THE RELATIONSHIP BETWEEN SOIL RADON CONCENTRATIONS AND THE HUNTINGDON VALLEY SHEAR ZONE, SOUTHEASTERN PENNSYLVANIA

A Thesis Submitted
to the Temple University Graduate Board

---

in Partial Fullfiment
of the Requirement for the Degree

MASTER OF ARTS

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by

Paul Douglas James, Jr.

January 1996

DEPARTMENT COPY

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ABSTRACT

The Huntingdon Valley shear zone is a zone of high-strain ductile deformation which strikes N70E between the Schuylkill River and the Delaware River. In the study area, there are seven lithologic units within the shear zone: Wissahickon Formation (oligoclase-mica schist), Chickies Formation (quartzite), felsic gneiss (pyroxene-bearing rock), mafic gneiss (hornblende-bearing rock), and three carbonate units. Strain is heterogeneous across these units. High soil-radon (^{222}Rn) concentration correlates both with lithology and the magnitude of strain of the bedrock. High concentrations of radon gas (^{222}Rn) were found in soils derived from highly deformed rocks of the Huntingdon Valley shear zone and two other zones to the south.

For this study, the Huntingdon Valley shear zone (HVSZ) was verified as being a structure associated with high radon emissions regardless of lithology. Within one lithology, Wissahickon Formation, radon levels outside the zones of shear range from 170 to 2,639 pCi/L, whereas inside the zone, soil radon was recorded as high as 6,380 pCi/L. The Chickies Formation averages 1,931 pCi/L inside the shear zone and 634 pCi/L outside the shear zone. The felsic gneiss has low radon emissions throughout, while the Conestoga shows differences. These differences could be the result of unexposed shear zones.

ACKNOWLEDGMENTS

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CHAPTER 1

INTRODUCTION

The purpose of this study is to determine if correlations exist between radon concentration found in *in situ* soils and the composition and shear zone fabric of the underlying parent rock in the eastern Pennsylvania Piedmont. To the field geologist, this relationship provides a useful tool for mapping lithologies and structures that lack exposure in a particular study area. To the environmental scientist, these correlations could be useful in defining areas which may have a higher risk of indoor radon problems.

The study area is located in southeastern Pennsylvania, within the central and northern portions of the Germantown and Frankford 7½ minute quadrangles. The center of the study area lies ten miles north of center city, Philadelphia (Figure 1). The western border of the study area is the Wissahickon Valley, and the eastern border is the Pennypack Creek Valley.

With in the study area there has been a history of dangerously high indoor radon problem. The Westminster Seminary is located on the trace of the Huntingdon Valley shear zone within the study area. The Philadelphia Inquirer (Rubin, 1989) reported that the seminary's library had the highest levels of radon ever detected in a public building in the United States (2,200 picocuries per liter).

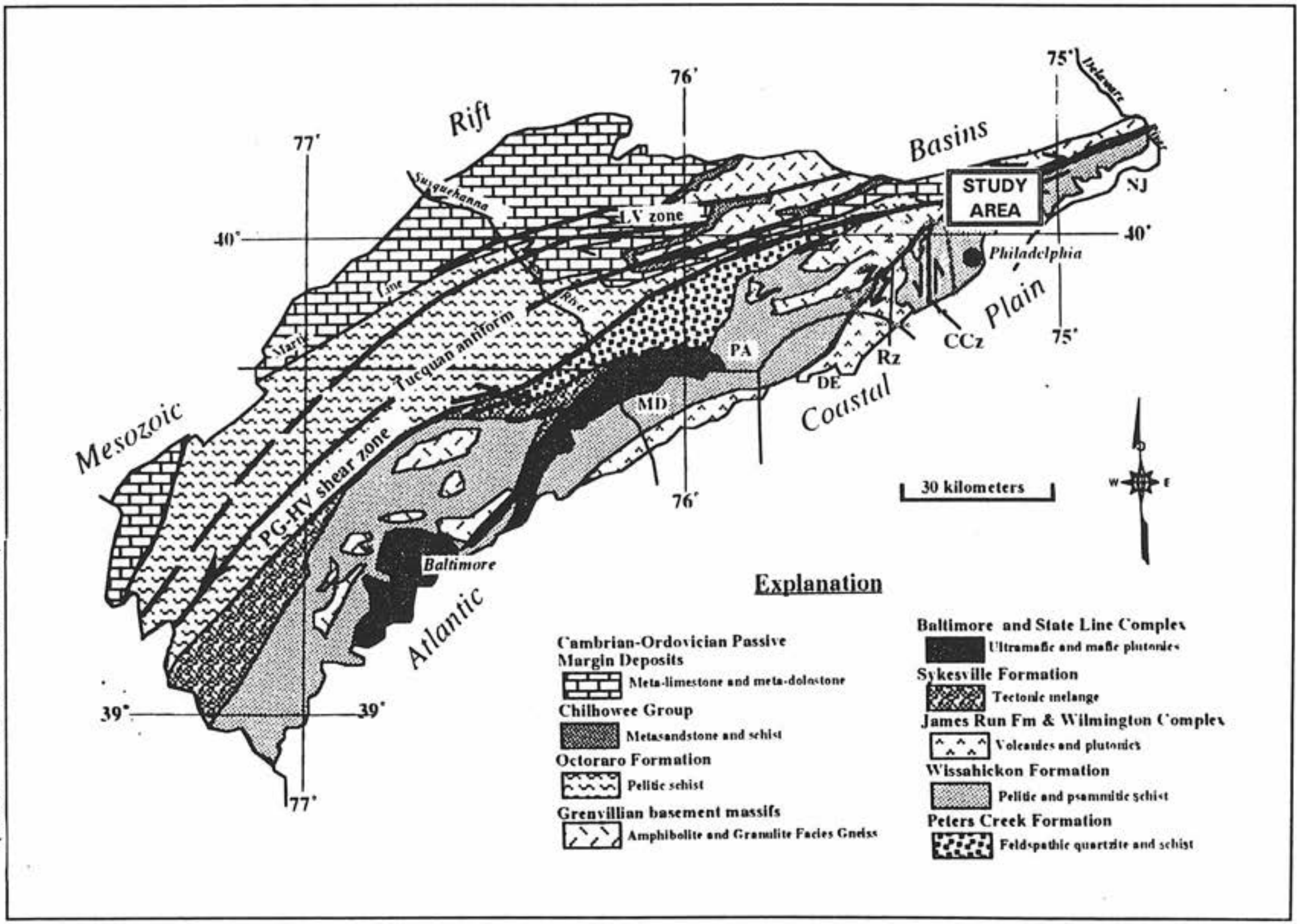

Figure 1. Study area location map. (Valentino et al., 1995).

Geologic Setting and The Lithologies

The study area is located in the Piedmont Terrane, a broad northeast-southwest trending terrane consisting mostly of pre-Silurian metamorphic rock (Bascom, 1905 and Socolow, 1980). To the southeast, these rocks are covered by Cretaceous and Tertiary coastal gravel and sand deposits (Socolow, 1980). To the northwest, the terrane is covered by Triassic arkosic sandstones and shales (Bascom, 1905 and Socolow, 1980).

The southern portion of the study area (Figure 2) is underlain by the Wissahickon Formation, an oligioclase-mica schist, which underlies most of Philadelphia (Bascom, 1905; Wyckoff, 1952 and Socolow, 1980). It consists of alternating pelitic and psammitic layers which are heterogeneous in composition and strain throughout (Armstrong, 1941 and Wyckoff, 1952).

North of the Wissahickon Schist is a felsic gneiss (pyroxene-bearing gneiss) and the Chickies Formation (quartzite)(Armstrong, 1941). The gneiss is likely Precambrian and the quartzite is Cambrian in age (Socolow, 1980). These lithologies are exposed in an east-northeast trending outcrop pattern (Armstrong, 1941). The exposure of felsic gneiss covers a wider area in the east and narrows to the west (Socolow, 1980). The Chickies Formation is exposed at the surface in four different locations, including a two and a half mile lens that lies between the felsic gneiss and the Wissahickon Formation. It is also exposed as a narrow belt along the entire northern border of the felsic gneiss, and there are two small lenses within the Ledger Formation (a metamorphic dolostone in the

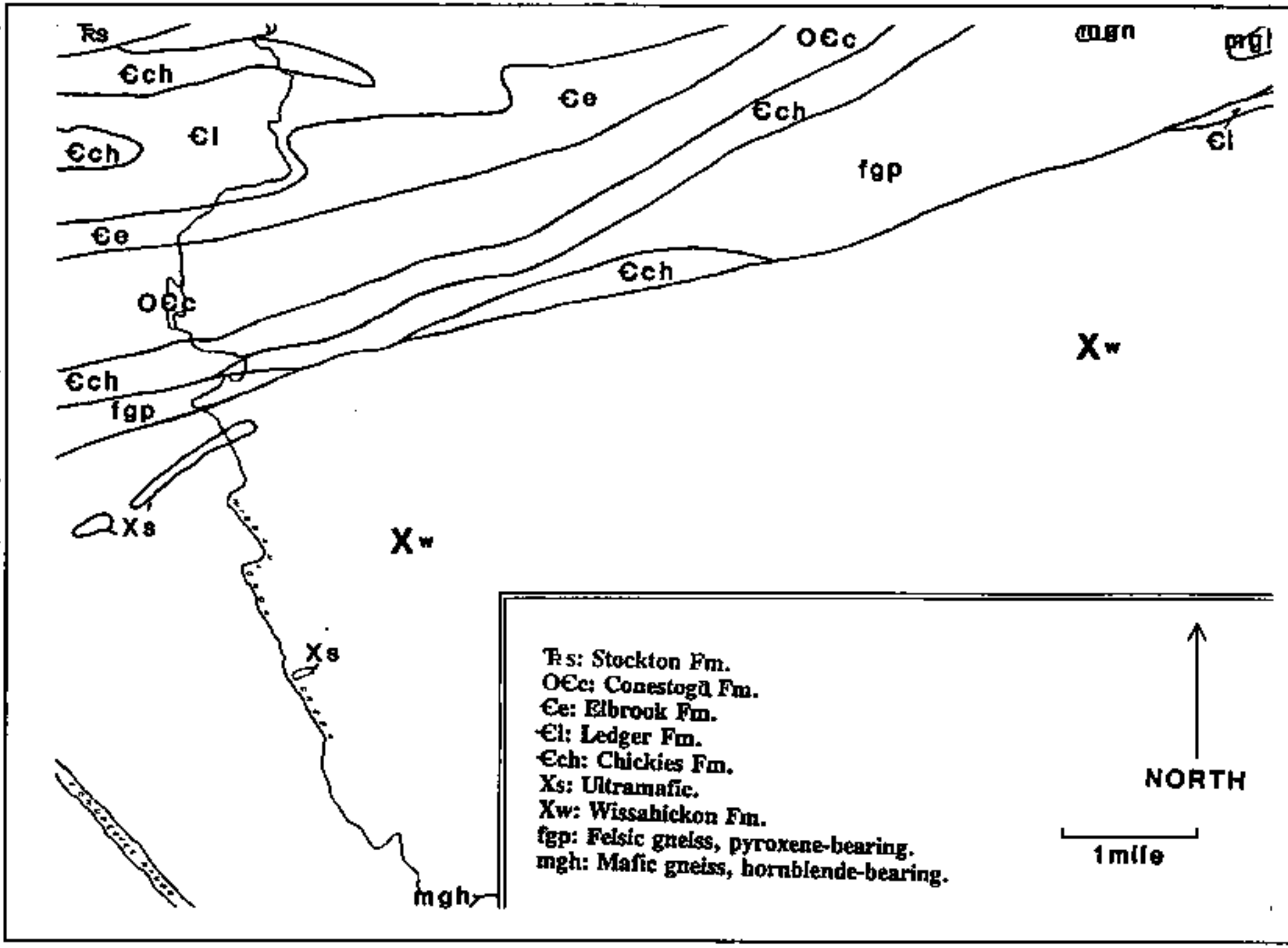

Figure 2. Map of the lithologies in the study area.
(Revised from Socolow, 1980)

northwest corner of the study area). The age of the Chickies and Ledger Formations is Cambrian, with the Chickies Formation having an older relative age (Socolow, 1980). Between the Ledger Formation in the northwest corner of the study area and the Chickies Formation in the south, are the Elbrook Formation and the Conestoga Formation. Both formations are Cambrian or Cambrian-Ordovician marbles (Socolow, 1980) and they are the only formations that do not outcrop in the study area. The Elbrook Formation is mapped to the north of the the Conestoga Formation (Figure 2).

Ductile Shear Zone Deformation

Shear zones are deep-seated equivalents of brittle faults where the rock acts ductilely during the deformation processes (Simpson, 1986). Within the ductile shear zone, mylonites are produced by predominantly crystal-plastic deformation mechanisms (Figure 3), but brittle fracture of relatively competent grains may occur (Simpson, 1986). The result of this deformation is a rock with a strong planar fabric and commonly with a strong

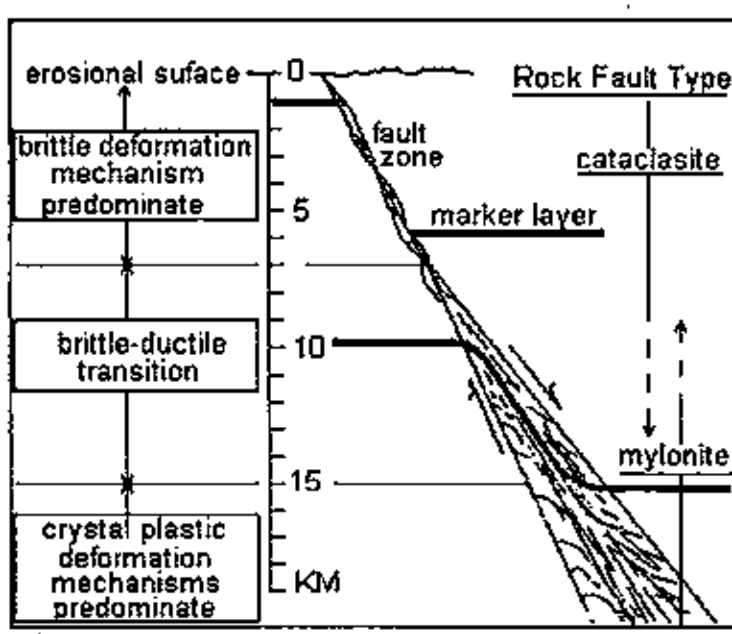

Figure 3. Cross section of an idealized shear zone (Simpson, 1986).

mineral elongation (Simpson, 1986). During deformation, chemical alterations may occur as mobile elements tend to retreat, leaving an enrichment in nonsolubles (Gates and Gundersen, 1992). After the establishment of planar fabric, paths for gasses may be developed along the foliation planes.

According to Gates and Gundersen (1992) there are several factors that contribute to high radon concentration associated with mylonites:

1. Volume loss during deformation increases the concentration of immobile elements, including uranium if the mineral grains within the mylonite are in an oxygen-reducing state.

2. Planar fabric due to shear zone deformation increases weathering, permeability and emanation.

3. Deformation and fluid interaction redistributes uranium from sites in a mineral grain to alteration products along foliation planes, increasing emanation.

On the western border of the study area, the Rosemont shear zone is truncated by the Huntingdon Valley shear zone. West of the truncation, the Huntingdon Valley shear zone becomes the Cream Valley shear zone (Hill, 1990). The fabric of the Huntingdon Valley shear zone has a near vertical dip and strikes N70E through the Wissahickon Formation, felsic gneiss unit, Chickies Formation, Conestoga Formation, and possibly the Elbrook Formation (Ketterer, 1995). It extends from Wissahickon Creek, near Chestnut Hill and Erdenheim, where it is met by the Rosemont shear zone, to the Delaware River at Trenton, New Jersey, where it is covered by Coastal Plain sediments to the east (Armstrong, 1941 and Ketterer, 1995). Also, there are two smaller shear zones to the south of the Huntingdon Valley shear zone with the same or similar orientations that exist only within the Wissahickon Formation (Figure 4). All three shear zones show dextral transcurrent displacement.

The absolute ages of the Huntingdon Valley shear zone and the two smaller zones are uncertain, but the Huntingdon Valley shear zone is most likely one of the later active shear zones found in Southeastern Pennsylvania and is thought to be Paleozoic in age (Hill, personal communication, 1995).

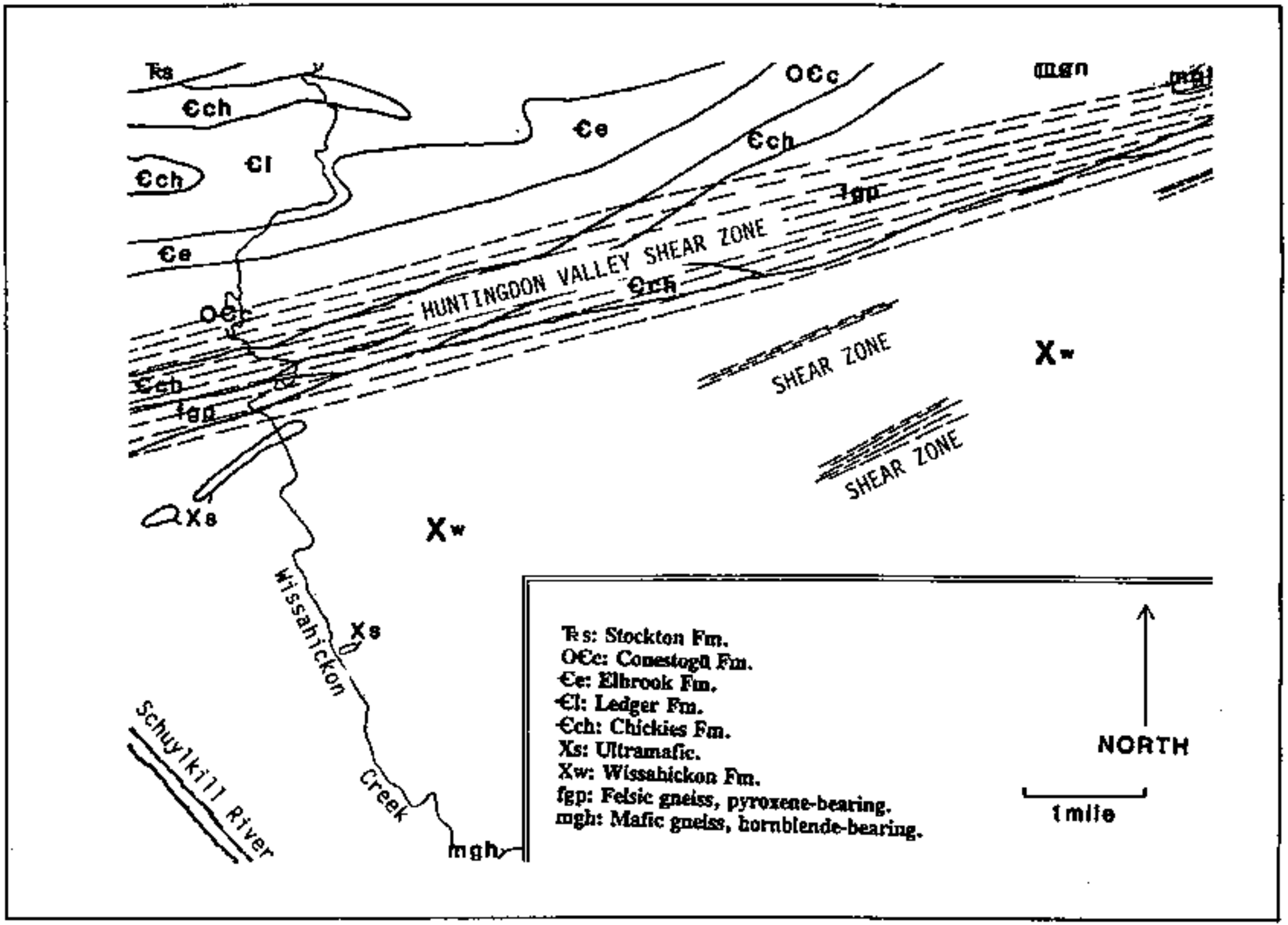

Figure 4. Shear zone map of the study area.

CHAPTER 2

METHODOLOGY

Field work was done to map out the different lithologies and structures that could play a role in radon emissions. Second, thin-section analysis of each lithology was done to observe the compositional, textural, and microstructural differences that exist inside and outside the shear zones. Third, chemical analysis was done to observe any differences in composition for each lithology inside and outside the shear zones. Finally, and the most crucial analysis, was the collection of soil gas from *in situ* soils to measure possible differences in the concentration of radon gas and to compare these with lithology or structure.

Field Methods

Field work was carried out between May, 1991 and June, 1992. Of the 211 outcrops mapped, 192 outcrops were of the Wissahickon Formation. Other exposed lithologies that were examined were the Chickies Formation (nine outcrops), felsic gneiss (three outcrops), mafic gneiss (three outcrops), amphibolite (one outcrop), and three small outcrops of meta-ultramafic rocks. The Elbrook Formation and the Conestoga Formation, two carbonate lithologies, do not crop out in the study area. The Ledger Formation does not have any natural outcrops in the study area, but there is an active quarry where samples and descriptions were taken. A Brunton compass was used to measure the attitude of foliation. Later, if needed, a stereonet was used to get an average plot of rock foliation and lineations. Rock composition and texture were noted. Grain sizes, grain orientations, and a description of the overall fabric were noted. Representative hand samples were collected and described.

The location of each outcrop was mapped, showing the overall fabric orientation and lithology. This base map provided the foundation needed to see if any correlation exists between radon concentrations and the characteristics of the bedrock.

Methods for Thin-Section Analysis

Thin sections were made to analyze the differences in composition and texture inside and outside the shear zone. Thin sections were cut perpendicular to foliation and parallel to lineation as shown in Figure 5. This orientation was chosen to display the greatest ratio of strain, and to see if microstructures could play a role in high radon emissions. Fifteen oriented samples were cut by a diamond saw for thin-sectioning. The thin-sections were made with Hillquest thin-sectioning equipment.

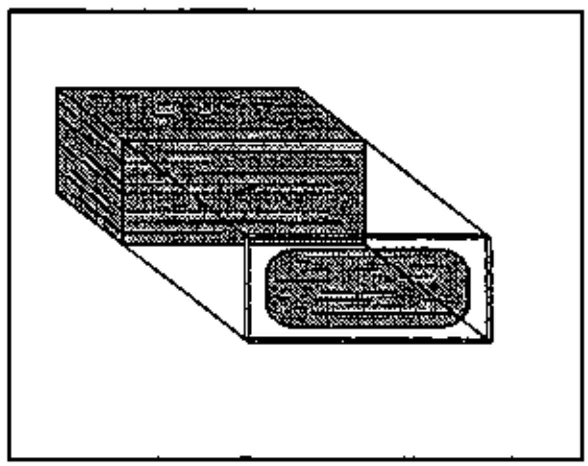

Figure 5. Orientation of a thin section in relation to foliation and lineation.

Methods for Strain Analysis

Stretched quartz pebbles from several sections within a single outcrop of the Chickies Formation were used to measure strain. An average of sixty pebbles was used to determine the mean strain for each section of the outcrop. Paired measurements were used to determine the strain ratio by measuring S_1: the average of the long axes parallel to foliation and lineation with S_2: the average of the axes parallel to foliation and perpendicular to lineation for one cutting orientation; and S_2 with S_3: the ratio of the axes parallel to foliation and perpendicular to lineation, and perpendicular to foliation and lineation for another cutting orientation. With two-dimensional strain ratios (S_1:S_2 and S_2:S_3) measured, three-dimensional strain ratios (S_1:S_2:S_3) can be calculated as shown in Table 1. Since the size of grains before deformation is unknown, the absolute strain is unknown as well.

Table 1.

An example of calculating a 3-dimensional strain ratio.

$S_1:S_2 = 4.55:3.04 = 1.49:1.00$	$S_1:S_2:S_3 = 1.49:1.00:0.86$
$S_2:S_3 = 3.14:2.71 = 1.00:0.86$	

Methods for Chemical Analysis

Two methods were used in collecting the chemical analysis data, Inductively Coupled Plasma (ICP), and Delayed Neutron Counting (DNC). The ICP work was done with assistance from Steve Sylvestri at Franklin and Marshall College of Lancaster, Pennsylvania. The DNC was done by Chemex Labs Inc. of Reno, Nevada. These two different tests were used to get a complete analysis of the elements needed to observe how and why different rock types have different radon concentration signatures (Table 2).

ICP Procedures

The ICP analysis measures immobile trace elements such as Zr, Ti, and Ba. It would have been preferable to measure thorium and radium, but they were out of range of the ICP. A total of eight (8) samples were analyzed using ICP.

At Temple University, each rock sample was broken up and placed in a shatter box until the sample became a fine powder (less than 0.08 millimeters). Between samples the shatter box was cleaned by running it two to three times with laboratory standard silica sand (Ottawa Sand). After each run, the shatter box was air blown clean with clean filtered air. At Franklin and Marshall College, each measured sample was mixed with hydrochloric acid and placed in disposable glass tubes. After preparation, the samples were then run through the ICP by the laboratory staff at Franklin and Marshall.

Table 2.

Samples Analyzed.

	ICP	DNC
Wissahickon Formation		
Sheared	-	3 rock, 1 soil
Not Sheared	-	3 rock, 1 soil
Chickies Formation		
Sheared	4 rock samples	6 rock, 2 soil
Not Sheared	1 rock sample	1 soil
Felsic Gneiss Formation		
Sheared	1 rock sample	2 rock, 2 soil
Not Sheared	2 rock samples	2 rock
Conestoga Formation		2 soils *
Sheared	-	-
Not Sheared	-	-
Elbrook Formation		
Sheared	-	-
Not Sheared	-	2 soils
Ledger Formation		
Sheared	-	-
Not Sheared	-	2 soils

*- Structure unknown due to lack of outcrops.

DNC Procedure

The DNC analysis measured concentration of uranium in different lithologies, inside and outside the zone of shear. Rock and in-situ soils were both used as samples to determine if there was a relationship between the rock and the overlying soil, and to ascertain which medium (rock or soil) was the controlling factor for high radon emissions. DNC analysis also indicated whether uranium was in a mobile or immobile state during the shearing event.

The DNC technique consists of irradating a capsulated sample in a constant neutron flux for ten seconds. The flux rate is 1.0×10^{12} neutrons per square centimeter per second. After irradation, the sample was pneumatically transferred to a neutron detector and then cooled for ten seconds to remove the interference from delayed neutron emission for the nitrogen isotopes formed from oxygen that was contained in the specimen. Following the cooling period, a ten-second count began for the number of neutrons being emitted by the sample. The number is directly proportional to the uranium content of the sample. The factor that was used to convert from the number of emitted neutrons to parts per million uranium was obtained by calibrating the system with certified reference materials, which were irradiated, cooled and counted under the same conditions.

Methods for Measuring Radon Soil Gas

In measuring radon gas, a soil gas sampling probe, an alpha spectrometer (Radon/Radon Daughter Detector RDA-200), and a gamma spectrometer (GRS 200 Spectrometer/Scintillometer) were used. Sampling took place in the months of September and October, 1991 and June, 1992. During the three months, 173 sites were tested. Repeated tests were made at control sites in different lithologies and structures to observe if any seasonal or weather changes played a role in the radon concentrations.

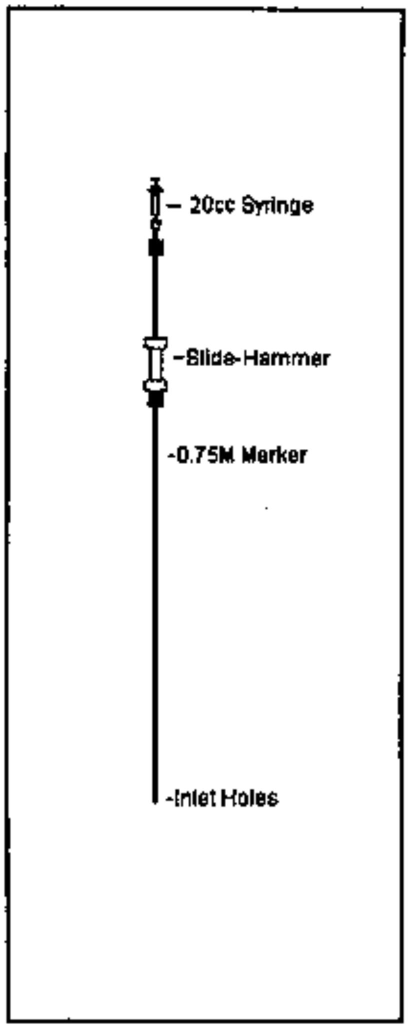

Figure 6. Schematic drawing of the soil-gas probe with slide-hammer, syringe and syringe attachment.

A soil gas sampling probe, attached slide-hammer, and a syringe were used to extract 20cc of soil gas from 0.75 meters depth within in-situ soils (Figure 6). In the eastern United States, this sampling depth generally corresponds to the lowermost B and the uppermost C soil horizons (Reimer, 1991). An average of 18 samples were collected each day. Each time a sample was taken, soil moisture, soil composition, soil compaction (hardness), date and time was noted on the radon field form (Figure 7). If the soil was saturated with water, the sample was discarded, since soil moisture inhibits permeability. The 20cc samples of soil gas were used to determine the concentration of radon in soil gas

FIELD DATA SHEET

Paul D. James, Jr. Dept. of Geology
Temple University

SAMPLE NUMBER: HV-☐-☐☐-☐☐☐

DATE: ☐☐☐

TIME: ☐☐

LOCATION: ____________________

TOTAL COUNT FOR GAMMA: ☐☐☐☐

AMOUNT OF Rn: ☐

DEPTH OF PROBE: ____________

SOIL HARDNESS (1-3): ☐

EFFORT IN GETTING SAMPLE (1-3): ☐

SOIL MOISTURE: __________ ☐☐

SOIL TYPE: ______________________________

____

NOTES:

Figure 7.Radon Field Form.

by using an alpha-spectrometer. Samples were injected in an alpha-sensitive scintillometer/ spectrometer adapted with a Lucas Cell and then counted for two minutes. Five measurements were made for each sample and then averaged. After each sample was measured five times, ambient air was pumped through the Lucas Cell for approximately 20 minutes and then remeasured to assure radon concentrations were at a clean level. If concentrations exceeded the clean level, ambient air was pumped through the Lucas Cell again until clean levels were met and confirmed.

The RDA 200 is an instrument designed to measure radon and it daughters concentrations (Radon-222 and Radon-220) in picoCuries per liter (pCi/L) by the activity of the alpha particles originating from the radon isotopes. Since radon 222 has a half-life (t1/2) of 3.82 days and some amount of time (T) was passed between the extraction of soil gas from the ground and the analyses for radon concentrations, the following correction formula was used: $N_0 = N_1 / [0.5^{T/(t1/2)}]$. This formula calculates the radon concentration at the time the soil gas was extracted from the ground (N_0), instead of the concentration at the time of analyses (N_1).

The gamma-spectrometer was used at ground surface at each radon site location to measure the total gamma ray activity resulting from the uranium series decay. This instrument was useful to find unusual gamma activity that could help explain certain radon concentration readings, for example, pegmatitic bodies or mylonitic zones. The instrument measures in counts per second.

Methods for Statistical Analysis

Statistical analysis was done on I.B.M. compatible computers with several statistical and graphical software packages: NCSS° (Number Crunching Statistical Software), CSS° (Statistica), and Axum°. All rock and radon data were arranged by lithology and then subdivided into the categories "inside" and "outside" of shear zone-structures.

CHAPTER 3

GEOLOGY IN STUDY AREA

Lithologies

Many previous studies on the petrology and structure of the lithologies in this particular field area (e.g., Bascom, 1905; Weiss, 1949; Wyckoff, 1952; Johnson and Myer, 1975; Tearpock and Bischke, 1980; Myer et al., 1985) have focused on the Wissahickon Formation, especially the numerous outcrops along the banks of the Schuylkill River and Wissahickon Creek. Due to the distribution of lithologies relative to the region's shear zones, the petrology and structural analyses in this study focus on the Wissahickon, the Chickies and the felsic gneiss formations.

Wissahickon Formation

The Wissahickon Formation is an oligioclase mica-schist (Bascom, 1905) with alternating pelitic and psammitic layering. The mineralogy consists of plagioclase, quartz, biotite, muscovite, chlorite, garnet, staurolite and other aluminosilicate minerals. Quartz is found in abundance in psammitic layers and narrow lenses. The pelitic layers consist mainly of muscovite with subordinate amount of chlorite and biotite. The index minerals include almandine garnet, staurolite, kyanite and sillmanite (Wyckoff, 1952).

The degree of metamorphism varies from upper amphibolite facies in the southern part of the study area, to greenschist facies (Wyckoff, 1952; Johnson and Myer, 1975) in and near the Huntingdon Valley shear zone. The greenschist facies metamorphism in the north is due to retrograde metamorphism that occurred during the deformation of the Huntingdon Valley shear zone (Hill, 1989).

Typical Wissahickon Schist samples within all shear zones consist of fine grained (mylonitized) pelitic rocks with narrow (up to 3.5 centimeters) quartz bands. The thick (up to 0.25 meters) psammitic layers seen in the amphibolite facies schist are not evident in the shear zones which are at the greenschist facies. This is likely due to transposition and possible volume loss within the shear zones.

Within the shear zone, muscovite and biotite grains in the Wissahickon Formation exhibit a "wavey" texture, with partial recovery by solution relief. This is evidence of high strain. Muscovite, biotite and chlorite also can be found in pressure shadows around plagioclase and a few isolated quartz grains, giving evidence of dextral motion within the shear zone. Quartz in thin-sections of the sheared schist, is usually highly deformed, arranged in tight rows, and displays partial solution under plain light. The plagioclase grains have little to no internal deformation.

Chickies Formation

The Chickies Formation is a Cambrian quartzite. Its composition and structure tend to be quite different from locality to locality, owing to primary sedimentologic differences and to shear zone deformation. The basal portion of the formation is coarse-grained whereas the upper portion is generally finer-grained and better sorted. Exposures within the Huntingdon Valley shear zone consist mostly of the coarse basal portion. Where the basal portion (Hellam Member) and shear zone fabric exist together, stretched conglomerate grains can be found (Murphy, 1973).

In this study area, the Chickies Formation tends to be more resistant to weathering than the surrounding lithologies, especially outside the shear zone. Outside the shear zone, the Chickies Formation consists primarily of quartz (greater than 95%), and small amounts of muscovite and feldspar. Outcrop localities within the Huntingdon Valley shear zone consist of quartz (approximately 85%), feldspar, muscovite, phlogopite and chlorite. This difference is due to both the stratigraphic location and the heterogeneity of the strain throughout the region.

Trace-element analysis (Table 3) were done on the Chickies Formation found inside the shear zone within the study area and basal Chickies Formation from outside of the study area in Valley Forge Stone Quarry of Honey Brook, Pennsylvania. Basal Chickies Formation from Honey Brook was analyzed rather than undeformed Chickies in the study area because it is not stratigraphically or compositionally equivalent to the Chickies found in the shear zone.

Immobile elements, Ti, Zr, Y and Ba, tend to be higher in rocks within the shear zone (Figures 8 and 9). The most likely reason for this is volume loss during the deformation, which would increase the concentration of the immobile elements by removal of more mobile elements (see next section on shear zone structures and implications). This is a key to the problem of why high radon concentrations are related to shear zones.

Table 3.

ICP analysis of the trace elements found in the sheared Chickies Formation.

Elem / Samp	Outside-SZ	Inside-Xa	Inside-Xd	Inside-Yc	Inside-Yd
Be ppm	0	0	0	0	0
Ce ppm	58	111.3	51.9	371.1	226.6
Sc ppm	1.2	3.1	2.9	6.3	7.5
TiO_2 %	0.32	1.2	1.8	2.9	4.2
V ppm	6	66.3	40	135.3	162.6
Yb ppm	2.3	3.2	3.2	5.8	11.8
Sr ppm	6	47.2	28.6	20.5	29.3
Y ppm	14	33.9	26.1	54.7	103.4
Zr ppm	1415	3048	2936	1887	2748
Ba ppm	78	417.2	11.2	139.6	150.2
Co ppm	3	2.3	8	36.4	83.2
Cr ppm	5	26.8	19.2	52.2	65.0
Strain Ratio	1.0:1.0 :1.0	1.92:1.0 :0.52	1.68:1.0 :0.49	2.01:1.0 :0.58	1.98:1.0 :0.44

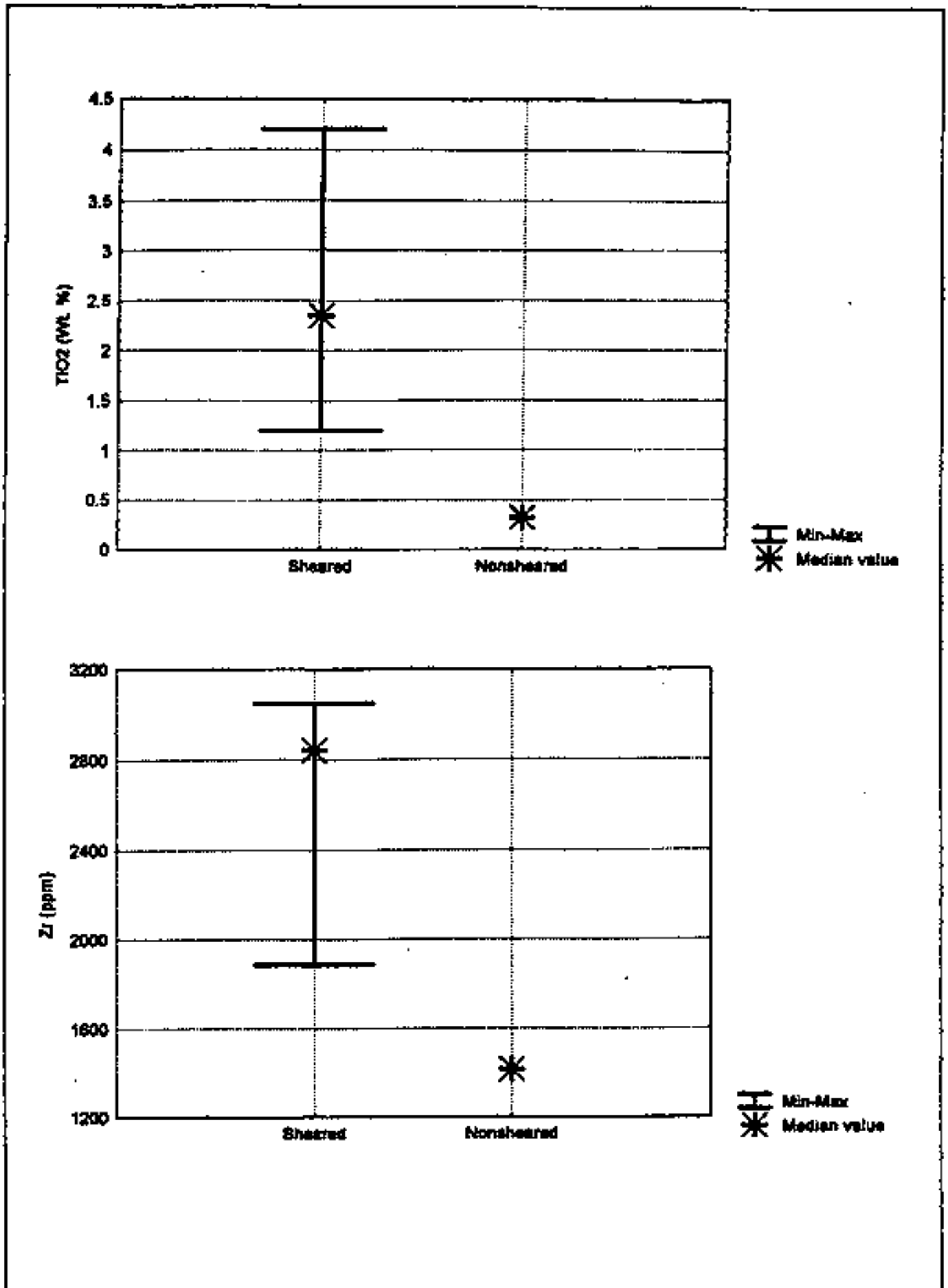

Figure 8. Whisker plots of TiO_2 and Zr concentrations of samples from the Chickies Formation.

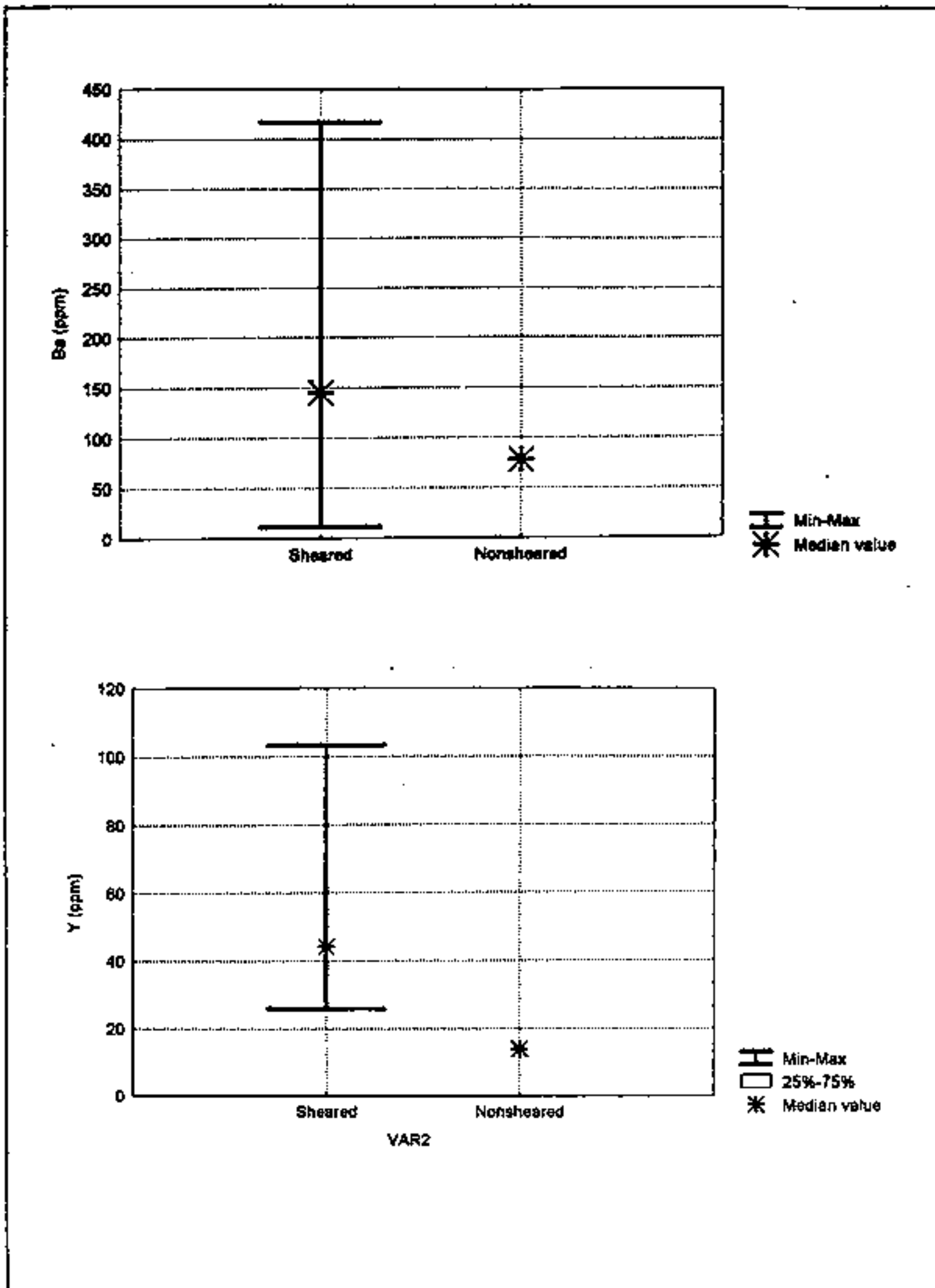

Figure 9. Whisker plots of Ba and Y concentrations of samples from the Chickies Formation.

Felsic Gneiss

Between the Wissahickon and Chickies Formation is a Precambrian felsic gneiss (pyroxene-bearing gneiss) (Socolow, 1980). The felsic gneiss in the study area (HV-018) is found in outcrop along the Wissahickon Creek north of Bells Mill Road (Figure 10, map pocket). This outcrop is within the Huntingdon Valley shear zone. Since this is the only outcrop found within the study area, samples outside the study area (FG-2C and FG-3C) (Figure 10) were taken for comparing the gneiss inside and outside the shear zone. Trace-element analyses (Table 4) were done on the felsic gneiss in both areas. Results show that the concentrations of Ti, Zr, Y and Ba correlate with the rocks within and outside the shear zone fabric (Table 4).

The Carbonates

According to the Pennsylvania Geologic Map (Socolow, 1980), the north-western portion of the study area contains the Ledger Formation (dolomitic marble),the Elbrook Formation (marble) and the Conestoga Formation (marble). The Ledger Formation crops out north of the Elbrook and the Conestoga marble formations. These formations, high in silica and magnesuim are quite micaceous in places with veins of quartz and calcite (Bascom, 1905) . Due to the rapid weathering of the carbonates in a humid climate, outcrops of these units are rare (Bascom, 1905).

Table 4.

ICP analysis of the trace elements found in the felsic gneiss

Elem\SampID	FG-2C	FG-3C	HV018-1
Be ppm	2.3	0.83	1.2
Ce ppm	256.1	179.0	88.7
Sc ppm	13.8	11.9	8
TiO_2 %	0.78	0.85	.78
V ppm	104.5	84.2	79.8
Yb ppm	3.3	1.7	0.75
Sr ppm	902.5	1052	639.5
Y ppm	29.5	16.0	7.3
Zr ppm	438	514.3	513.7
Ba ppm	1927	3236	2274
Co ppm	13.6	10.1	8.3
Cr ppm	59.5	44.4	107.0

Shear Zone Structures

Within the study area, the Huntingdon Valley shear zone strikes N70E with a near vertical dip through the Wissahickon Formation, felsic gneiss, Chickies Formation, and possibly the Conestoga and Elbrook Formations (Figure 10, map pocket). The width of the shear zone is approximately one mile. Geographically it lies between the Wissahickon Creek near Chestnut Hill and the Delaware River at Trenton, New Jersey where it is covered by Triassic and Coastal Plain sediments. Also there are two smaller shear zones to the south of the Huntingdon Valley shear zone with similar orientations (Figure 10). They seem to exist only within the Wissahickon Formation. Mylonites in shear zones are known to be the source of high radon and uranium (Gates and Gundersen, 1989; 1992). Geochemical and geologic studies of shear zones developed in igneous and metamorphic rock in Pennsylvania, Maryland, and Virginia have been used to construct a model for radon concentrations found in mylonites (Gates and Gundersen, 1989; 1993). This section will give structural evidence to explain why shear zones in the study area might contribute to higher radon emissions than rock outside these structures.

Fabric

The rock fabric (foliation) within the shear zones in the Huntingdon Valley study area has a near vertical dip and strikes N70E (Figure 11). Figure 12 presents two stereonets that show the average orientation for foliation within and outside of shear zones

A

B

Figure 11. Two field photographs of the Wissahickon Formation; (a)Outside the shear zone (b)Within the shear zone.

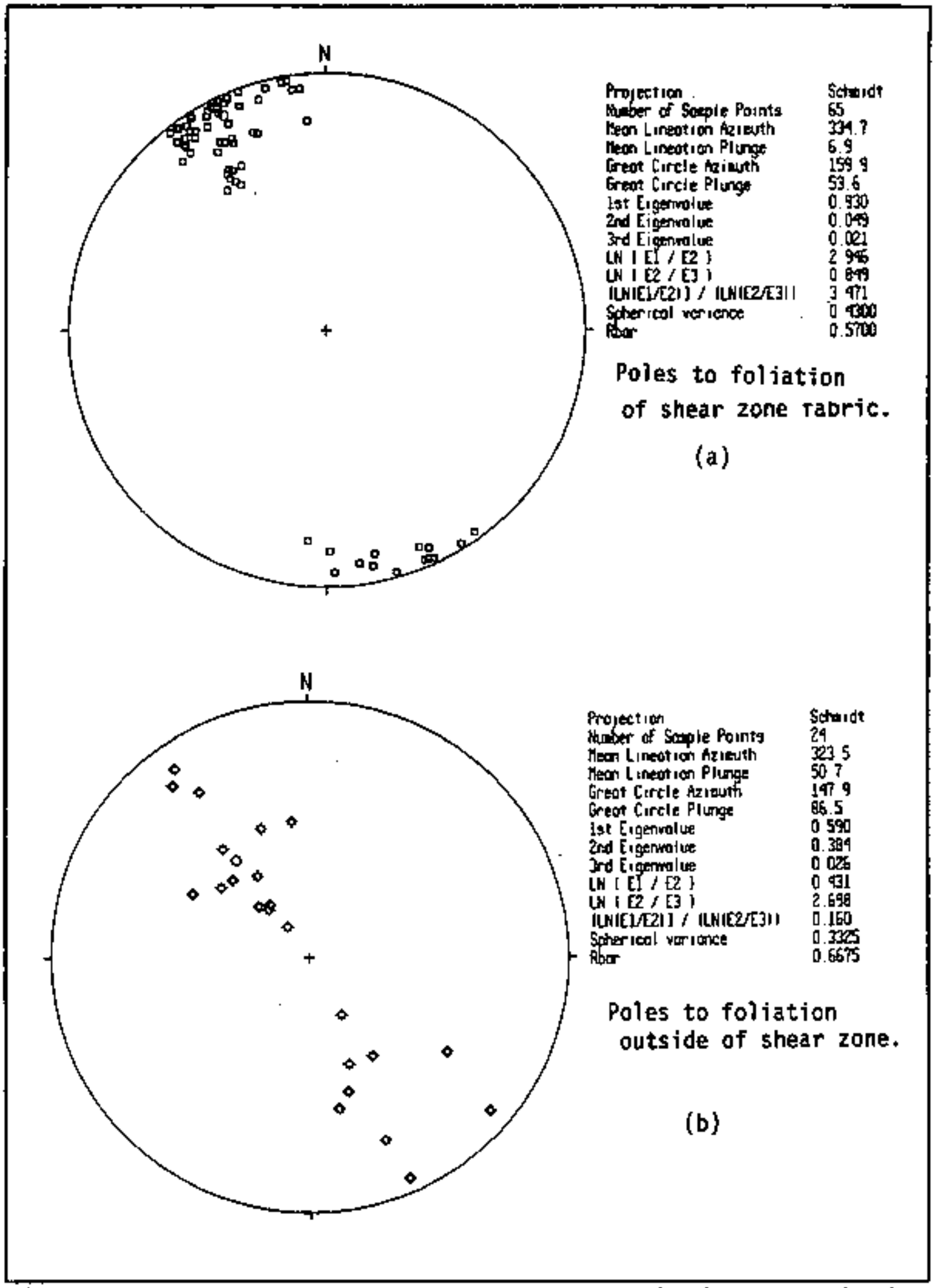

Figure 12. Equal-angle stereo-nets of foliation, (a) inside and (b) outside shear zone structures.

in the study area. The poles to the planar fabric form a tight cluster inside the shear zones (Figure 12-a), whereas outside, within 1 to 2 km of the shear zones, the dip of the fabric varies quite a lot but the strike orientations are very similar (Figure 12-b). This clustering of poles is due to the deformation during the shearing event. This mylonitic fabric overprints the existing regional metamorphic fabric that existed prior to the shearing event. Figure 12-b shows the Wissahickon Formation with a different fabric orientation due to the lack of the Huntingdon Valley shear zone deformation. This shear zone fabric contributes to the faster weathering rate of the rock thereby increasing the rate of radon emanation. This increase of radon emissions is caused by grain-size reduction, and an increase in fracture cleavage. Also, if uranium is redistributed along the foliation plane during deformation, weathering will enhance the availability of radioactive product to the new soil (Gates and Gundersen, 1989). Supporting this interpretation is evidence of the soluble interstitial material in shear zone samples, for example the brown or dark grunge coating grains in thin-section. In a planar fabric, the grains are less likely to be intergrown or sutured and therefore more likely to have connected inter-granular spaces for out-gassing.

Grain-Size Reduction

Within the shear zones there is evidence of grain-size reduction especially in the Wissahickon Formation. Examination of grains perpendicular to foliation and parallel to lineation in the Wissahickon Formation revealed grain size reduction in most minerals including quartz, muscovite and biotite, whereas plagioclase grains showed little to no internal deformation. Grain size reduction appears to be due to plastic deformation.

Strain Analysis

Heterogeneous strain can be observed in the Chickies Formation outcrop HV-003 (Figure 13). Figure 13-a is a photograph of an antiform within HV-003 with its axial plane parallel to shear zone fabric, but penetrative shear zone fabric is absent. Figure 13-b shows the same formation, approximately 12 meters away from the antiform, with definite shear zone fabric with blue quartz with a strain ratio up to 3.41:1.0:0.47 (Figure 14).

A strain analysis was done for strained quartz in the Chickies Formation. Results showed heterogeneous strain with a difference of 1.78 in the ϵ_1 direction and 0.14 in the ϵ_2 direction (Table 5) even though the orientation of the fabric is quite consistent. Several deformation mechanisms acted on the stretched quartz grains. Pressure solution is evident in the Wissahickon Formation, Chickies Formation and felsic gneiss inside the shear zone, but undulose extinction within larger grains indicates plastic strain as well, both inside and outside the shear zone fabric. The orientation of extinction under cross-polarized light is more consistent for sheared rock than for unsheared rock, indicating a preferred crystallographic orientation fabric.

A

B

Figure 13. Two field photographs of the Chickies Formation; (a) unsheared, (b) sheared.

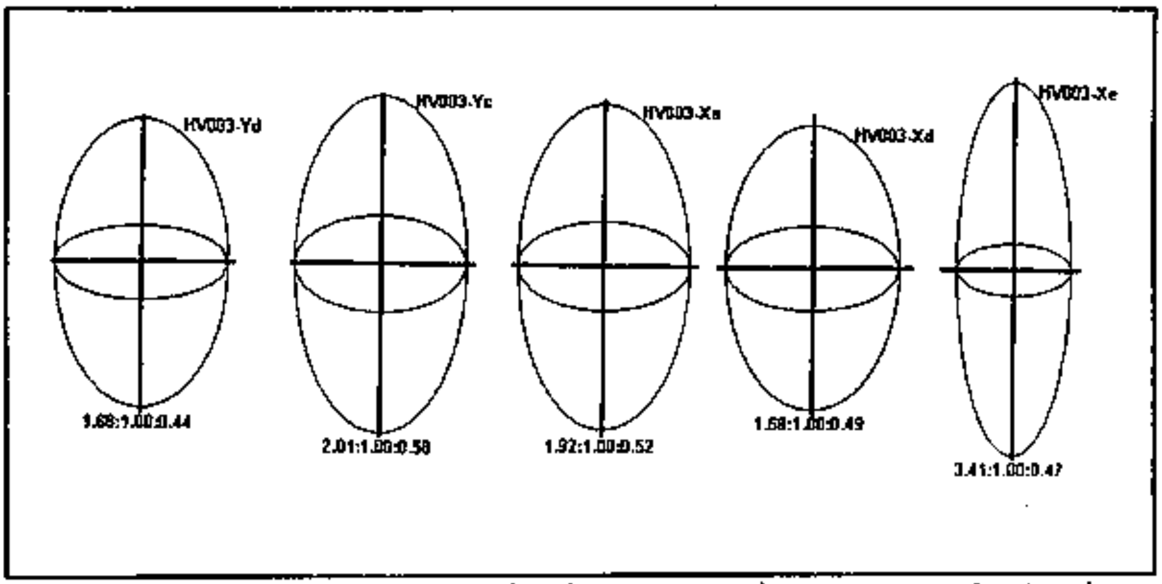

Figure 14. Sketches of Chickies Formation averaged strain quartz ellipsoids.

Table 5.

Strain analysis results of the strained quartz in the Chickies Formation.

Sample Location	HV003 -Yd	HV003 -Yc	HV003 -Xa	HV003 -Xd	HV003 -Xe
Strain Ratio	1.68:1.00: 0.44	2.01:1.00: 0.58	1.92:1.00: 0.52	1.68:1.00: 0.49	3.41:1.00: 0.47

CHAPTER 4

THEORY OF RADON TESTING

AND ITS APPLICATIONS AND PROBLEMS

Aerial radioactivity anomalies or uranium occurrences are correlated with many of the major shear zones in the Eastern United States (Gundersen, 1991a). Soil radon analysis has been used to delineate geology in several different ways. This chapter will discuss the prior uses of soil radon testing, the usefulness of soil radon measurements in delineating geology, and the use of radon gas measurements in precise geologic mapping of lithology and structure.

Prior Uses in Testing Radon

Most of the recent studies that used radon to delineate geology incorporated the concentration of radon in soil gas (e.g. Gates and Gundersen, 1989; Gundersen, 1991b; Agard and Gundersen, 1991; Henry et al., 1991; and Gates and Gundersen, 1992).

Gates and Gundersen (1989) showed that there was a correlation between the amount of shearing deformation and the concentration of radon found in soil gas of in-situ soils in the Brookneal zone, Virginia. As the angle between the s- and c-fabric become smaller, indicating higher strain, uranium, thorium and radon increased. Their study was conducted within one lithology, the Melrose Granite, limiting the variable parameters.

Gundersen (1991b) discussed the factors that control radon concentration within four major shear zones in the eastern United States. These factors are bedrock uranium concentration, high permeability, and high radon emanation. Gundersen (1991b) has shown that these factors can be produced by the ductile deformation process.

Agard and Gundersen (1991) observed that the soil derived from bedrock in the Reading Prong exhibits secular equilibrium between uranium and radium. They showed a direct correlation between the amount of radon found in soil gas and uranium concentration within the in-situ soil. They also stated that the permeability of the soil does not vary enough to affect the radon availability except where fractures and jointed bedrock are close to the surface. In this case, convective flow, rather than diffusion, becomes the dominant radon transport mechanism (Agard and Gundersen, 1991). If this was true, the radon measured would have come mostly from the soil except where shear zones are located, in which case permeability would play a larger role.

Henry and others (1991) showed that high radon levels in soil gas generally correlate with high values of gamma-ray activity. But this correlation is not always the case (Henry et al., 1991 and this study). In a plot of gamma-ray activity versus radon gas concentrations from this study (Figure 15), the regression line has a slight positive slope with tight confidence lines. Data from this study does not fall along this correlation line. Data suggests that there is a 95 percent confidence that gamma-ray activity does not correlate well with the alpha-decay rate of radon.

Gates and Gundersen (1992) showed that shear zones and bedrock units as thin as three to five meters in width can be detected using radon concentrations in in-situ soils.

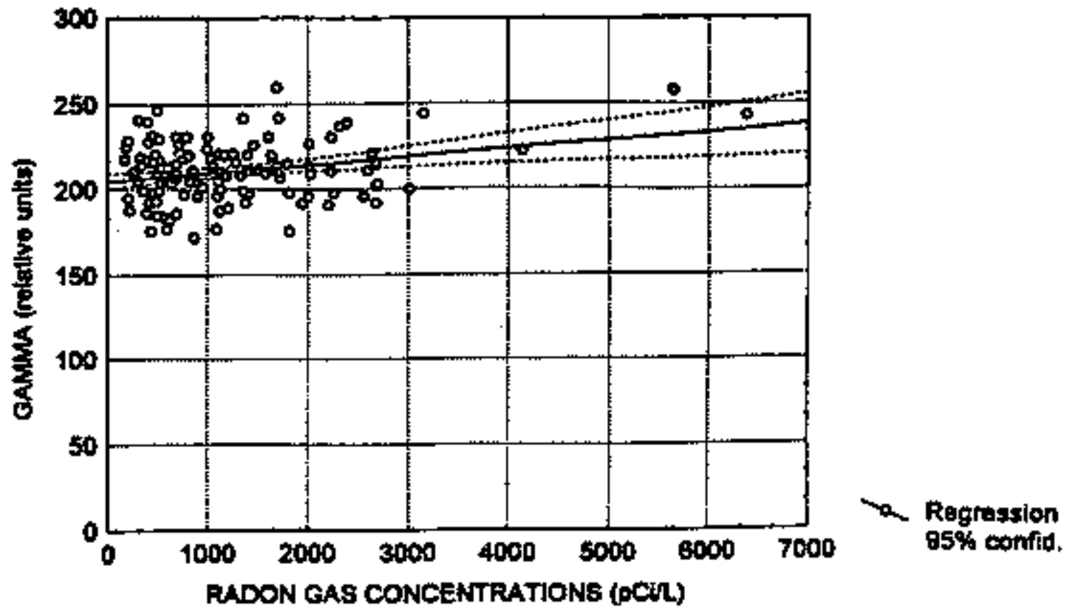

Figure 15. Regression plot showing gamma ray activity vs. radon gas concentration within the study area.

This was the first published work that viewed several different rock units affected by shear zone deformation with the use of radon soil gas as a tool to map lithologies inside and outside of the shear zone structure. Gates and Gundersen (1992) again showed a direct correlation between strain and the amount of radon found in soil gas.

During mylonitonization, the uranium concentration is increased due to loss of mobile elements (Gates and Gundersen, 1992). Grain size reduction of uraniferous accessory minerals common to igneous and metamorphic rocks makes uranium available for redistribution into and along foliation planes (Gates and Gundersen, 1992).

The advantage of the soil gas probe technique is that the sample of gas comes directly from the in-situ soils at the top of the soil horizon C and from the bedrock below. This technique is probably more precise than the surface (disperse) radon technique and sampling by basement cannisleves.

Surface remote sensing devices, such as NURE aerial gamma-ray surveys, frequently exhibit obvious disagreements when data are merged and portrayed in an image format (Landa, 1991). This disagreement is due to background error, different measuring techniques, and scaling errors caused by calibration errors (Landa, 1991). Also surface techniques such as NURE test aerial anomalies, so radioactive particles have to pass through several mediums (e.g. rock, soil, pavement, surface air, etc.) before reaching the remote sensing device. Data from Henry and others (1991), Gates and Gundersen (1992) and my work suggest gamma ray activity cannot be used to help map boundaries of covered lithologies or structures (see section on prior uses).

Basement cannisleves work well for finding the concentration of radon in a particular building, but are not useful aids in mapping boundaries of lithologies or whole structures because radioactive particles have to pass through several domains (e.g. vapor-barrier, basement foliation, internal walls). Also differences in building design and material could cause a large error in measuring radon for lithological or structural studies (Reimer et al., 1991).

The Application of Radon Soil Gas Measurements

Work on the Brookneal zone (Gates and Gundersen ,1989) and the Hylas zones (Gates and Gundersen ,1992) shows that the soil probe method works very well in correlating high concentration of radon with shear zone fabric found in a specific lithology. This method is appropriate for the Huntingdon Valley shear zone in the study area. The area consists of several distinct lithologies which have a shear zone system running through them (Chapter 3). Each lithology is expected to have a different radon signature, and if a shear zone exists within each lithology, the lithology should tend to have a higher concentration of radon within the zone. Radon samples were collected along three traverses and a grid (Figure 19, found in rear map pocket) through several lithologies and shear zone structures in the study area. The traverses were made perpendicular to the strike of lithologies and shear zone fabric. The grid was made to be sure representative data was collected throughout the area.

In sampling for radon in soil gas, there are several procedures that must be followed to get the most accurate concentration readings. The soil gas probe must enter the soil to a depth of 0.75 meters to retrieve $20cm^3$ of soil gas for the radon analysis. This constant measuring depth is crucial to receiving the soil gas from a consistent and standard medium. In the eastern United States, this sample depth corresponds approximately to the boundary of the lowermost B and the uppermost C soil horizons (Gates and Gundersen, 1989, Henry et al., 1991). In this study, 0.75 meters is into the uppermost portion of the

C soil horizon for the Chickies and the Wissahickon Formation. For the Cambrian Carbonates, 0.75 meters in depth is in the lowermost portion of the B soil horizon, due to a deeper soil profile. This could have an influence on the results for the carbonate formations.

Changes in weather could have an effect on radon concentrations in soil gas (Gates, personal communication 1991), but in this study, repeating radon tests at control sites under different weather conditions did not demonstrate any significant problem. At selected test sites radon was measured under a variety of conditions thoughout the whole investigation to see if variations in concentrations could be detected. As a low weather front moves through a region, the barometric pressure will change from high to low then back to high again. These weather fronts might have an effect on the soil gas by acting as a pump, literally pushing and pulling on the interface between the surface air and subsurface gases. Another way that weather may affect radon emissions is through soil moisture. When moisture meets dry soil, molecular forces draw the water into the mineral grains forming hydrogen bonds. If precipitation continues, more water enters the soil and surface tension causes water to enter most of the small pores. As more water seeps into the soil the menisci are destroyed, and soil gas is replaced with water. Once the supply of water tapers off, water will drain due to gravity until the menisci begin to reappear and the forces of surface tension again dominate, holding water in the pores. Even though radon is a noble gas, the process of infiltration could interfere with radon results. Also the menisci interfaces between water and soil gas could act as barriers, capping or slowing down the radon from escaping. To avoid this possible problem, radon samples were only taken from dry to slightly damp soils and a brief description of the soil moisture was recorded.

When the soil probe is brought to the surface it brings up a small sample of soil at the end of it. It is important for the soil to be *in situ* for the purpose of relating radon to bedrock lithology and structure. At each test site, a description of the soil was recorded, as well as the name of the underlying lithology that was mapped earlier in the study. During the study, soil analysis associated with the radon testing made it possible to redefine the contact between the Wissahickon Formation and the felsic gneiss. The contact between these two lithologies only crops out at one place in the study area, so the radon study contributed significantly (see Chapter 5).

Another concern in collecting radon soil samples is topography (Gates, A. E., personal communication, 1991). It is ideal to collect from horizontal ground surfaces to ensure that the sample soil is derived from immediately underlying bedrock, not from up-slope lithologies and/or structures (Gates, A. E.,personal communication, 1991). Also there could be increased exchange of soil gas and surface air due to the topographic gradient (Gates, A. E., personal communication, 1991).

The study region is mostly in a suburban residential area, so finding suitable sites for radon probe work was just as difficult as searching for outcrop in the region due to accessibility and the large proportion of private property. Most of the samples were collected from public parks, school properties, church properties, public lands, and lots without houses.

CHAPTER 5

RESULTS OF RADON ANALYSIS IN STUDY AREA

This study demonstrates a definite correlation among soil gas radon, lithologies, and shear zones fabric. This section will discuss the correlation and the statistical validity of the data. All radon data were arranged by lithology and then subdivided into the categories "inside" and "outside" of shear zone-structures. These subdivisions were determined by previous work and the mapping that was accomplished for this study. To observe whether the concentration of radon is higher over shear zones, the radon signature of each lithology was first examined. This observation was important because each lithology had different physical and chemical properties before the shear zone deformation (Chapter 3).

Lithologic Control on Radon

This section reviews the radon soil data for each lithology to reveal the characteristic radon signature for each rock type. Figure 16, found in the rear map pocket, shows the location and concentration of each radon soil sample. Table 6 gives basic statistical values for each lithology in the study area and Figure 17 represents those values graphically with box plots.

Table 6.

Statistical analysis of radon emissions for each lithology.

	# of Samples	Minimum Value	Maximum Value	Mean	Standard Error	Standard Deviation	Upper Limit p=0.95	Lower Limit p=0.95	Skewness	Kurtosis
Wissahickon	85	170	6380	1072	108	991	1286	858	3.18	12.68
Chickies Fm.	13	331	2552	1653	175	654	2034	1272	-0.56	-0.89
Felsic Gneiss	16	202	1085	554	56	224	675	434	0.45	0.00
Conestoga Fm.	15	525	2691	1617	175	676	1994	1240	0.31	-1.08
Ledger Fm.	6	356	991	616	98	240	888	344	0.31	-1.65
Elbrook Fm.	8	1160	4133	2097	330	932	2905	1290	1.04	0.08

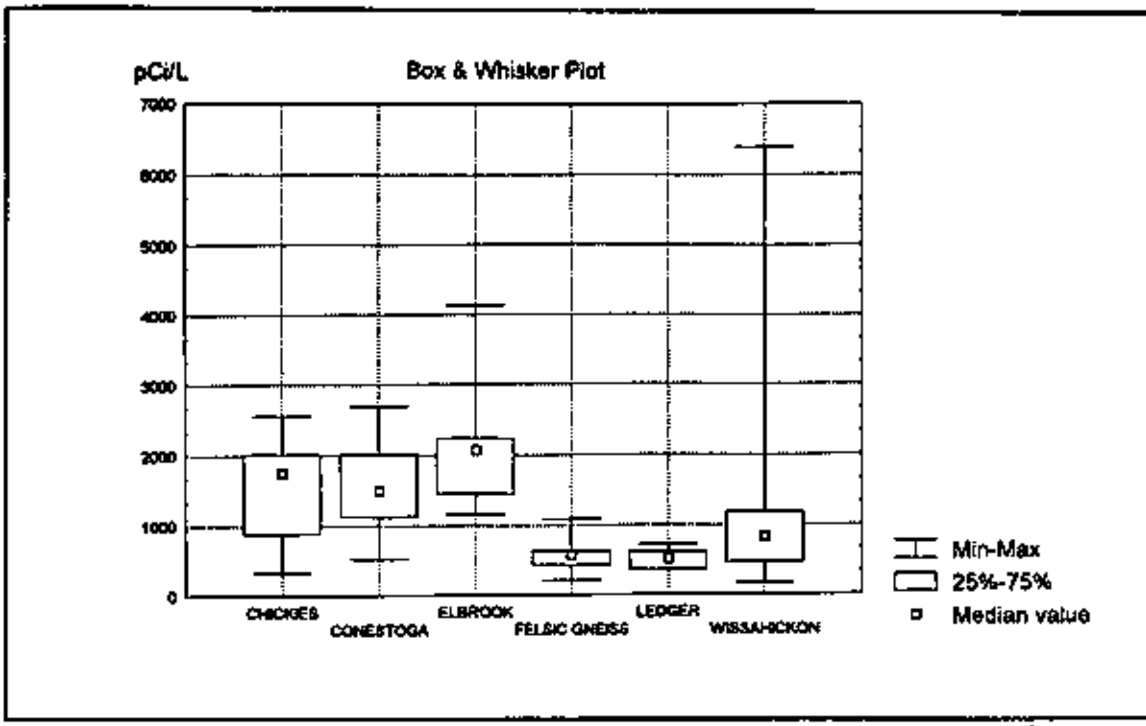

Figure 17. Min-max box-plots of the lithologies' soil radon within study area.

Wissahickon Formation

The Wissahickon Formation has the most heterogeneous composition of any lithology in the study area, and its radon concentrations exhibited the largest range, the largest standard deviation (991 pCi/L) and the largest kurtosis (12.7) (Table 5). The radon data does not have a normal distribution for the Wissahickon Formation (Figure 18), even though there are more radon data for this lithology than for any other lithology. The skewness of the data (+3.17) is due to the several points of extremely high radon concentration found in the shear zones. The reason for the non-normal distribution is that the concentration of radon within the Wissahickon Formation has come from several

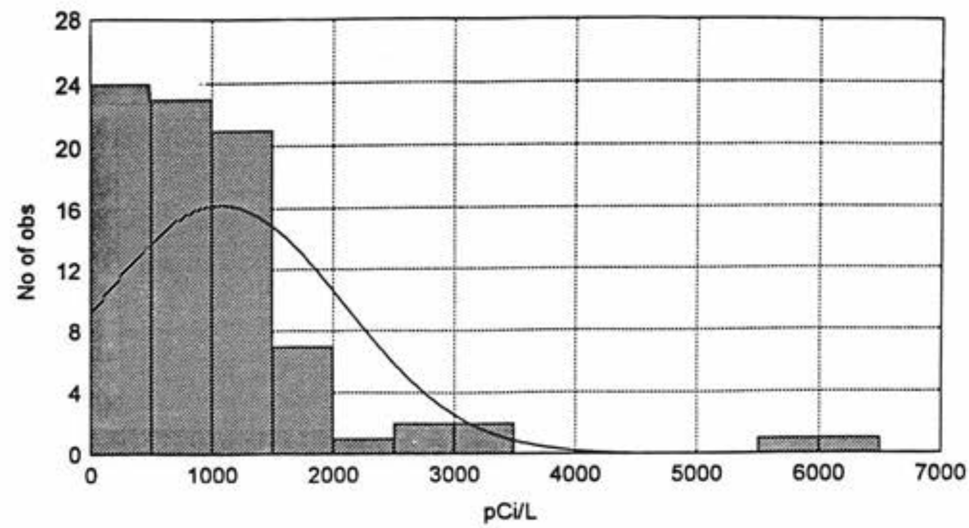

Figure 18. Histogram showing a non-normal distribution for soil radon concentrations(pCi/L) over Wissahickon Formation.

different populations. The heterogeneity in composition, the heterogeneity in shear zone deformation (Chapter 3), and prior regional deformation contribute to the non-normal distribution. If the concentration of radon is plotted in log(x) (Figure 19), it shows a normal distribution.

Chickies Formation

The Chickies Formation has a composition that is more homogeneous than that of the Wissahickon Formation, so the standard deviation (684 pCi/L) and the kurtosis (-0.89)

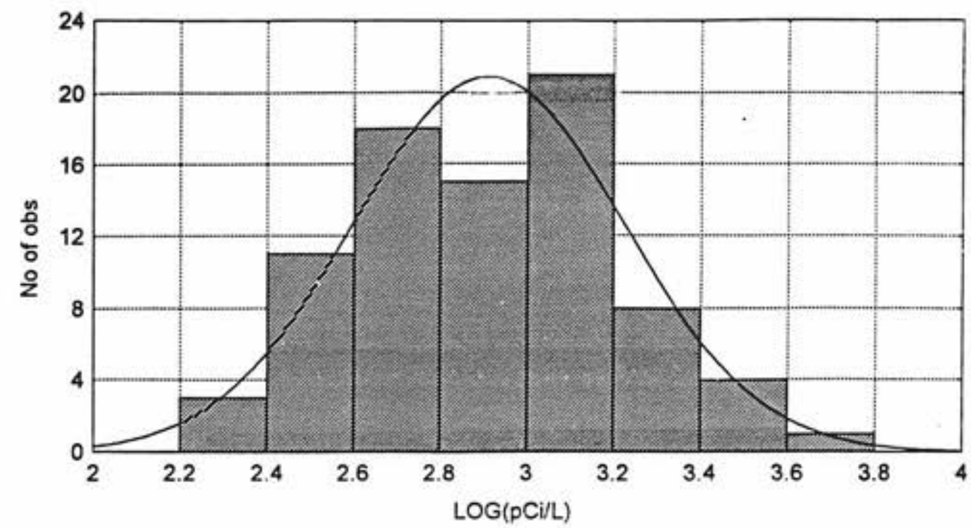

Figure 19. Histogram of log soil radon concentrations over Wissahickon Formation, showing a log-normal distribution.

for the concentrations of soil radon are much smaller. The Chickies Formation data have a normal distribution (Figure 20) compared to the Wissahickon Formation in spite of a smaller population. Along the contacts of the felsic gneiss (μ=554 pCi/L), and the Ledger Formation (μ=616 pCi/L), the Chickies Formation (μ=1,653 pCi/L) shows a distinctive higher radon concentration compared to the other lithologies. This sharp difference in radon concentrations can be used in redefining the borders of the lithologies. The first three data bars (Figure 20) represent tests performed outside the shear zones and the remaining data bars represent test performed on the shear zones.

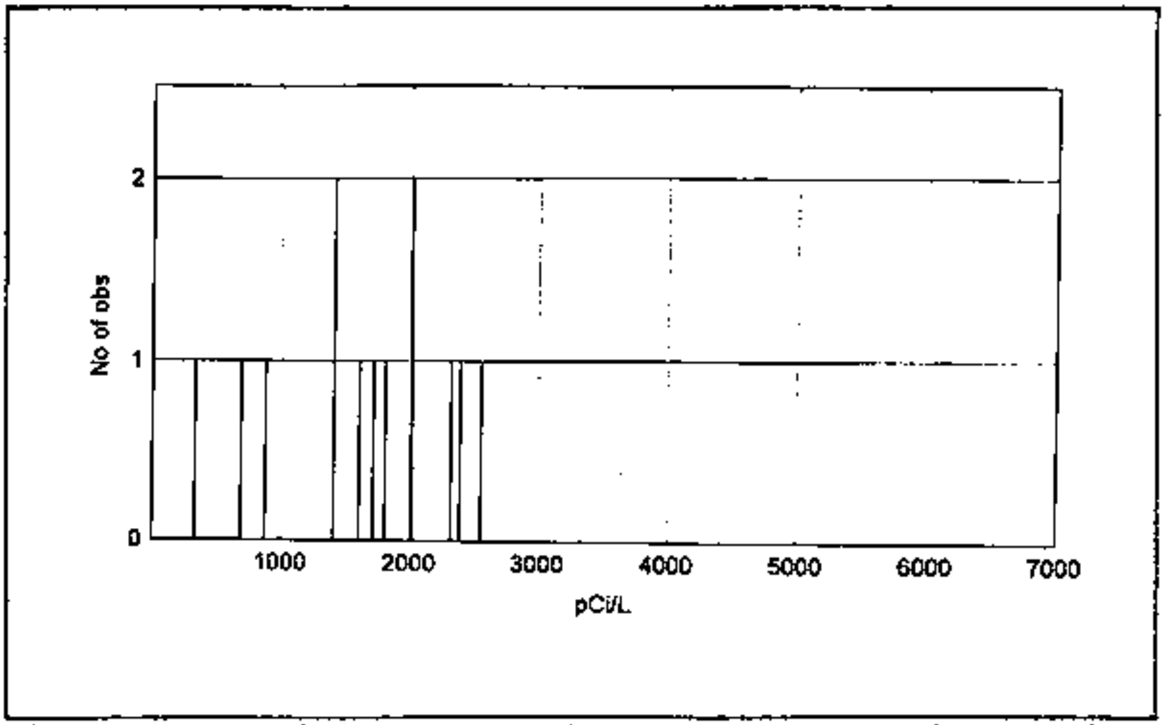

Figure 20. Histogram of soil radon concentrations (pCi/L) over Chickies Formation.

Felsic Gneiss

With the low mean radon concentration of 554 pCi/L, a standard deviation of 224 pCi/L and a kurtosis of 0.001, this unit shows a totally different radon signature than any of the lithologies adjacent to it (Figure 21). Therefore in this area, it is reasonable to use radon concentration as a tool in mapping borders of the felsic gneiss where outcrop is limited.

The highest radon count in the felsic gneiss, 867 pCi/L is much lower than the lowest counts of radon of the Chickies Formation (1,408 pCi/L) even where the lithologies are contiguous (Figure 16). The differences between the radon soil data of the felsic

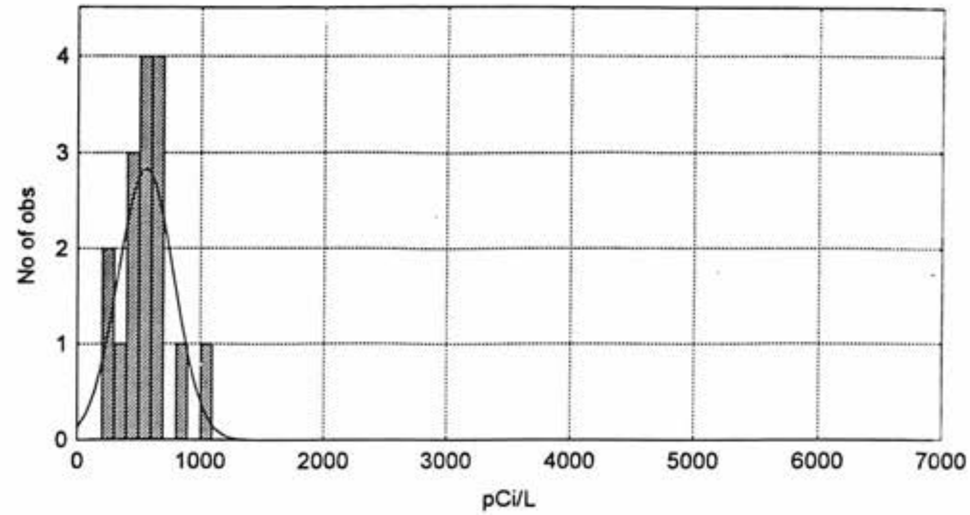

Figure 21. Histogram of soil radon concentrations (pCi/L) over the felsic gneiss.

gneiss and those of the Wissahickon and the Chickies Formations are also very noticable. Using these differences, the borders of these two lithologies were redefined.

The Carbonates

Only one outcrop of the Ledger Formation and no outcrops of the Conestoga and the Elbrook Formations were observed in the study area. This made it difficult to differentiate between the various units, especially since they appear to weather to similar soil compositions. The radon soil analysis however showed different signatures for each lithology (Table 11, Figure 19, 22, 23, and 24), and again it was possible to map the

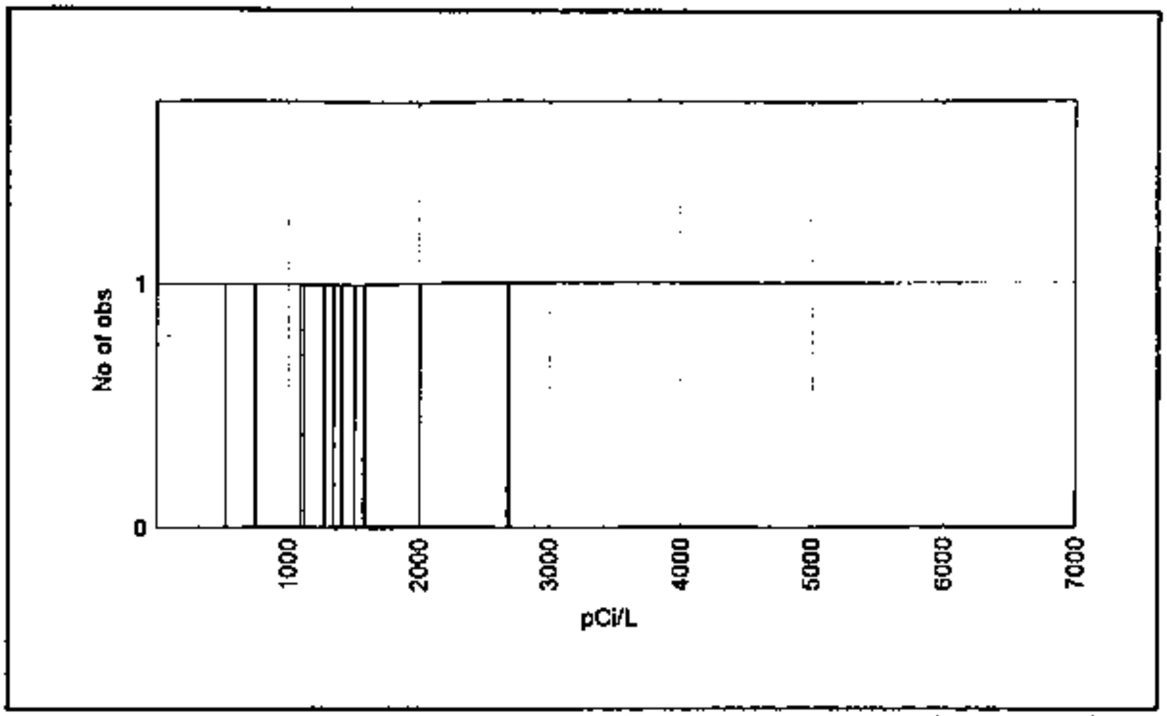

Figure 22. Histogram of soil radon concentrations (pCi/L) over Conestoga Formation.

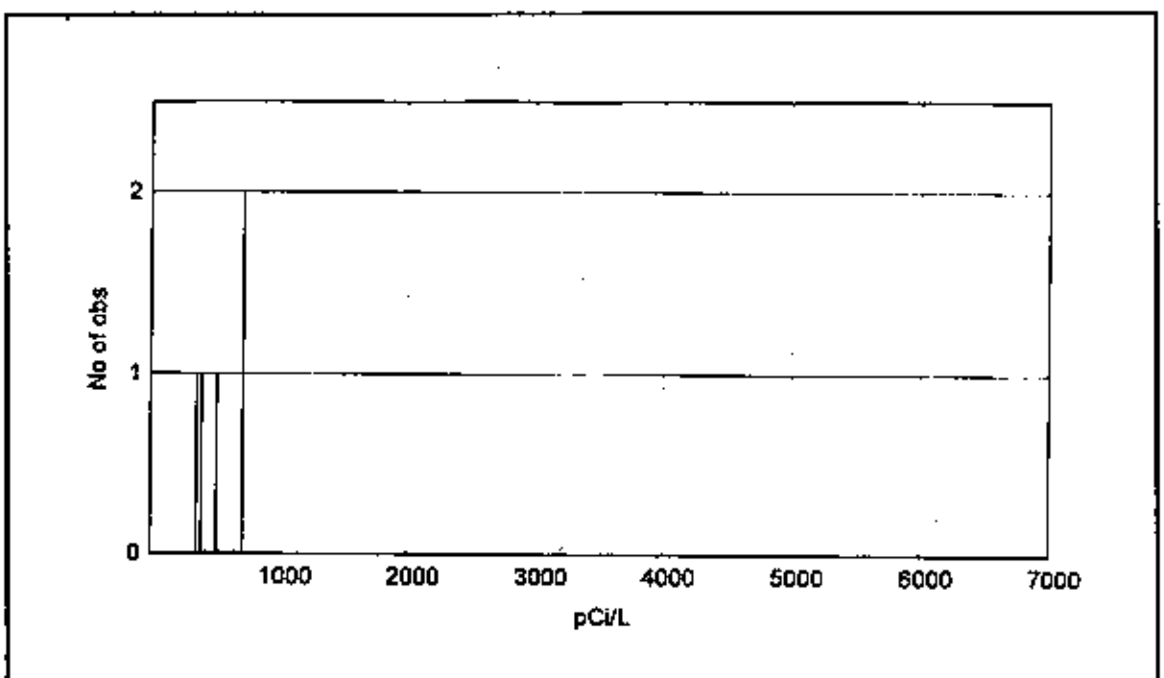

Figure 23. Histogram of soil radon concentrations (pCi/L) over Ledger Formation.

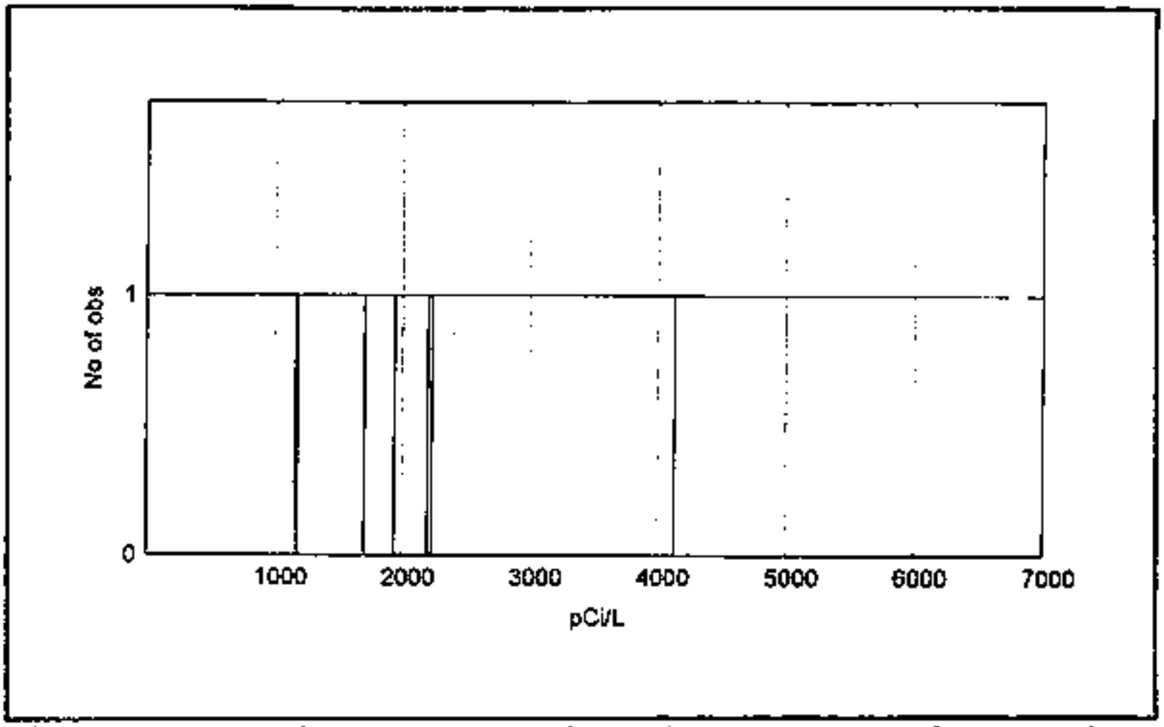

Figure 24. Histogram of soil radon concentrations (pCi/L) over Elbrook Formation.

different lithologies by their radon signatures (Figures 16 and 17). For instance, the Ledger Formation has a low radon concentration, but borders on Elbrook Formation which has a high radon concentration. But mapping using radon signatures does not always work. The Conestoga and the Chickies border each other and have similar radon signatures; in this case mapping lithology by using radon measurements does not work.

Shear Zone Control on Radon

This section will give measured and statistical evidence that soil derived from shear zones have a higher concentration of radon than soils derived from rocks outside the zone of shear. For each of the lithologies that were affected by the Huntingdon Valley shear zone (Figure 4), data were separated into two sample populations (inside and outside shear zones structures).

Wissahickon Formation

Since radon soil data for the Wissahickon Formation have a non-normal distribution, the box-plot in Figure 25 was plotted using log(pCi/L) for concentration. Even when the concentration is in log(x) form, there is a measurable difference between the soils derived from sheared and non-sheared rock. Also the Mann-Whitney U Test, a non-parametric t-test, was done on the two sample populations to see if the confidence

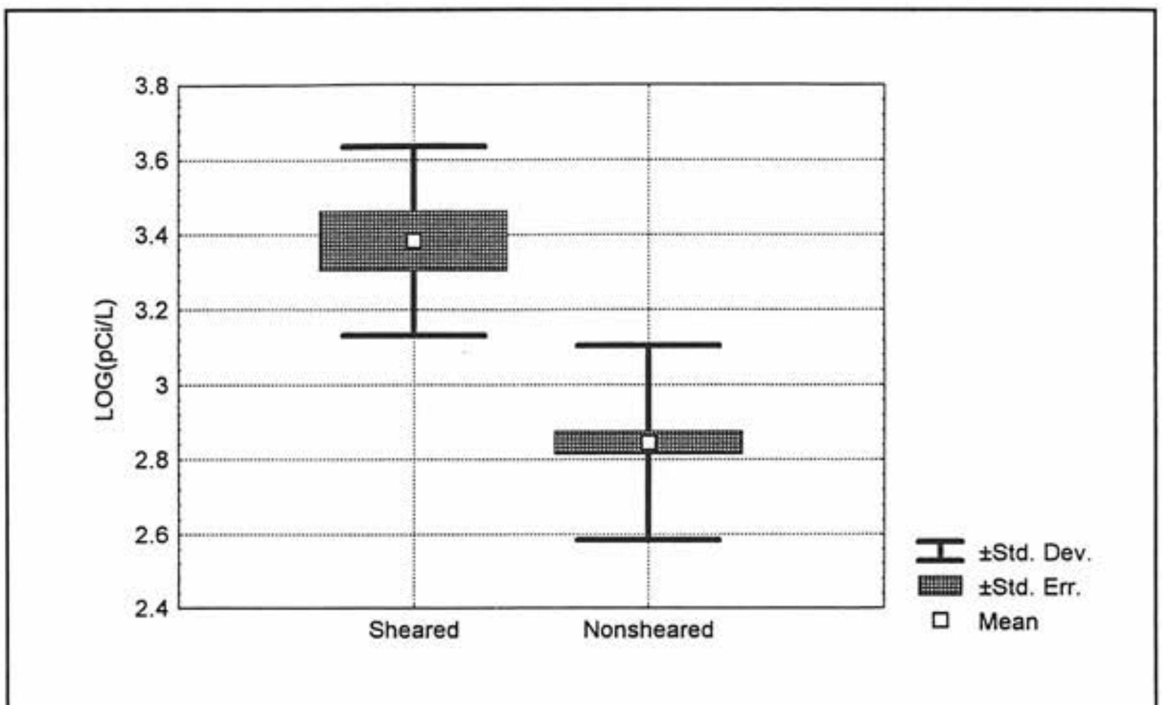

Figure 25. Log-box plot of radon concentrations in the Wissahickon Formation, sheared vs. unsheared.

level shows that the two populations are different. This test was chosen since the general population has a non-normal distribution. The test results show that there is a 99% confidence level that the soil radon over the shear zones is higher than soil radon over non-sheared Wissahickon Formation.

Chickies Formation

The sheared and unsheared Chickies Formation are easily distinguished with soil radon concentration data, supported by numerous outcrops. Inside the shear zone the soil radon concentrations range from 1404 to 2552 pCi/L and outside the shear zone they range from 331 to 879 pCi/L. The Chickies Formation yields the most consistent radon data of any lithology with a small standard deviation of 278.46 pCi/L inside and 384.77 pCi/L outside the shear zone (Figure 26). Unfortunately this was the only lithology where radon concentrations were an aid in mapping the northern border of the Huntingdon Valley shear zone.

Felsic Gneiss

Soil radon concentrations throughout the felsic gneiss tend be very low compared with other lithologies (Figure 16). Also, in the field area, there is limited outcrop of the gneiss, so it was impossible to obtain two sample populations to observe any differences between radon inside and outside of known shear zone structures. Ambiguity in past and present mapping also prohibits shear zone mapping based on radon values.

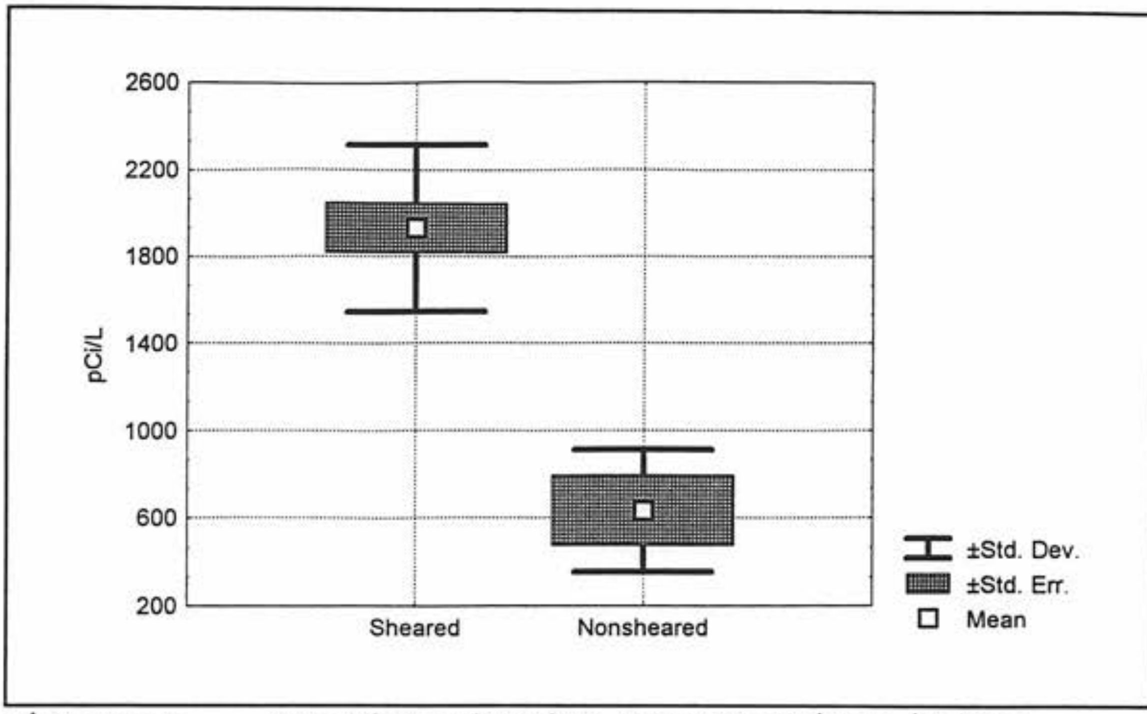

Figure 26. Box plot of radon concentrations in the Chickies Formation, sheared vs. unsheared.

The Carbonates

Owing to lack of outcrop, it was not possible to map the northern border of the Huntingdon Valley shear zone using standard field methods. Unfortunately, radon emissions were not much help. The Paleozoic carbonates have their own distinctive radon signatures, with little or no evidence of sub-populations. The only evidence of a possible northern border in the carbonates is within the Conestoga Formation (Figure 16). The high radon anomaly associated with the Conestoga has several possible explanations. One is shear zone deformation; the Huntingdon Valley shear zone is very heterogeneous in strain, so the radon concentration will reflect this heterogeneity. Second is that the marble provides an oxygen-reducing environment allowing uranium to be precipitated into the marble during the shearing event (Gates, 1993). This event would have taken place along and next to the border of the shear zone. The last possibility is that the shear zone did not control this radon anomaly.

Geochemical analysis by Brower (1991) on carbonate rocks in the Great Valley, indicated very little enrichment in uranium. However, soils derived from the carbonate rock are predominantly residuum minerals after dissolution of $CaCO_3$, so the resultant soils have very high uranium, radium and radon concentrations (Brower, 1991). His work also suggests no distinct correlation with lithology. Rather, soil development and thickness are much better predictors of radon potential. Geochemical analysis by Schultz and others (1992) shows that carbonate rocks with greater percentage of detrital material have higher radioactivity and higher concentration of uranium than carbonates with little or no siliciclastic component. They assume that the higher amount of these elements in both carbonate and non carbonate siliciclastics are chiefly due to higher concentration of detrital clay minerals and primary uranium derived from reducing depositional environments (Schultz and others, 1992).

My data suggest that each lithology does have a distinct radon signature compared to other carbonate and noncarbonate lithologies. This signature is most likely due to each carbonate formation having a distinctive weathering rate and soil thickness and the amount of detrital material, so mapping of the lithologies using radon concentration is still suitable (Figures 16 and 27).

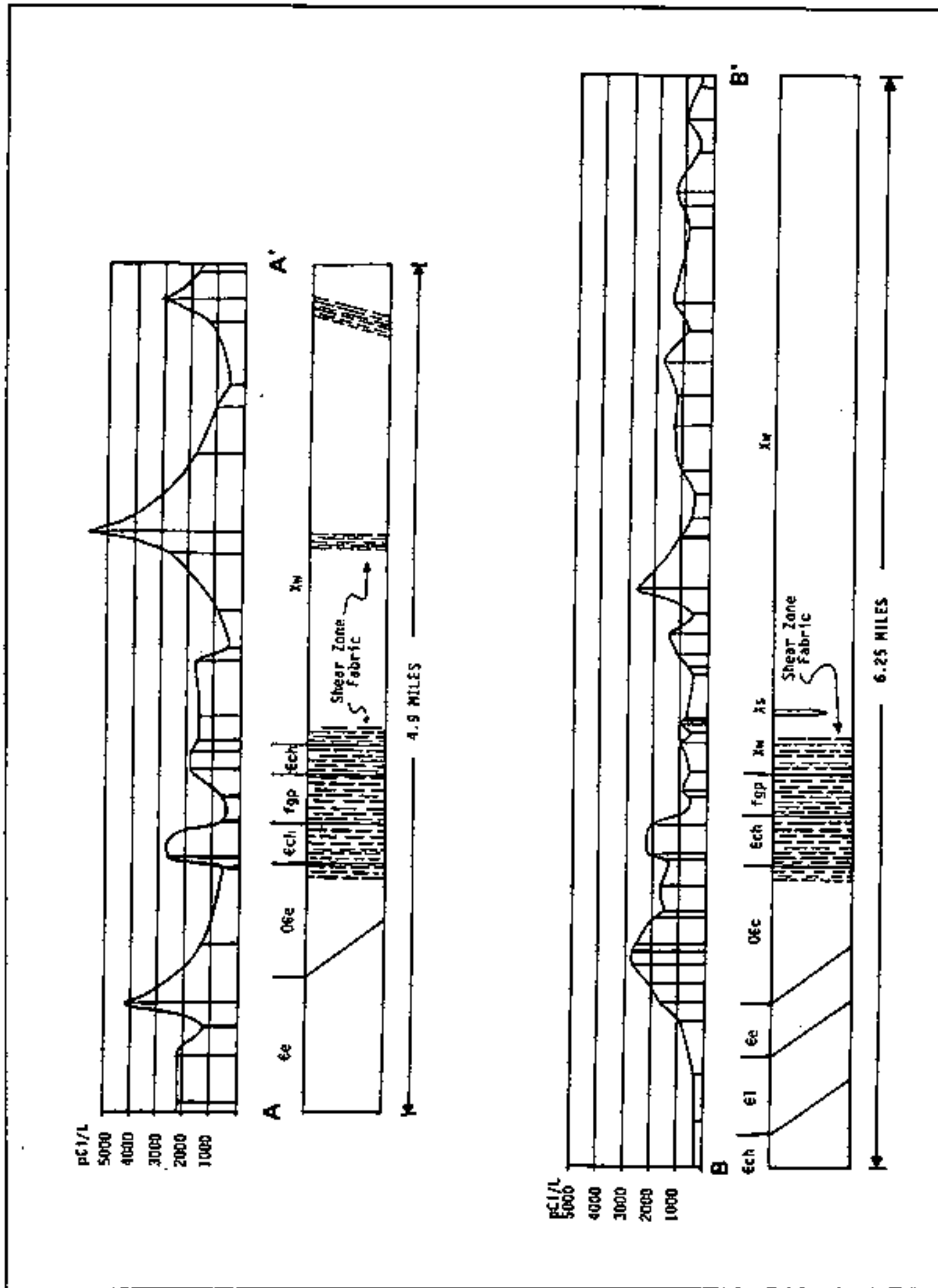

Figure 27 Two traverses and cross-sections showing radon concentration (pCi/L)in soil gas overlying rock formation.

CHAPTER 6

CONCLUSION

The purpose of this study was to observe correlations that exist between radon concentrations of *in situ* soils and the composition and shear zone fabric of the underlying parent rock. Field work has shown that within the study area, the Huntingdon Valley shear zone, with a near vertical dip, strikes N70E through the Wissahickon Formation, felsic gneiss unit, Chickies Formation, Conestoga Formation, and possibly the Elbrook Formation. The Huntingdon Valley shear zone and the two minor shear zones were verified as being structures associated with high radon emissions regardless of lithology. Within one lithology, the Wissahickon Formation, radon levels outside shear zone fabric range from 170 to 2,639 pCi/L, while inside shear zone fabric, the radon was recorded as high as 6,380 pCi/L. Radon concentrations in the Chickies Formation average 1,931 pCi/L inside shear zone fabric and 634 pCi/L outside shear zone fabric. The felsic gneiss has low radon emissions throughout, while the Conestoga Formation shows differences. These differences could be the result of either an unexposed shear zone or the distinctive weathering rate and soil thickness of the carbonate units.

The results showed that radon was a useful tool for mapping lithologies and structures in places of limited outcrop. Also these results could and should be used in defining areas which may have a higher risk of indoor radon problems.

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APPENDIX

RESULTS OF ROCK AND SOIL URANIUM ANALYSES

Uranium rock analysis results of certain lithologies and structures.

Map Location	Lithology	Sheared (Y/N)	U (ppm)
WI1	Wissahickon	Yes	2.2
WI2	Wissahickon	Yes	2.0
WI3	Wissahickon	Yes	3.0
WO1	Wissahickon	No	2.4
WO2	Wissahickon	No	3.0
WO3	Wissahickon	No	2.0
HV003Xa	Chickies	Yes	3.8
HV003Xd	Chickies	Yes	6.0
HV003Yc	Chickies	Yes	10.2
HV003Yd	Chickies	Yes	9.8
HV018-A	Felsic Gneiss	Yes	0.2
HV018-B	Felsic Gneiss	Yes	1.4
FG2	Felsic Gneiss	Yes	3.2
FG3	Felsic Gneiss	Yes	1.2

Soil analysis results of uranium and radon concentrations over certain lithologies and structures in the study area.

Map Location	Lithology	Sheared (Y/N)	U (ppm)	Rn (pCi/L)
WS1	Wissahickon	Yes	5.0	5645
WS2	Wissahickon	No	3.6	1688
CS3	Chickies	Yes	5.0	2390
CS5	Chickies	Yes	3.2	1408
FG-S1	Felsic Gneiss	Yes	3.4	
FG-S2	Felsic Gneiss	Yes	1.6	
FG-S3	Felsic Gneiss	Yes	1.8	
FS4	Felsic Gneiss	Yes	6.8	560
CON-S2	Connestoga	?	4.8	
CNS6	Connestoga	?	4.8	1278
ES7	Elbrook	No	3.0	1160
ELB-S2	Elbrook	No	3.4	
LED-S2	Ledger	No	4.6	
LS8	Ledger	No	4.0	720
CS9	Chickies	No	1.2	879