributions (Figure 10; Table 2). The different units in the Stanhope area, quartz-oligoclase gneiss (Ylo-1) and pyroxene granite (Ypg-1), also did not have significantly different radon

concentration distributions (Figure 10; Table 2), although clearly their mineralogies and structure are different.

### B. Linear Regression Modeling

To further investigate the possible relationships between geology and ground water radon concentrations, linear regression models were developed to test the data for significant correlations. The models had significant power to explain the data, with coefficients of determination greater than 0.5.

As discussed earlier, two treatments of well depth were used to develop the models. The groupings model ( $r^2 = 0.57$ , P-value = 0.0001) described the data marginally better than the continuum model ( $r^2 = 0.54$ , P-value = 0.0001). However, it also included many more adjustable parameters (degrees of freedom). Quantitative results of the two models are presented in Tables 3 and 4. Parameters found to be significant were rock unit, well proximity to the unit contact, and within some rock units, well depth. Well proximity to the nearest fault was not found to be a significant parameter. Recall that the radon values were logarithmically transformed before input to the linear regression models. Therefore, the parameters indicate a multiplicative effect on radon concentrations.

An example should serve to illustrate the results of the models. According to the groupings model coefficients, wells in the Stanhope pyroxene granite (Ypg-1) deeper than 250 feet and not within 320 feet of a unit contact have the lowest expected radon concentrations ( $\ln(Rn) = 6.59 - 1.86 + 0.00 + 0.00$ , or  $Rn = 113$  pCi/L). Wells in the Hamburg quartz-oligoclase gneiss shallower than 149 feet and within 320 feet of a unit contact have the highest expected radon concentrations ( $\ln(Rn) = 6.59 + 1.23 + 0.60 + 0.71$ , or  $Rn = 9,100$  pCi/L). Other high expected radon

Table 3. Parameters for the groupings model are shown. Parameters that are significant at the 90% confidence level are marked with an "\*". Distances are given in feet. Unit signifies a well's location in one of the 6 sample areas; BD = well's distance from the unit contact; WD = well's depth. For example, the estimate of WD-Ybh-1 <200, is related to the contribution to the expected radon level associated with a well being in the unit Ybh-1 (High Bridge hornblende granite) and being shallower than 200 feet. The estimate of BD < 320 is related to the contribution to the expected radon level associated with a well in any of the three units being within 320 feet of a unit contact. For brevity, the insignificant well depth parameters are not shown, except for Ylo-2 <149, which is used in the text's example.

<u>Parameter</u>	<u>Estimate</u>	<u>Std. Error of Estimate</u>	<u>P-value</u>
Intercept	6.59*	0.48	0.0001
Unit-Ybh-1	0.45	0.64	0.48
Unit-Ybh-2	-0.42	0.62	0.49
Unit-Ylo-1	0.25	0.60	0.67
Unit-Ylo-2	1.23*	0.68	0.074
Unit-Ypg-1	-1.86*	0.68	0.007
Unit-Ypg-2	0.00 <sup>a</sup>	--	--
BD < 320	0.71*	0.22	0.002
BD > 320	0.00 <sup>a</sup>	--	--
WD-Ybh-1 <200	1.20*	0.60	0.05
WD-Ybh-1 →>200	0.00 <sup>a</sup>	--	--
WD-Ybh-2 <200	2.10*	0.49	0.0001
WD-Ybh-2 200-400	1.52*	0.53	0.005
WD-Ybh-2 >400	0.00 <sup>a</sup>	--	--
WD-Ypg-1 <151	1.69*	0.57	0.004
WD-Ypg-1 151-250	1.41*	0.60	0.02
WD-Ypg-1 >250	0.00 <sup>a</sup>	--	--
WD-Ylo-2 <149	0.60	0.58	0.30

a. These parameters were arbitrarily set to zero to provide necessary reference points.

Table 4. Parameters for the continuum model are shown. Parameters that are significant at the 90% confidence level are marked with an "\*". Distances are given in feet. Unit signifies a well's location in one of the 6 sample areas; BD = well's distance from the unit contact; WDEP = well's depth. For example, the estimate of WDEP-Ybh-1 is a multiplicative factor indicating the contribution to the expected radon level associated with a well in the unit Ybh-1 (High Bridge hornblende granite) having a certain depth. As in Table 3, the estimate of BD < 320 is related to the contribution to the expected radon level associated with a well in any of the three units being within 320 feet of a unit contact.

<u>Parameter</u>	<u>Estimate</u>	<u>Std. Error of Estimate</u>	<u>P-value</u>
Intercept	6.47*	0.61	0.0001
Unit-Ybh-1	1.65	1.02	0.11
Unit-Ybh-2	2.12*	0.73	0.005
Unit-Ylo-1	-0.68	0.72	0.35
Unit-Ylo-2	2.17*	0.71	0.003
Unit-Ypg-1	0.94	0.77	0.22
Unit-Ypg-2	0.00 <sup>a</sup>	--	--
BD < 320	0.89*	0.24	0.0003
BD 320-625	0.59*	0.28	0.04
BD > 625	0.00 <sup>a</sup>	--	--
WDEP-Ybh-1	-0.0033	0.0035	0.33
WDEP-Ybh-2	-0.0039*	0.0012	0.0015
WDEP-Ylo-1	0.0024	0.0017	0.16
WDEP-Ylo-2	-0.0018	0.0014	0.19
WDEP-Ypg-1	-0.0076*	0.0020	0.0003
WDEP-Ypg-2	0.0002	0.002	0.90

a. These parameters were arbitrarily set to zero to provide necessary reference points.

concentrations are in the Bernardsville hornblende granite (Ybh-2) shallower than 200 feet and within 320 feet of a unit contact ( $R_n = 7,900$  pCi/L) and the High Bridge hornblende granite (Ybh-1) shallower than 200 feet and within 320 feet of a unit contact ( $R_n = 7,900$  pCi/L). Regardless of a well's unit, if within 320 feet of a contact, it is expected to have a higher radon level than would a comparable well further from the contact.

The continuum model also predicts that deep wells in the Stanhope pyroxene granite (Ypg-1) have the lowest radon concentrations, although the interpretation of the model's well depth parameters (WDEP, in Table 4) is not as straightforward. To compare the importance of the well depth parameters with other model parameters it is necessary to multiply the WDEP parameters in the continuum model by the depth of a typical well in that unit. For example, a 100 foot well in the Stanhope pyroxene granite (Ypg-1) more than 625 feet from a contact would have a low expected radon concentration ( $\ln(R_n) = 6.47 + 0.94 + 0.00 - (0.0076 \times 100)$ , or  $R_n = 770$  pCi/L) and a 100 foot well in the Hamburg quartz-oligoclase gneiss (Ylo-2) within 320 feet of a contact would have the highest expected radon concentration ( $\ln(R_n) = 6.47 + 2.17 + 0.89 - (0.0018 \times 100)$ , or  $R_n = 11,500$  pCi/L). According to the continuum model, a 100 foot well in the Bernardsville hornblende granite (Ybh-2) within 320 feet of a contact ( $R_n = 8,900$  pCi/L) should not be as elevated as wells in the Hamburg quartz-oligoclase gneiss (Ylo-2). As in the groupings model, wells near a unit contact were associated with elevated radon levels.

Of the models considered, the most reasonable one includes sample area, well depth within each rock unit as a continuous variable, and whether or not a well is within 320 feet, 320 to 625 feet, or further from a unit contact. This model has 12 degrees of freedom and an  $r^2$  of 0.54.

## 5. Discussion

One of this study's primary objectives was to investigate whether relationships between ground water radon concentration and different geological units in the New Jersey Highlands could be determined. It has been suggested by other studies that both mineralogy and structural features might be important in controlling the ground water radon distribution (Gunderson 1988; Muessig and others 1989). The rock units studied here were selected based on their suspected uranium content. The hornblende granite units were known to be uraniferous, while the other units were thought not to have high concentrations of uranium. It was assumed that uranium content from primary and secondary sources would be a critical factor in controlling ground water radon concentrations.

Descriptive statistics and field observations suggest that both the mineralogy of the rock unit and geologic structures, such as faults and contacts, are important in controlling ground water radon concentrations. Linear regression models were used to test whether these mineralogical and structural relationships were statistically significant. Simple relationships, not surprisingly, do not immediately fall out of the data. The geologic complexity of these heterogeneous, highly deformed and faulted rocks in the New Jersey Highlands requires cautious interpretation of results. Below we discuss what significance the results from the field observations, descriptive statistics and linear regression models may have on our ability to understand the complex distribution of ground water radon concentrations in the Highlands.

For the region in which we sampled, the mean and median ground water radon concentrations were both 1600 pCi/L. This agrees well with results from 100 wells sampled in the Highlands that yielded a geometric mean of 1700 pCi/L (NJDEPE 1989). The range of concentrations from that study of 150 pCi/L to 32,700 pCi/L is

consistent with our range of 36 pCi/L to 24,000 pCi/L. The distribution seen in the Confirmatory Monitoring Program (CMP) data does have significantly more weight above 10,000 pCi/L than was observed in this study (Cahill 1987; NJDEPE 1988). With the CMP's much larger sample size, it is not surprising that some very high levels (greater than 100,000 pCi/L) are seen. The larger proportion of CMP wells with levels over 10,000 pCi/L is probably due to a bias from sampling only at homes with elevated indoor air radon levels.

Taken together, results from various studies provide a consistent picture of the occurrence and geographical distribution of radon in the state's ground water. Data for the southern Piedmont Province (Anderson 1983; Szabo and Zapezca 1987; NJDEPE 1989; Moon 1990) indicate that, while ground water radon concentrations are generally somewhat lower than those in the Highlands, high levels (between 10,000 and 100,000) can be found. There are relatively few data on ground water radon concentrations in the Valley and Ridge Province, but a study of 55 wells found a maximum of 5,700 pCi/L (NJDEPE 1989). Levels up to 200,000 pCi/L have been found in unspecified parts of northwestern New Jersey (Cahill 1987; NJDEPE 1988; Moon 1990). Ground water radon concentrations in the northern Piedmont Province (Szabo and Zapezca 1987; NJDEPE 1989; Moon 1990) and the Coastal Plain (Anderson 1983; Kozinski and others 1991) are consistently much lower than those of the northwestern physiographic provinces. No levels above 2200 pCi/L have been found in southern New Jersey (Kozinski and others 1991).

These studies show that many public and private wells are likely to exceed the Maximum Contaminant Level (MCL) of 300 pCi/L radon in drinking water that USEPA recently proposed (USEPA 1991).

In the six selected areas, mineralogy was found to influence ground water radon concentrations. The hornblende granite units,

originally identified as potentially uraniferous by Markewicz (1967), Volkert (1988), and Muessig and others (1989) yielded the two highest radon concentrations and the second and third highest geometric mean concentrations (Table 1). The high radon concentrations found in the hornblende granite rocks may be attributed to the occurrence of uranium bearing alaskite, migmatite and pegmatite pods. Volkert (1989a) suggests that these pods and lenses may be ubiquitous within the High Bridge hornblende granite, as well as elsewhere in the Highlands, often occurring as small, unexposed bodies that may consequently go unrecognized. Therefore, the importance of these pods in controlling ground water radon concentrations may be more important than previously recognized. In this study, the wells that occurred in association with these pods in the High Bridge hornblende granite had consistently high ground water radon concentrations. This suggests that uraniferous alaskite, migmatite and pegmatite pods could influence high ground water radon concentrations. Unfortunately, the limited number of wells sampled near these pods precludes a comprehensive understanding of the influence of these pods on radon concentrations.

The pyroxene granite units have low geometric mean ground water radon concentrations (Table 1). This is consistent with the mineralogy of these units reported by Volkert (1989a). He found that both the High Bridge pyroxene granite and the Stanhope pyroxene granite were not uraniferous, suggesting the lack of a source mineral for radon. In addition to the pyroxene granite units, the Stanhope quartz-oligoclase gneiss unit had low geometric mean ground water radon concentrations. This unit is also reported to be non-uraniferous (Volkert 1989a) and was not expected to have high radon concentrations.

The Hamburg quartz-oligoclase gneiss unit, contrary to expectations, yielded the highest geometric mean ground water radon concentration of any unit (Table 1). The NURE aeroradiometric data

for the Hamburg quartz-oligoclase gneiss unit show elevated equivalent uranium levels in the near-surface (Popper and Martin 1982). Field investigation resulting from this study found thin, localized veins and seams of microperthite alaskite intruding the Hamburg quartz-oligoclase gneiss. These intrusions are a possible uranium source for the anomalously high ground water radon values found in the quartz-oligoclase gneiss in this area.

Differences in rock type at depth may explain why adjacent rock units of high and low uranium content (for example, the High Bridge hornblende granite and the High Bridge pyroxene granite) were not statistically significantly different (Figure 10 and Table 2). The uranium bearing High Bridge hornblende granite may intrude at depth into the High Bridge pyroxene granite, may have caused uranium enrichment along faults, or may be a source of ground water rich in radon for the High Bridge pyroxene granite.

In the Stanhope region where the pyroxene granite and the quartz-oligoclase gneiss are both non-uraniferous, the lowest mean ground water radon concentrations were measured (Table 1). Although these units are faulted, their predominantly low ground water radon concentrations may be strongly attributed to a paucity of uranium bearing rocks in the area. Only one well in the Stanhope quartz-oligoclase gneiss had a radon concentration above 5,000 pCi/L. This well occurs along a fault and is adjacent to another unit in the Highlands of uranium bearing hornblende granite that was not part of this study (Figure 13). Although no real significance can be based on the results of a single well, anomalous concentrations in specific wells within the different units suggest that both structure and mineralogy are important factors contributing to ground water radon concentrations in these highly complex rocks.

According to the linear models, proximity to mapped faults was not significant. This lack of significance is not surprising

because there were very few wells near faults (specifically, 3 wells were within 125 feet, 4 wells between 125 and 320 feet, and the other 125 were further away). In contrast, unit contact proximity was associated with a small but significant increase in radon levels. Proximity to a contact could either increase or decrease radon levels, depending on the conditions at the individual unit contact. However, the model did not assess contact proximity separately for each contact, nor even for each unit, due to the large number of adjustable parameters that would need to be introduced. It would be desirable to determine whether the significance of contact proximity seen in this data set arises from physical causes, or is simply an artifact of the distribution of wells sampled. No significant difference was observed between the 16 wells within 125 feet of a contact and the 14 wells 125 to 320 feet from a contact. It is possible, but not obvious, that the mineralogical and structural influences of faults extend such distances.

It was expected that, within a given rock unit, the depth of wells might affect radon concentrations significantly. A study in Maine (Brutsaert and others 1981) found that deeper wells had higher radon levels. Other studies (for example, Dillon and others 1991) have seen no correlation between well depth and radon levels. The continuum model found that, for the two units in which well depth was significant (Bernardsville hornblende granite and Stanhope pyroxene granite), the deeper wells had lower radon levels. This is in contrast with results from other studies. However, the statistical depth effects seen in these two units are highly significant. There is not an obvious explanation for this. It is interesting that depth is significant in a unit of high (hornblende granite) and a unit of low (pyroxene granite) uranium content. That well depth is significant in some units and not in others is another example of the heterogeneity of these rocks.

Possible causes of a depth effect could be the occurrence of

changes in source rock, uranium enrichment, fracture density, or well yield around a certain depth. Wells drawing water from rocks at that depth could have higher radon levels than other wells. The groupings model was used to investigate this hypothesis. We had no information about uranium concentration versus depth for the wells studied. Therefore, groupings were assigned based on apparent clumpings in the well depth distributions within each unit. The groupings model has many drawbacks. It is not possible to tell whether the groupings of well depths assigned have physical meaning or are arbitrary. Even if the groupings are meaningful in some rock units, they are likely to be artificial in others. Still, this model has an advantage of being sensitive to effects that are not linear in depth. For the hornblende granite (at both locations) and the Stanhope pyroxene granite, the well depth groupings were significant. In these units, the shallower wells had higher radon levels, consistent with the continuum model, and in contrast to results from other studies.

Of the two models, the continuum model describes the data equally well and is more physically realistic. It eliminates the imposition of artificial groupings on the data and it has fewer adjustable parameters (its depth parameters contribute only five adjustable parameters, as compared with twelve for the groupings model). However, it would not be expected to give results that approximate reality unless the influence of well depth were roughly linear. The continuum model results are similar to the groupings model, except that well depth in the High Bridge hornblende granite is no longer significant. This suggests that the effect of well depth in the High Bridge hornblende granite is not linear.

The major working hypothesis of this study was that rock units with higher uranium content would yield ground water with higher levels of radon. Thus, it was expected that the hornblende granite would be more likely to have wells with elevated radon levels than the quartz-oligoclase gneiss or pyroxene granite. The model

confirmed that rock unit was a significant variable. However the variable, rock unit, did not always correlate with radon levels in the manner predicted based on the expected uranium content of the rock type. One reason for this deviation is the difficulty in predicting uranium concentrations from generic mineral classifications (for example, Sachs and others 1982). It is probable that the predictive capability would improve if knowledge of local variations in uranium content, could be included in the model.

The  $r^2$  of 0.54 for the model indicates that the parameters included in the model have significant power to explain the observed variation in radon levels. However, such an  $r^2$  is not high enough to give any predictive confidence. Given the complexity of geological systems it would have been surprising if a predictive model could have been developed. Rather, the value of the statistical modeling has been to allow semiquantitative study of the data, specifically, hypothesis testing. It is possible that parameters not included in the model (such as ground water pH and dissolved oxygen content, and the source, composition and thickness of overburden) could have improved the predictive capability. These parameters were excluded due to missing values for many wells.

There are many other factors affecting ground water radon concentrations than could be measured in this research study. Two factors that preclude development of a strong predictive capability are geologic heterogeneity and the variation in the concentration and mobilization of radioactive minerals under various geochemical regimes. More precise models of these dynamics are needed and are currently being developed (see Cerfes, M., in preparation).

The data available on the distribution of ground water radon concentrations in the New Jersey Highlands indicate that, while

levels can be quite high, they are not as elevated as the highest levels found in granite and granitic gneiss bedrock of New England, or granitic gneiss bedrock of Georgia's Piedmont. Not only are the extreme levels found so far higher in the New England and Georgia rocks (Lowry and others 1987, Dillon and others 1991) but the distributions seen in New England and Georgia have much higher percentages of wells above 10,000 pCi/L (Brutsaert and others 1981, Siniscalchi and others 1990, Gregg and Coker 1990, and Dillon and others 1991).

While New Jersey does not have the highest ground water radon concentrations in the country, the New Jersey Highlands does have levels high enough to pose a public health threat if exposure is repeated over many years. Ninety percent of the wells in this study have radon levels greater than the USEPA's proposed MCL for radon in drinking water, 300 pCi/L (USEPA, 1991). The highest ground water radon concentration found in this study was nearly one hundred times the proposed MCL.

## 6. Conclusions

Ground water radon concentrations of three crystalline rock units in New Jersey's Highlands were characterized. Different rock units had significantly different distributions of ground water radon concentration, although all units had some overlapping levels (Table 1). With one exception, the trend for each unit was as expected from geochemical information on uranium content of the respective rock units that was reviewed prior to the testing. It was in the Hamburg quartz-oligoclase gneiss, subsequently found to contain microperthite alaskite veins and seams (which have elevated uranium content) that the values were higher than expected. Wells close to a unit contact were associated with a small but significant increase in ground water radon concentration. In several rock units, shallower wells were associated with higher radon levels than were deeper wells.

Mineralogy and structure were found to have an influence on variability of radon in ground water within rock units. Migmatites, alaskites and pegmatites which may not appear on a geologic quadrangle map (due to their small size or because they are not exposed) can affect radioactivity on a local scale.

Ninety percent of the wells sampled in this study have ground water radon concentrations greater than the USEPA's proposed MCL for radon in drinking water of 300 pCi/L (USEPA, 1991). The maximum concentration found was 24,000 pCi/L and the geometric mean concentration was 1600 pCi/L.

## 7. Policy Implications

This research shows that geologic models of uranium occurrence can help guide the use of limited resources in identifying areas with possibly elevated levels of radon in ground water. Certain rocks known to be uraniferous do show elevated levels of radon in ground water. However, if these data alone are used as a search criterion, then areas of high radon in ground water may be overlooked. There is always a possibility that uraniferous zones could remain undetected when an area is surveyed. Thus, reports of high levels of radon in air or water should be followed by mineralogical and structural investigations in an area to enhance the understanding of radon source distributions.

The levels of radon found in this research study provide an indication of the range of radon in water levels that can be expected in the crystalline rocks of the Highlands. One goal of this project was to determine whether it might be possible to prioritize areas of the New Jersey Highlands for testing of radon in water once the USEPA drinking water standard is promulgated and statewide testing becomes mandatory. None of the rock units studied had levels consistently low enough to be regarded as a low priority for testing. Regardless of the level at which USEPA

ultimately finalizes the Maximum Contaminant Level (MCL) for radon in drinking water, many of the wells sampled in this study, and in other parts of northwestern New Jersey, will exceed the MCL (Keith and others 1991).

Public water supplies that exceed the drinking water standard will require treatment. Many private well owners will need and want water treatment as well. Guidance about the correct use of radon removal systems will be needed. Additional research and policy development may be needed to enable NJDEPE to provide guidance to both public water supply operators and private well owners on how to manage elevated concentrations of radon in water supplies.

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Appendix A. Well Owner Interaction Materials

1. Letter for soliciting participants
2. Fact sheet
3. Letter to local health officers
4. Letter for reporting sampling results to homeowners
5. Letter for reporting sampling results to water purveyors

1. Letter for soliciting participants

Let's protect our earth



State of New Jersey  
DEPARTMENT OF ENVIRONMENTAL PROTECTION  
OFFICE OF SCIENCE AND RESEARCH  
CN 409, TRENTON, N.J. 08625

ROBERT K. TUCKER, Ph.D.  
DIRECTOR

Dear Sir or Madam:

As you may know, radon, a naturally occurring radioactive gas, has been found in elevated levels at some locations in New Jersey. Elevated radon levels have been linked to adverse health effects. Radon gas is a natural component of certain rock types and may seep into buildings constructed upon those rocks or soils. Researchers are uncertain if radon in groundwater may also contribute radon gas to buildings.

In order to better understand the occurrence and distribution of radon in groundwater, the New Jersey Geological Survey (NJGS) and the Office of Science and Research (OSR) have joined with Princeton University to conduct a research study which should help us understand what geologic conditions may affect the concentration of radon gas in groundwater. We have enclosed a brief fact sheet with more information.

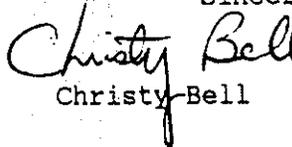
We are writing to you because your help is needed to conduct this research study. We need to collect water samples from wells in parts of northern New Jersey and have reviewed state well records to select specific wells that we think will be helpful to our research. Your well(s) is included on the list of wells we hope to sample. We would like your permission to visit your well(s) this spring in order to collect water samples. The results of the water test for radon will be sent to you and kept strictly confidential. Any reports that may present the findings of this study will not include the well owners' names or addresses. If high levels of radon are detected in your well, we will advise you as to what to do.

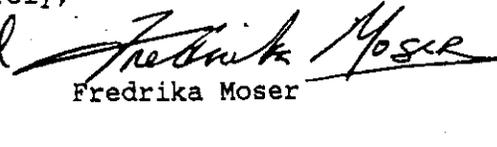
We urge you to participate in this research study; we believe that as well as providing us with the information we need to conduct this study, you will also be gaining important information about your well(s) at no cost.

Enclosed is a self-addressed card on which you can indicate whether we may sample your well or not. Since state well records are old, the name on this letter may not be that of the present owner. Please also indicate a change in ownership on this card. We would appreciate it if you could return this card to us by \_\_\_\_\_.

If you have any questions about this study, please feel free to contact Christy Bell (609-292-2576) or Fredrika Moser (609-633-3834). We greatly appreciate your time and cooperation on this research study.

Sincerely,

  
Christy Bell

  
Fredrika Moser



## **RADON IN GROUNDWATER RESEARCH INVESTIGATION**

The New Jersey Geological Survey (NJGS) and the New Jersey Department of Environmental Protection's Office of Science and Research (OSR), in cooperation with Princeton University, are undertaking a research study to better understand the occurrence and distribution of radon gas in New Jersey's groundwater. You have received this fact sheet in the mail because your help is urgently needed to conduct this research study. This fact sheet provides basic information about radon gas and outlines the following information:

- . The need for research about radon in groundwater
- . Goals of the NJGS/OSR groundwater research study
- . How the NJGS/OSR study will be conducted
- . How you can help

### **RADON IN GROUNDWATER**

Radon ( $^{222}\text{Rn}$ ) is a naturally occurring radioactive gas found in low concentrations almost everywhere on earth. Radon gas is prevalent in certain soil and rock types and, thus, higher levels of radon are found in areas where those soil and rock types exist. Federal, State and local governments recommend that New Jersey homeowners have their homes tested for radon in air. Since radon is fairly soluble in water, all groundwater contains some level of radon. However, radon levels in groundwater may vary considerably from one area to another because of differences in soil and rock types.

Elevated levels of radon gas are linked to certain health effects, including lung cancer. Current research indicates that the primary way radon gas may pose health risks to people is through inhalation. Therefore, radon in well water may pose health risks to humans primarily because radon escapes from water to the air, thus increasing radon levels in the air inside a home. Previous research has identified levels of radon in groundwater that may cause elevated levels of radon in indoor-air. The federal government has established guidelines for acceptable levels of radon in indoor-air and is currently developing guidelines for radon in water; OSR will compare well water test results with these federal guidelines.

### **THE NEED FOR RADON IN GROUNDWATER RESEARCH**

Presently, little is known about the occurrence and levels of radon gas in New Jersey's groundwater. Preliminary tests conducted by U.S. Geological Survey and the New Jersey Department of Environmental Protection detected a wide range of radon levels in groundwater from very low to moderately high. The ultimate goal of the current NJGS/OSR study is to determine if radon in groundwater poses a potential hazard to New Jersey residents. However, in order to achieve that goal, NJGS and OSR must first identify what geologic features in New Jersey might affect the concentration of radon in well water and whether concentrations of radon found in New Jersey well water are high enough to pose possible health hazards.

## NJGS/OSR RESEARCH STUDY

The current NJGS/OSR research is the first comprehensive attempt to understand the distribution of radon in groundwater in northern New Jersey. The research study will focus on areas in northern New Jersey that are within a geologic region called the "Reading Prong." NJGS and OSR researchers plan to collect water samples from 150 domestic and public wells within the study area. The water samples will be analyzed for temperature, pH and radon. Researchers will compare the radon levels found in the water with the distribution of certain rock types that are known to contain uranium minerals and could be a source of radon. These comparisons will allow researchers to identify areas of New Jersey that contain rock and soil types that may be the source of elevated levels of radon in groundwater. The research study may point out certain areas in the State where routine testing for radon in groundwater should be conducted.

### HOW YOU CAN HELP

In order to conduct the research study, NJGS and OSR must collect water samples from 150 wells within target areas of northern New Jersey. NJGS and OSR have mailed this fact sheet to you because you currently own a well(s) that is in the targeted study area. NJGS and OSR are requesting that you allow water samples to be taken from your well for the purposes of conducting this research study. By permitting your well(s) to be sampled, you will be providing NJGS and OSR with the critical information that is needed to accurately conduct this study.

If you agree to participate in this research study, a water sample will be collected from your well in the spring. The results of the tests conducted on your water sample will be sent to you. The test results will be kept strictly confidential. Any reports that may present the findings of this research study will not include the well owners' names or addresses.

As well as providing the information that is needed to conduct this research study, the well owner will also benefit from participating in this study. If high concentrations of radon are found in your water, we will advise you as to what to do. If it is necessary for you to reduce the amount of radon in your well water, several techniques to decrease radon in water are currently commercially available at reasonable prices.

To give your permission to have NJGS and OSR sample your well, please return the self-addressed card or call Fredrika Moser (609-633-3834) or Christy Bell (609-292-2576) by \_\_\_\_\_.

With your cooperation, NJGS and OSR can help New Jersey residents protect themselves against potential health hazards caused by radon in groundwater.

3. Letter to local health officers

Let's protect our earth



State of New Jersey  
DEPARTMENT OF ENVIRONMENTAL PROTECTION  
OFFICE OF SCIENCE AND RESEARCH  
CN 409, TRENTON, N.J. 08625

W. K. WALKER, Ph.D.  
DIRECTOR

March 16, 1987

Dear Health Officer:

The New Jersey Geologic Survey and the NJDEP Office of Science and Research have joined with Princeton University to conduct a research study on radon gas in New Jersey's groundwater. The extent to which radon gas is present in New Jersey's groundwater and its potential contribution to overall radon levels inside buildings is not clearly understood. The goal of our current groundwater study is to investigate the distribution and levels of radon in groundwater throughout targeted areas of northern New Jersey, including municipalities covered by your agency.

In order to conduct this study, we need to collect water samples from 150 wells within the targeted study areas. To this end, the Geologic Survey and Office of Science and Research recently sent the attached cover letter and informational fact sheet to residents in your jurisdiction with wells that meet our water sampling criteria. We have asked these residents for permission to take a water sample from their well during the spring as part of this research study.

I wanted to inform you that these letters have been sent to residents in your area and to make our researchers available to you should you have any questions concerning this study. Please feel free to contact Christy Bell of the Geologic Survey (609-292-2576) or Fredrika Moser of the Office of Science and Research (609-633-3834) if you have any questions regarding this study. Thank you for your cooperation.

Sincerely,

A handwritten signature in cursive script that reads "Barbara R. Litt".

Barbara R. Litt  
Research Scientist

attachments

4. Letter for reporting sampling results to homeowners

Let's protect our earth



State of New Jersey  
DEPARTMENT OF ENVIRONMENTAL PROTECTION  
OFFICE OF SCIENCE AND RESEARCH  
CN 409, TRENTON, N.J. 08625

ROBERT K. TUCKER, Ph.D.  
DIRECTOR

Dear Sir or Madam:

Thank you for participating in the radon in groundwater research investigation being conducted by the New Jersey Geological Survey, Office of Science and Research, and Princeton University. The assistance provided by you and other well owners was invaluable to this study and we greatly appreciate your cooperation.

The radon level measured in your water supply is indicated on the attached report.

As you probably know, radon is a naturally occurring radioactive gas which is always found in groundwater at varying concentrations. The purpose of our research study is to understand the influence of geologic factors on levels of radon in groundwater. We are investigating radon in groundwater because it may cause elevated levels of radon in indoor air. Elevated levels of radon gas in the air are linked to an increased incidence of lung cancer.

Levels of radon in water and air are measured in units called "picocuries per liter", abbreviated "pCi/l". Previous research has indicated that radon in groundwater at a level of 10,000 pCi/l can contribute approximately 1 pCi/l to radon levels in air. This means that your radon level in air could be increased by high levels of radon in your water supply. If the radon level in your water supply is greater than 10,000 pCi/l the Department of Environmental Protection (NJDEP) recommends that additional testing of radon levels in the air of your home be conducted.

If you have questions about the behavior of radon in homes call the Radon Information Line (800-648-0394 in state, 201-879-2872 out of state). If you have further questions about this work, please call Fredrika Moser (609-633-3834) or Christy Bell (609-292-2576). We appreciate your participation in our study.

Sincerely,

Fredrika Moser

Christy Bell

Attachment

(1) The level of radon detected in your water supply is \_\_\_\_\_.

(2) Because this level is less than 10,000 pCi/l, remedial measures to reduce the radon content in your water are not presently recommended. We will notify you if this recommendation should change in the future.

(3) NJDEP strongly recommends that all homeowners in northern New Jersey have their homes tested for levels of radon in indoor air. Therefore, regardless of the radon level in your water supply, if you have not had the air in your house tested for radon, you should do so.

Call NJDEP's Radon Information Line (800-648-0394 in state, 201-879-2872 out of state) to find out how to have an air test done.

(4) Other parameters measured in your water supply were

Temperature \_\_\_\_\_  
Dissolved oxygen content \_\_\_\_\_  
Specific conductivity \_\_\_\_\_  
pH \_\_\_\_\_

5. Letter for reporting sampling results to water purveyors

Let's protect our earth



State of New Jersey  
DEPARTMENT OF ENVIRONMENTAL PROTECTION  
DIVISION OF SCIENCE AND RESEARCH  
CN 409, Trenton, N.J. 08625

Robert K. Tucker, Ph.D.  
Director

Leslie J. McGeorge, M.S.P.H.  
Deputy Director

Dear Public Water Supply Operator:

Thank you for participating in the radon in groundwater research investigation being conducted by the New Jersey Geological Survey, Division of Science and Research, and Princeton University. The assistance provided by you and other well owners was invaluable to this study and we greatly appreciate your cooperation.

As you probably know, radon is a naturally occurring radioactive gas which is always found in ground water at varying concentrations. The purpose of our research study is to understand the influence of geologic factors on levels of radon in ground water. We are investigating radon in ground water because it may cause elevated levels of radon in indoor air. Elevated levels of radon in the air are linked to an increased incidence of lung cancer. Levels of radon in water and air are measured in units called "picocuries per liter", abbreviated "pCi/L". Previous research has indicated that radon in water at a level of 10,000 pCi/L can contribute approximately 1 pCi/L to radon levels in air. This means that radon levels in air could be increased by high levels of radon in a water supply.

The radon level measured in your well(s) is indicated on the attached report.

It is important to note that the water samples were drawn from as close to the well head as possible, before any treatment, storage or distribution system. In many cases these results are indicative of the geology but are not indicative of human exposure. This is due to the presence of large reservoirs for storage, as well as other factors involving distribution or treatment. If the radon level in your well water is greater than 10,000 pCi/L the Department of Environmental Protection (NJDEP) strongly recommends that additional testing of radon levels in your water supply be conducted. For this testing, sampling should occur in the distribution system.

If you have questions about additional radon testing, call Mr. Sonny Saroya of the Bureau of Safe Drinking Water (609-292-5550). If you have further questions about this work, please call Fredrika Moser or Barbara Litt (609-633-1398).

Sincerely,

*Barbara Litt*

Barbara Litt

b1  
Attachment

1. The level of radon detected in your well(s) is:

well location:

2. Because this level is less than 10,000 pCi/L, further testing of the radon content of your water supply is not an immediate recommendation. However, you should be aware that the United States Environmental Protection Agency will be proposing a Maximum Contaminant Limit (MCL) for radon in 1990, and adopting an MCL either later that year or in 1991. Currently, the range of MCL's they are considering is 200 pCi/L to 2,000 pCi/L, measured at the entry point to the distribution system. Several major water systems in New Jersey have already begun monitoring their systems, and are considering the ramifications of the radon levels they find when considering treatment for other chemicals. Depending on your specific situation, additional testing might be desirable. For information about such testing you may contact Mr. Sonny Saroya of NJDEP's Bureau of Safe Drinking Water.

Mr. Sonny Saroya  
Bureau of Safe Drinking Water  
New Jersey Department of Environmental Protection  
CN 029  
Trenton, New Jersey 08625

(609) 292-5550

## Appendix B. Analytical Details

To convert the counts obtained to a specific radon activity at analysis time the following equation was used:

$$\text{Rn (pCi/l)} = \frac{\text{cpm(gross)} - \text{cpm(bkgd)} - \text{cb}}{\alpha \cdot 2.2 \times \text{eff} \times \text{vol}}$$

with cpm = counts per minute  
cb = circulation blank (cpm)  
eff = cell efficiency  
vol = sample volume (liters)  
 $\alpha$  = number of alpha decays observed for one radon atom decay.

The cell efficiency was determined biweekly for each of eight cells by running dilutions of National Bureau of Standards radium-226 standards. The cell efficiency was known to an accuracy of +/- 3% on average, and ranges from 70 to 90%. The circulation blank was known to be 0.02 +/- 0.04 decays per minute (dpm). Because levels being measured were greater than 10 pCi/L, a blank of 0.02 dpm was considered negligible. The factor  $\alpha$  depends on the time between cell filling and radon counting, and on the counting time. This factor was calculated by computer each time the cells were counted. The sample volume was determined by weighing the full sample bottles and subtracting their dry weights.

The major sources of error for this technique are the uncertainty in the Lucas cell efficiency and the variability due to sample collection. The expression for uncertainty which includes the above sources of error, except variability due to field sampling, is given in Key (1983). The error reported with the data was either the error-weighted propagated error (discussed below under Quality Assurance/Quality Control), or 5% of the measured sample activity, whichever was greater.

### Back Calculation for Decay

From the radon concentration at the cell filling time, a correction for decay can be made to obtain the radon concentration at the time of sampling. This correction is

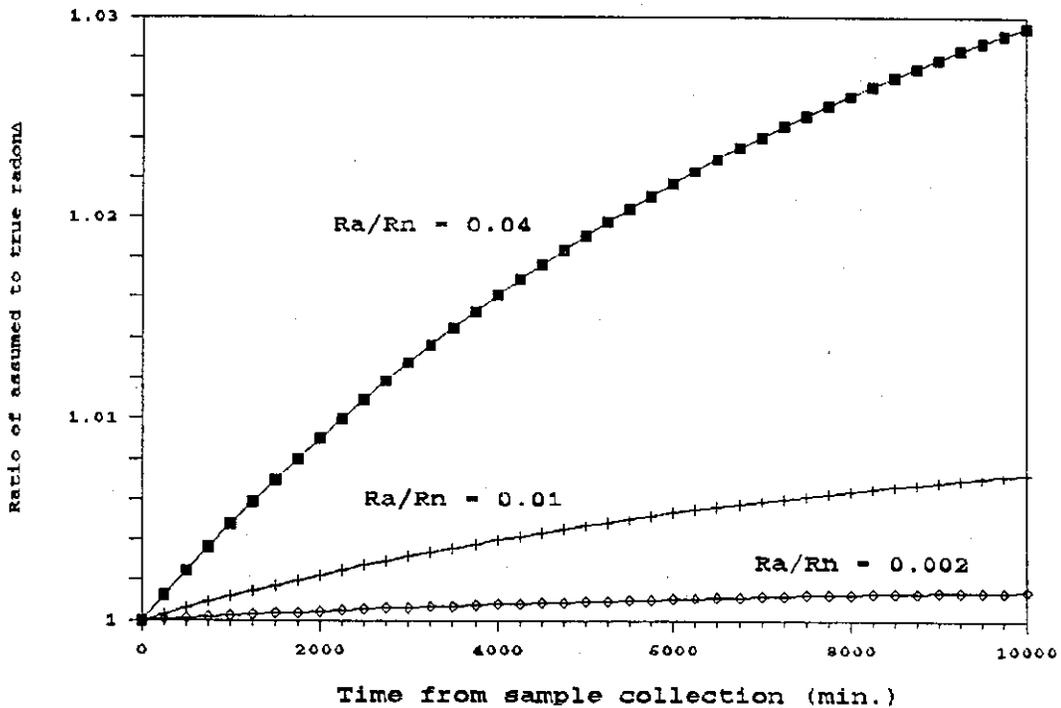
$$\text{Rn}(t_s) = (\text{Rn}(t_d) - \text{Ra}) e^{\lambda(t_d - t_s)} + \text{Ra}$$

$t_s$  = time of sample collection  
 $t_d$  = time at end of degas phase of sample analysis  
 $\text{Rn}(t)$  = radon concentration at time  $t$   
 $\text{Ra}$  = radium concentration  
 $\lambda$  = radon decay constant ( $1.259 \times 10^{-4} \text{ min}^{-1}$ ).

The radium concentration was not measured in this work, but was assumed to be zero for purposes of back calculation. The ratio, R, of assumed radon concentration (radium concentration assumed to be zero) to true radon concentration is given below and is shown in the accompanying figure.

$$R = [1 - (Ra/Rn)(ts)) (1 - e^{-\lambda(td-ts)})]^{-1}$$

This ratio is dependent on the ratio of radium activity to radon activity and increases exponentially with the time between sample collection and counting. For times between sample collection and counting used in this project (generally less than 2000 minutes) and for typical well water radon/radium values, the error due to assuming the absence of radium was less than 1%.



### Appendix C. Field Duplicate Results

No.	sample date	bottle number	Radon A	Radon B	percent differ.	RSD (percent)
1	05/13/87	3,4	3847	3807	1	1
2	05/13/87	1,2	1197	1446	19	13
3	05/14/87	5,6	858	832	3	2
4	05/14/87	7,8	247	260	5	4
5	05/21/87	7,1	1081	882	20	14
6	05/22/87	3,4	390	350	11	8
7	05/28/87	3,1	325	387	17	12
8	06/03/87	3,1	388	370	5	3
9	06/04/87	8,7	388	368	5	4
10	06/09/87	6,3	2766	2360	16	11
11	06/10/87	2,7	683	702	3	2
12	06/16/87	5,6	636	548	15	11
13	06/17/87	7,8	48	46	4	3
14	07/13/87	7,8	2155	2409	11	8
15	07/14/87	2,1	1442	1349	7	5
16	07/22/87	8,4	152	148	3	2
17	07/23/87	1,3	2433	2331	4	3
18	07/29/87	3,8	1741	1754	1	1
19	07/30/87	7,2	2594	2675	3	2
20	08/12/87	6,2	944	1077	13	9
21	08/12/87	4,8	16628	16946	2	1
22	08/12/87	3,5	481	452	6	4
23	08/26/87	2,10	7144	6874	4	3
24	09/30/87	3,12	5567	5599	1	0
25	10/01/87	1,4	5482	3945	33	23
26	10/14/87	2,12	1664	1625	2	2
27	10/28/87	3,4	1211	1281	6	4
28	10/29/87	19,18	3451	4106	17	12
29	11/04/87	3,17	3262	3084	6	4
30	11/09/87	11,12	2993	2973	1	0
31	11/17/87	12,14	1351	1529	12	9
32	11/19/87	3,18	1426	1213	16	11
33	09/28/88	6,15	2523	4606	58	41
34	10/06/88	3,14	5886	5847	1	0
35	10/06/88	12,9	6666	4947	29	21
36	10/20/88	7,12	771	620	22	15
37	11/17/88	13,14	558	631	12	9

## Appendix D. Split Sample Results

Results of samples collected at the same time, comparing the method of the Ocean Tracers Laboratory (OTL) and the Bureau of Radiation and Inorganic Analytical Services (BRIAS) are shown in the table. The OTL method generally gives slightly lower values than the BRIAS method. If all samples are included, the best fit linear least squares line is  $Rn_{OTL} = 0.90 Rn_{BRIAS} + 0.03$  ( $R^2 = 0.99$ ). The OTL reported that the calibration factor used may have been biased low for the two highest concentration data points, due to dead time of the detector (the samples normally counted by OTL are much lower than the highest encountered in this study). If the highest two datum are not considered, the best fit line becomes  $Rn_{OTL} = 0.95 Rn_{BRIAS} + 0.04$  ( $R^2 = 0.99$ ). There is quite good agreement between the two methods, especially considering that the sample is collected differently in each of them.

No.	Sadate	Bottle number	Radon OTL	Radon BRIAS	Percent differ.
1	06/16/87	1	2236	1930	15
2	06/16/87	5,6	585	640	-9
3	08/05/87	3	1420	1640	-14
4	08/05/87	1	3282	3700	-12
5	09/30/87	12,3	5582	5980	-7
6	10/07/87	6	5094	5280	-4
7	10/07/87	3	1668	1740	-4
8	10/07/87	15	1612	1610	0
9	10/07/87	2	4823	4480	7
10	10/08/87	12	3713	4000	-7
11	10/14/87	11	12204	14140	-15
12	10/28/87	14	9458	9400	1
13	10/28/87	9	1756	1860	-6
14	10/28/87	3,4	1225	1230	0
15	10/28/87	6	4180	4300	-3
16	10/29/87	20	2508	2730	-8
17	11/04/87	3,17	3168	3420	-8
18	11/04/87	19	2434	3300	-30
19	11/04/87	18	716	810	-12
20	11/17/87	7	491	610	-22

## Appendix E. Statistical Models

The linear regression analysis investigated the influence of the following factors on the radon level measured in a well: (1) location in a specific rock unit; (2) proximity to the nearest fault; (3) proximity to the nearest unit boundary; and (4) well depth.

To investigate the effect of a well's proximity to faults or boundaries, the wells were grouped as either being within 320 feet of a fault (boundary), or greater than 320 feet from a fault (boundary). Proximity to faults and proximity to boundaries were considered to be separate variables. The 320 foot delineation was not made on physical grounds, but due to guesses about the extent of fault (boundary) zones, and gaps in the distribution of distances from faults (boundaries). Distances of 125 feet and 625 feet were also investigated, but the 320 foot break point described the data best.

Two models were used to investigate the data. All components of the two models other than the well depth terms remained the same. A generic version of the first model is:

$$\ln(Rn_m) = \gamma + \sum_{i=1}^6 \alpha_i r_i + \sum_{j=1}^4 \beta_j x_j + \sum_{k=1}^{18} \delta_k d_k + e_m \quad (1)$$

In Equation 1, the subscript "m" refers to the individual well,  $\gamma$  is an intercept,  $r_i$  is 0 if the well is not in the  $i^{\text{th}}$  unit and 1 if it is in this unit,  $x_j$  is 0 if the well is not in the  $j^{\text{th}}$  distance group from a unit boundary and 1 if the well is in this distance group,  $d_k$  is 0 if the well is not in the  $k^{\text{th}}$  depth group and 1 if the well is in this depth group, and  $e$  is an error term. The  $\gamma$ ,  $\alpha_i$ ,  $\beta_j$ , and  $\delta_k$  are adjustable parameters of the model. An analogous term for the distance from faults was included, but has been omitted here for brevity. Either  $\gamma$  or one each of the  $\alpha$ ,  $\beta$ , and  $\delta$  must be fixed in order to have a unique representation of the model.

This model considered ranges of well depths in each rock unit. In the absence of cross sectional information, these groupings were chosen by natural clumpings of well depths in each unit, rather than by depths with any obvious physical interpretation. Also, it was necessary to have the groupings cover large depth ranges, so as not to introduce a huge number of adjustable parameters into the model, and to try to keep similar numbers of wells in each group. For example, of 23 wells in the Bernardsville hornblende granite, 10 were 98 to 199 feet deep, 7 were 222 to 399 feet deep, and 6 were greater than 440 feet deep. There were 18 such groupings in the six units, contributing 12 degrees of freedom to the model.

The other model is shown in Equation 2.

$$\ln(Rn_m) = \gamma + \sum_{i=1}^6 (\alpha_i + \delta_i d) r_i + \sum_{j=1}^4 \beta_j x_j + e_m \quad (2)$$

A term that multiplies the well depth,  $d$ , by an adjustable parameter,  $\delta_i$ , is substituted for the term that included the well depth groupings. In this way, the well depth (within a unit) is treated as a continuous variable, rather than lumped into one of three depth groupings. With this treatment, well depth terms contribute only five degrees of freedom to the model.

Appendix F. Laboratory and Field Data

Key to Data Table

code no.	random code number
rock unit	ybh1 = High Bridge hornblende granite ybh2 = Bernardsville hornblende granite ylo1 = Stanhope quartz-oligoclase gneiss ylo2 = Hamburg quartz-oligoclase gneiss ypg1 = Stanhope pyroxene granite ypg2 = High Bridge pyroxene granite
STP x-coord	well's state plane x coordinate
STP y-coord	well's state plane y coordinate
faultd	distance from the nearest fault (feet)
bdryd	distance from the nearest unit boundary (feet)
termin	n = north of terminal moraine s = south of terminal moraine
wdepth	well's depth (in feet)
sadate	date of sample collection
bottle	bottle number
T	water temperature (°C)
pH	pH
SC	specific conductance ( $\mu$ mhos/cm)
DO	dissolved oxygen (mg/L)
radon	radon (pCi/L)

(-32768 = missing value)

LABORATORY AND FIELD DATA, Page 1

No.	code no.	rock unit	STP	x-coord	STP	y-coord	faultd(=)bdryd(=)	termin	wdepth	satdate	bottle	T (C)	pH	SC(umho/cm)	DU(mg/l)	Radon(pCi/L)
1	31867	ybh1	1914447	667696.3	625	625	247	08/06/87	6			12.5	-32768	166	6.45	525
2	39695	ybh1	1934303	685218.1	2187	1000	170	09/03/87	13			11.1	-32768	179	4.91	3037
3	41241	ybh1	1937952	686479.9	875	500	250	08/26/87	5			12.0	6.97	247	5.63	642
4	60284	ybh1	1916729	676648.0	4125	62	150	08/18/87	12			12.4	-32768	467	8.23	23935
5	62588	ybh1	1916590	676507.5	4250	62	125	08/18/87	9			13.0	-32768	192	5.01	4183
6	68632	ybh1	1945825	690590.5	625	625	125	08/12/87	1			10.9	-32768	91	6.31	6516
7	73266	ybh1	1927289	679693.9	2125	0	210	08/19/87	10			14.0	-32768	100	4.69	4351
8	74215	ybh1	1946303	689631.5	1312	1312	329	08/12/87	3,5			14.9	-32768	100	4.62	466
9	82683	ybh1	1912270	674837.8	4187	125	408	08/19/87	4			16.0	-32768	206	6.02	11828
10	91712	ybh1	1910884	674197.4	3875	187	188	08/05/87	1			12.5	-32768	146	9.07	3282
11	7849	ybh2	2027208	698907.0	8437	1625	198	11/17/87	12,14			12.1	6.08	96	6.45	1430
12	9448	ybh2	2014607	690844.5	1750	1375	198	11/19/87	1			11.7	5.79	123	7.18	11019
13	10432	ybh2	2015943	689709.1	3500	2437	175	11/04/87	1			12.3	6.51	130	4.37	20945
14	11487	ybh2	2018181	689528.4	7312	1042	32768	10/13/88	12			11.6	7.13	233	1.94	988
15	12531	ybh2	2020891	697831.0	12250	5250	447	11/11/87	2			9.9	7.13	126	6.82	128
16	12700	ybh2	2009015	693262.9	937	375	398	11/19/87	2			12.5	6.1	126	6.82	2036
17	20442	ybh2	2005988	696641.4	5437	2875	350	11/19/87	15			11.7	6.18	212	4.82	2016
18	22191	ybh2	2030640	698814.6	3812	187	222	11/11/87	1			9.9	5.86	164	5.98	12541
19	22976	ybh2	2004094	697969.4	2375	500	399	11/05/87	13			12.9	7.2	210	6.52	6820
20	24628	ybh2	2015771	682945.5	1875	1000	297	11/19/87	3,18			10.6	6.17	191	6.06	1503
21	24921	ybh2	2019534	682978.9	375	0	150	10/20/88	14			13.2	6.25	313	4.25	10918
22	34010	ybh2	2016828	696312.8	0	0	349	11/17/87	7			10.4	5.68	82	6.35	8466
23	36690	ybh2	2020940	685019.8	11875	3000	98	11/04/87	19			11.8	6.6	408	4.99	491
24	36704	ybh2	2020215	682996.5	125	0	500	11/19/87	6			12.6	6.53	172	6.26	2434
25	40744	ybh2	2024134	697402.3	0	0	300	11/19/87	5			11.4	6.51	153	3.9	491
26	55438	ybh2	2021545	696620.5	10812	3875	122	11/11/87	5			10.7	6	360	7.5	4404
27	61419	ybh2	2019606	691952.1	8812	2125	198	11/09/87	13			12.1	-32768	237	5	3719
28	70112	ybh2	2003833	694252.8	5125	2625	198	11/09/87	14			11.3	6.8	304	6	2223
29	74448	ybh2	2026708	697350.8	7625	1125	557	11/09/87	7			12.7	7.25	237	0.8	729
30	76457	ybh2	2017893	693829.0	10250	4250	32768	10/20/88	7,12			12.1	5.44	206	5.2	4531
31	78208	ybh2	2017471	692048.8	9625	3437	557	11/09/87	7			12.1	6.55	206	6.66	533
32	79199	ybh2	2008809	681250.8	625	0	500	11/19/87	5			11.1	6.83	457	2.59	409
33	81707	ybh2	2021825	693958.9	8750	1500	98	11/05/87	2			10.4	5.82	186	6.97	1844
34	88350	ybh2	2020238	684546.4	1625	375	360	11/09/87	11,12			12.2	8.2	239	0.43	2983
35	94467	ybh2	2028810	698106.4	2312	625	690	11/05/87	10			12.0	6.72	190	1.62	5098
36	94938	ybh2	2022396	689837.3	5125	1000	500	11/04/87	18			12.6	6.85	233	6.54	716
37	95972	ybh2	2003176	695048.4	3125	1687	318	11/04/87	3,17			12.5	6.52	237	6.17	3168
38	98995	ybh2	2013978	689223.0	2375	1750	164	11/11/87	3			12.5	5.64	138	7.5	10386
39	99315	ybh2	2017792	699986.4	10750	875	275	05/28/87	8			14.5	6.03	177	5.75	7681
40	1737	y101	1987222	765355.0	1062	562	275	05/28/87	8			13.1	6.69	446	2.78	3689
41	6070	y101	1989382	765747.1	2750	1875	430	06/02/87	4			20.1	7.79	800	9.3	275
42	8150	y101	1993940	771034.8	2375	1125	125	06/10/87	4			11.8	6.58	600	6.54	156
43	8981	y101	1972835	744869.5	5812	1250	125	06/09/87	6,3			10.1	6.37	56.4	9.39	2563
44	9167	y101	1970487	744623.5	4500	0	315	05/13/87	3,4			11.1	5.75	437	7.09	3827
45	10814	y101	2038586	833107.3	3000	125	223	05/13/87	3			11.0	8.08	245	1.76	918
46	17227	y101	1989959	743759.1	8125	312	110	05/26/87	1,2			10.6	6.36	396	7.33	1299
47	23503	y101	1993083	771508.4	1437	1625	148	06/03/87	6			13.1	7.71	320	5.01	147
48	24812	y101	2013108	798061.5	1250	1250	405	05/22/87	3,1			12.6	7.2	468	6.45	379
49	25428	y101	2016084	802218.5	1500	1500	123	05/22/87	5,4			10.8	7.73	362	13.35	369
50	26803	y101	2027619	821383.4	5250	2375	123	05/28/87	3,1			11.8	6.63	280	3.53	367
51	27023	y101	1987680	762223.8	3325	187	350	06/03/87	5			11.0	6.58	137	12.67	351
52	42441	y101	2038015	833038.4	3375	125	150	05/27/87	6			12.4	6.68	676	3.04	1167
53	43832	y101	2016430	802349.4	1750	1437	550	08/26/87	2,10			10.1	7.18	372	11.27	544
54	44947	y101	1979566	769670.3	0	0	123	05/21/87	7,1			13.0	8.07	1052	4.31	6998
55	48270	y101	1983539	760987.6	500	500	123	05/21/87	7,1			10.9	6.89	644	7.15	961

LABORATORY AND FIELD DATA, CAPR

No.	code no.	rock unit	SIP	x-coord	SIP	y-coord	faulted (1) bdr/d(2)	termin	width	depth	sample	Y (C)	pH	SC (umho/cm)	DO (mg/l)	Radon (pCi/L)
56	52932	y101	1914832	764931.5	750	1750 n	146	08/26/87	13	11.5	7.19	591	3.87	912		
57	61467	y101	1920682	769948.9	1125	1125 n	147	05/14/87	5,6	11.8	-32768	654	3.28	843		
58	69777	y101	1989801	769394.6	875	875 n	195	05/14/87	7,8	12.0	-32768	340	0.79	253		
59	73842	y101	1988910	769532.5	125	125 n	222	05/26/87	7	10.7	7.47	154	4.17	1873		
60	76657	y101	1983714	761505.8	500	500 n	123	09/03/87	7	14.5	-32768	768	0.44	1500		
61	77646	y101	2015729	804028.8	250	250 n	123	05/27/87	2	11.1	7.41	958	8.01	765		
62	87990	y101	2029387	821024.9	4750	750 n	122	05/21/87	8	10.5	6.67	161	8.35	251		
63	88862	y101	1971175	745166.3	4437	0 s	173	07/14/87	3	11.3	6.51	198	4.97	2968		
64	4986	y102	2032105	862942.3	5000	1875 n	300	09/29/88	9	11.7	-32768	321	0.1	3903		
65	7685	y102	2030765	863652.0	6562	3375 n	121	10/14/87	11	11.3	7.9	459	0.26	12204		
66	8644	y102	2033394	867343.5	4125	750 n	-32768	09/28/88	6,15	11.7	6.47	1340	9	3004		
67	10413	y102	2029670	858690.9	4500	1375 n	149	10/07/87	2	12.3	5.87	207	6.2	4823		
68	11641	y102	2031999	870815.6	4500	2375 n	485	10/08/87	8	11.9	7.2	337	0.34	1644		
69	12666	y102	2030100	862480.8	6250	3250 n	549	10/14/87	2,12	12.2	7.83	574	0.49	1668		
70	17961	y102	2027814	861563.9	5062	1250 n	300	10/07/87	3	11.7	6.23	331	5.7	3975		
71	17290	y102	2029570	857370.4	3562	750 n	98	10/14/87	7	11.7	7.01	327	0.12	2967		
72	20907	y102	2034270	867388.6	5250	2000 n	160	10/14/87	15	11.0	6.93	495	1.1	5516		
73	22604	y102	2031733	862399.3	5000	1875 n	300	09/28/88	12	12.3	7.55	327	2.26	13222		
74	23516	y102	2032008	867853.3	6375	3375 n	-32768	10/06/88	12,9	11.6	7.52	546	2.4	4698		
75	33119	y102	2034407	868414.4	5375	1812 n	-32768	09/29/88	14	11.3	7.52	517	2.6	2948		
76	35764	y102	2033059	867206.1	6250	3000 n	-32768	09/29/88	7	11.6	7.56	244	5.7	5866		
77	39225	y102	2034478	863754.1	5375	312 n	174	09/30/87	13	12.1	7.89	390	9.43	13512		
78	41037	y102	2033491	865880.8	5250	2125 n	325	10/01/87	4,1	11.8	7.77	398	0.4	4468		
79	44809	y102	2032119	860156.5	3500	250 n	174	10/01/87	15	12.2	8.02	433	3.51	1612		
80	45158	y102	2030030	860944.5	5562	3750 n	155	10/14/87	5	12.0	7.75	548	2.55	4809		
81	43273	y102	2032451	867413.9	4875	1125 n	155	10/14/87	5	11.7	-32768	237	3.2	907		
82	50560	y102	2028098	855893.5	3562	2750 n	124	10/08/87	9	11.2	6.7	564	2.44	1964		
83	51145	y102	2033142	873004.8	4937	2875 n	500	10/08/87	7	12.2	7.66	541	0.95	9982		
84	56057	y102	2030015	861892.4	6250	2875 n	224	10/07/87	6	12.1	7.25	498	3.54	5094		
85	56554	y102	2030183	863625.1	7000	3250 n	224	10/08/87	12	12.8	7.81	367	3.4	3713		
86	60556	y102	2030502	862776.8	6312	3125 n	125	10/29/87	20	11.2	6.55	713	3.34	2508		
87	61797	y102	2032477	871567.9	2625	562 n	223	10/29/87	19,18	11.5	6.32	645	2.33	3723		
88	62684	y102	2029942	863174.0	6687	2812 n	498	10/28/87	1	11.5	6.85	300	4.4	2732		
89	65056	y102	2028586	857453.8	4312	1750 n	157	10/29/87	5	11.5	6.68	446	4.95	2937		
90	68338	y102	2029557	858608.4	4125	1500 n	122	09/30/87	12,3	11.8	6.4	288	5.73	5582		
91	69129	y102	2035324	876555.4	5437	2125 n	99	10/01/87	8	12.3	6.95	516	4.3	8128		
92	75972	y102	2035298	874041.3	5687	3062 n	198	09/30/87	10	12.4	7.88	737	2.54	1871		
93	76405	y102	2030855	864676.4	7000	3250 n	123	10/28/87	6	12.3	7.86	450	0.35	4180		
94	79158	y102	2031507	866413.4	7000	3250 n	170	10/01/87	7	12.2	7.98	364	1.9	9914		
95	81661	y102	2029332	863969.8	6500	2000 n	140	10/28/87	3,4	10.5	8.03	367	4.38	1225		
96	91230	y102	2033059	867820.1	6000	2000 n	180	10/28/87	14	11.6	7.86	421	0.33	9458		
97	91743	y102	2035366	875379.5	6000	875 n	213	05/27/87	4	12.3	6.87	604	1.51	1193		
98	99093	y102	2030391	860991.0	3875	2437 n	148	06/17/87	4	12.4	6.81	718	1.47	310		
99	3428	yp91	2002887	760891.0	4000	2750 n	132	08/12/87	6,2	12.1	-32768	213	6.34	1001		
100	16089	yp91	2004754	762520.4	4000	500 n	200	11/17/88	13,14	11.2	6.13	685	6.95	590		
101	23146	yp91	1983745	740466.3	375	2250 s	148	07/22/87	8,4	12.3	-32768	247	1.16	150		
102	29047	yp91	1981140	736427.4	5375	2187 n	165	06/09/87	5	11.4	5.87	312	1.18	137		
103	31250	yp91	1979988	732584.9	3875	2500 s	198	06/16/87	3	10.9	5.9	215	5.14	1509		
104	33307	yp91	2004402	762334.3	3875	2500 n	170	07/23/87	7	16.1	-32768	702	0.39	2997		
105	3307	yp91	2006504	762038.4	3000	687 n	-32768	11/17/88	12	11.2	6.12	626	9.08	36		
106	38811	yp91	2004618	762519.9	3875	2375 n	106	06/16/87	5,6	11.2	6.99	659	11.9	657		
107	39941	yp91	2009052	766694.9	2750	500 n	348	06/04/87		9	7.43	512	2.97	121		



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