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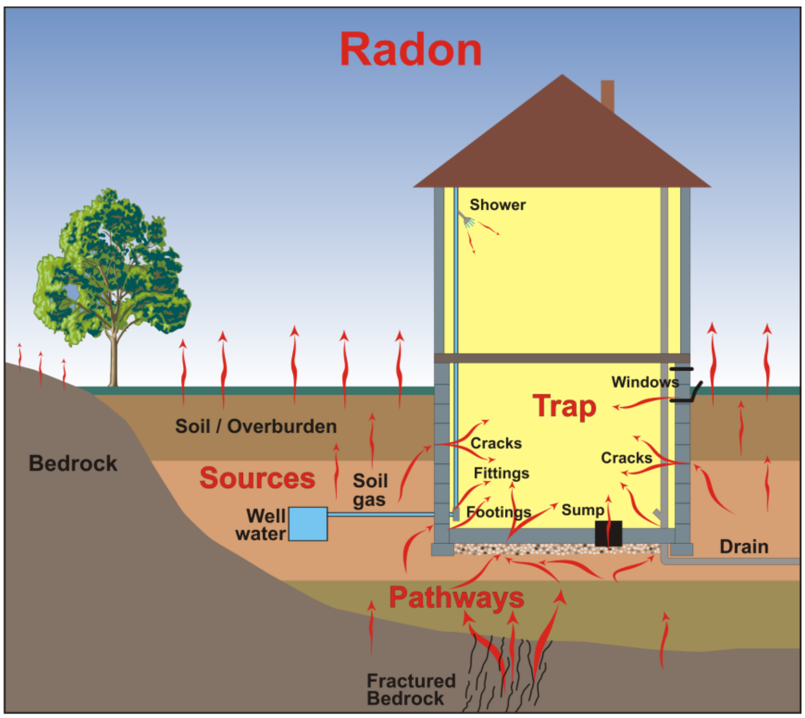
Predicting Geographic Variations of Indoor Radon Potential across southwestern Ontario using Geoscience Data



K.L. Ford, B.J.A. Harvey, J. Whyte and J. Chen

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Predicting Geographic Variations of Indoor Radon Potential across southwestern Ontario using Geoscience Data

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Abstract:

Estimating indoor radon variations using regional geoscience data for southwestern Ontario generally shows a progressive and clearly positive association. Uranium concentrations measured by airborne gamma ray spectrometry show the strongest positive association with elevated indoor radon concentrations followed by estimated radon potential derived from regional bedrock geology. Comparisons between relative permeability derived from regional surficial geology and indoor radon concentrations were inconclusive. Closer examination suggests that this may not always be the case and that permeability is still an important factor at local scales.

The positive associations between selected regional geoscience datasets, in particular uranium concentrations measured by airborne gamma ray spectrometry and elevated indoor radon concentrations, illustrates their use as effective predictive tools for the identification of areas with increased potential for overexposure to indoor radon, including areas without residential development. These positive associations can be used to support targeted or follow-up radon studies and for future land-use planning decisions.

TABLE OF CONTENTS

LIST OF FIGURES

Figure 15: Percentage of homes with greater than 200 Bq/m^3 compared with the estimated radon potential derived from the bedrock geology for southwestern Ontario.

Figure 16: Box and whisker plots comparing indoor radon concentrations with the estimated radon potential derived from the bedrock geology for southwestern Ontario.

Figure 17: Surficial geology of southwestern Ontario derived from the Ontario Geological Survey (2010) with average soil gas radon concentrations (kBq/m^3) presented as 3 proportionally scaled symbols (<10; 10-50 and >50 kBq/m^3).

Figure 18: Estimated radon potential derived from the relative permeability of the different surficial geology units for southwestern Ontario. Radon potential was classified into 5 categories of increasing relative potential with scores of 1 to 5 (1 - low, 2 - low-moderate, 3 - moderate, 4 - moderate-high, and 5 - high). Indoor radon concentrations presented as 3 proportionally scaled symbols (<200; 200-400 and >400 Bq/m^3).

Figure 19: Percentage of homes with greater than 200 Bq/m^3 compared with the estimated radon potential derived from the relative permeability of the different surficial geology units for southwestern Ontario.
* Insufficient sample population to calculate percentages.

Figure 20: Box and whisker plots comparing indoor radon concentrations with the estimated radon potential derived from the relative permeability of the different surficial geology units for southwestern Ontario.

Figure 21: Percentage of homes with greater than 200 Bq/m^3 compared with the estimated radon potential derived from addition of individual cell scores for the 3 input datasets (AGRS eU, Bedrock and Relative Permeability) for southwestern Ontario.

Figure 22: Percentage of homes with greater than 200 Bq/m^3 compared with the estimated radon potential derived from addition of individual cell scores for the 3 input datasets (AGRS eU, Bedrock and Relative Permeability) regrouped into 3 categories.

Figure 23: Box and whisker plots comparing indoor radon concentrations with the 3 categories of regrouped estimated radon potential derived from addition of individual cell scores for the 3 input datasets (AGRS eU, Bedrock and Relative Permeability) for southwestern Ontario.

Figure 24: Estimated radon potential map for southwestern Ontario derived from addition of individual cell scores for 3 input datasets (AGRS eU, Bedrock and Relative Permeability) with indoor radon (Bq/m^3) concentrations presented as 3 proportionally scaled symbols (<200; 200-400 and >400 Bq/m^3).

Figure 25: Percentage of homes with greater than 200 Bq/m^3 compared with the estimated radon potential derived from addition of individual cell scores for 2 input datasets (AGRS eU and Bedrock Geology) for southwestern Ontario.

Figure 26: Percentage of homes with greater than 200 Bq/m^3 compared with the estimated radon potential derived from addition of individual cell scores for 2 input datasets (AGRS eU and Bedrock Geology) for southwestern Ontario regrouped into 3 categories.

Figure 27: Box and whisker plots comparing indoor radon concentrations with the 3 categories of

regrouped estimated radon potential derived from addition of individual cell scores for 2 input datasets (AGRS eU and Bedrock Geology) for southwestern Ontario.

Figure 28: Estimated radon potential map for southwestern Ontario derived from addition of individual cell scores for 2 input datasets (AGRS eU and Bedrock Geology) with indoor radon (Bq/m^3) concentrations presented as 3 proportionally scaled symbols (<200; 200-400 and >400 Bq/m^3).

LIST OF TABLES

1. Introduction

Radon (^{222}Rn) is a naturally occurring, colourless, odourless and tasteless radioactive gas produced by the decay of uranium (^{238}U) that is found in all rocks and soils. Radon that originates from rocks and soils and contributes to the indoor environment is the main source of natural radiation exposure to the population. Prolonged exposure to elevated radon levels has been associated with an increased risk of developing lung cancer and is considered by the World Health Organization (2009) to be the second leading cause of lung cancer. It is estimated that about 16% of lung cancer deaths in Canada are related to radon exposure (Health Canada, 2012).

In 2007, Health Canada announced a National Radon Program for Canada which included a reduction of the Canadian indoor radon guideline from 800 to 200 Bq/m^3 (Canada Gazette, 2007). Above this new guideline remedial measures are recommended. As a contribution to this new program Natural Resources Canada, through the Geological Survey of Canada (GSC) acquired new baseline geoscience data and assessed this new data along with existing regional bedrock and surficial geology, to estimate the indoor radon potential of selected areas in Canada. This new baseline geoscience data included airborne gamma ray spectrometry (AGRS) surveys in selected areas of Canada (Figure 1), and reconnaissance ground surveys that included soil sampling, soil gas radon, soil permeability, ground and laboratory gamma ray spectrometry measurements as part of the North American Soil Geochemical Landscape Project (NASGLP) (Friske et al., 2010).

The aim of this investigation was to demonstrate the usefulness of readily available geoscience data for identifying areas prone to elevated levels of indoor radon, to validate these assessments using direct indoor measurements, and to be able to identify previously unknown radon prone areas including those with no residential development. Southwestern Ontario was chosen to demonstrate the effectiveness of regional geoscience data to identify radon prone areas as there exists for this region, excellent digital coverage of bedrock and surficial geology, and new AGRS data. An important component of this investigation is the availability of indoor radon measurements acquired as part of Health Canada's Cross-Canada Survey of Radon Concentrations in Homes (Health Canada, 2012). This data is necessary to test the validity of the geoscience data assessments.

2. Data Sets

2.1 Indoor Radon Survey Data

As part of Health Canada's National Radon Program approximately 14,000 indoor residential radon measurements were made in 2009-10 and 2010-11. Measurements were distributed across all Health Regions in Canada and covered both rural and urban areas. Health Regions are administrative areas defined by provincial health ministries where public health activities are implemented at regional levels within the Canadian provinces and territories. They can range in size from fairly small geographic areas to that of an entire province or territory. The measurements were made using alpha track radon detectors placed in a suitable occupied (more than 4 hours per day) area of each home for a period of 3 months during the fall and winter heating season. Key results of this two-year study indicate that 6.9% of Canadians live in homes with radon concentrations that exceed the new radon guideline of 200 Bq/m^3. The survey also confirmed that indoor radon levels can vary significantly across the country and that there are areas within individual provinces and Health Regions where high concentrations of indoor radon are prevalent (Health Canada, 2012).

For southwestern Ontario the Health Canada indoor radon survey measured over 2,100 homes within the same area covered by the AGRS surveys (Figure 2). To protect the locational confidentiality of individual homeowners the actual latitude and longitudinal coordinates for each measurement were replaced with the latitude and longitude coordinates of the centroid of the raster cell from the AGRS grid in which the

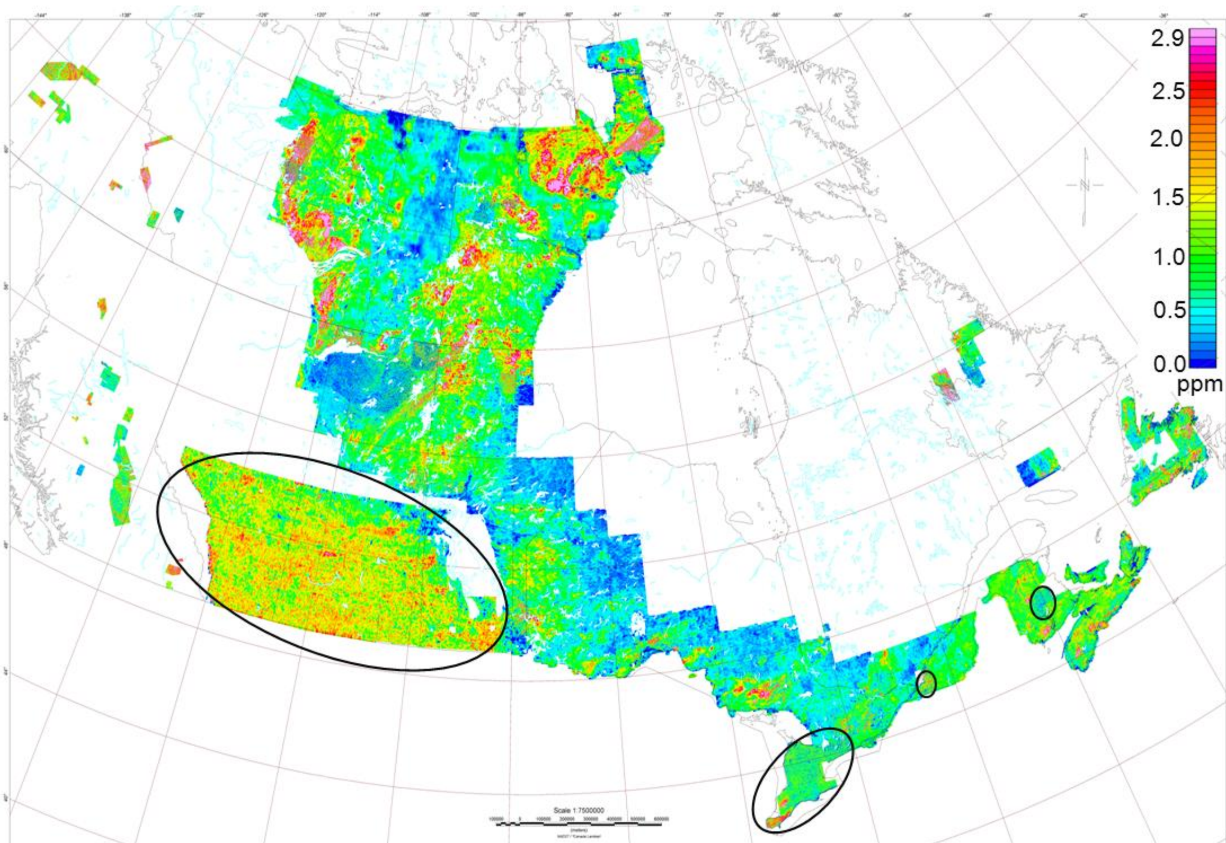

Figure 1: Equivalent uranium (ppm) map of Canada compiled from airborne gamma ray spectrometry surveys flown between 1969 and 2011. New data acquired by the GSC as a contribution to Health Canada's National Radon Program indicated by circled areas. This compilation grid and all data for individual surveys is available from Natural Resources Canada's Geoscience Data Repository for Geophysical and Geochemical Data at **http://gdr.agg.nrcan.gc.ca/gdrdap/dap/search-eng.php**

measurement occurs. Of homes measured in the southwestern Ontario study area, 8.5% returned radon concentrations that exceeded 200 Bq/m^3. Frequency and cumulative frequency distributions for the indoor, residential radon measurements are shown in Figure 3. Indoor radon concentrations range from the lower limit of detection (15 Bq/m^3) to greater than 2700 Bq/m^3 with mean and median concentrations of 84 and 50 Bq/m^3 respectively. For purposes of calculating mean indoor radon values, concentrations below the lower limit of detection were set to one half this value.

A goal of Health Canada's indoor residential radon survey was to sample all Health Regions across Canada with approximately an equal number of measurements in each region. An important consequence of having a good distribution of geo-referenced measurements is that they will provide not only a reasonable estimate of indoor radon levels in areas with residential development but will also provide important validation of geoscience assessments that may then be extended to areas with no residential development.

2.2 Soil Gas Radon and Soil Permeability Survey Data

Soil gas radon and soil permeability surveys can also be used to identify radon prone areas (Harrell et al, 1991; Tilsley and Baker, 1992; Barnet et al, 2006; Neznal et al, 2004; Chen et al, 2008). As a contribution to Health Canada's National Radon Program, the GSC through the NASGLP (Friske et al, 2010) collected reconnaissance soil gas radon, soil permeability and in-situ gamma ray spectrometry

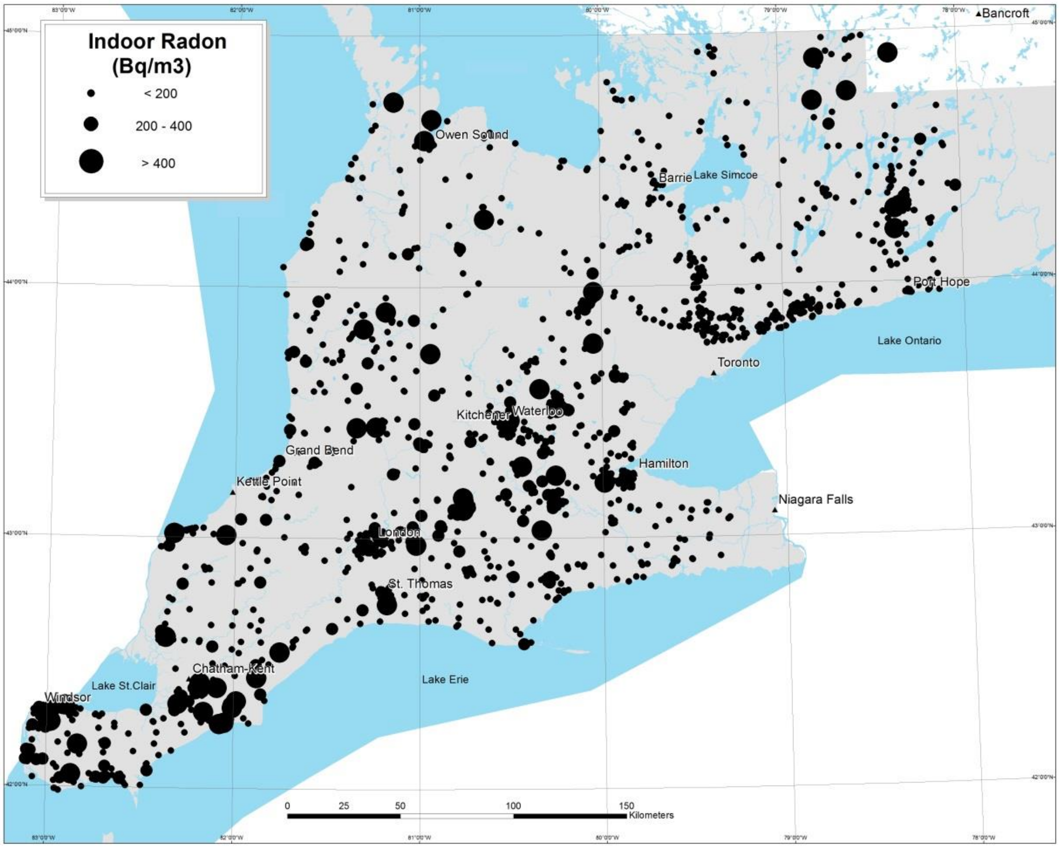

Figure 2: Distribution of indoor, residential radon measurements across southwestern Ontario from Health Canada's Cross-Canada Survey of Radon Concentrations in Homes (Health Canada, 2012).

measurements at selected sites across Canada. Equipment and field sampling protocols used to conduct these measurements are described in Friske et al, (2010). Survey results for southwestern Ontario, excluding urban sample sites and sites around Bancroft, have recently been published in GSC Open File 7344 (Friske et al, 2013).

Average soil gas radon concentrations were calculated at each site, generally from measurements made using 5 probes inserted to a depth of 60 to 80 cm in a 10m by 10m area. Figure 4 shows the distribution of average soil gas radon concentrations across southwestern

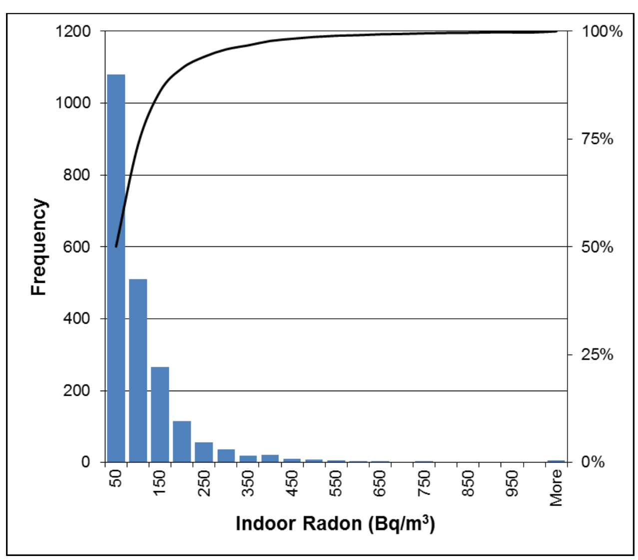

Figure 3: Frequency and cumulative frequency distributions of indoor, residential radon measurements across southwestern Ontario.

Ontario. Excluding urban and Bancroft area locations 104 sites were sampled. Frequency and cumulative frequency distributions for the soil gas radon measurements are shown in Figure 5. Average soil gas radon concentrations varied between 0.5 and 108 kBq/m^3 with a mean value of 28 kBq/m^3. Chen et al, (2008) noted that radon potential or radon risk is often classified as low, moderate or high depending on whether the soil gas radon concentration in a particular area is < 10, 10–50, or > 50 kBq/m^3 respectively. Based on this classification 30 (29%) of the 104 sites sampled would be low risk sites, 56 (54%) would be moderate, and 18 (17%) would be high risk. The distribution of average soil gas radon values (Figure 4) indicate that some areas of southwestern Ontario could have a high radon risk potential, particularly some of those areas west of London. Most of southwestern Ontario west of the Niagara escarpment would have a moderate risk with the exception of areas where thick, coarse glaciolacustrine deposits are prevalent (see Figure 14). Tilsley and Baker (1992) and Tilsley et al (1993) determined the level of naturally occurring soil gas radon in overburden for 4 selected areas in southern Ontario. Three of these areas (Essex County-Windsor, Kent and Lambton Counties-Wallaceburg, and Markham-Stouffville) occur within this current southwestern Ontario study. A fourth area is located in Prince Edward County west of Kingston. While their instrumentation and sampling protocols were different than those used in this current study their results showed a similar relative distribution. Of the 4 areas, the highest average soil gas radon values occurred in black shale rich tills in the Kent-Lambton-Wallaceburg area. Similar values were found in the Essex-Windsor area. The lowest levels were found in the Markham-Stouffville and Prince Edward County areas.

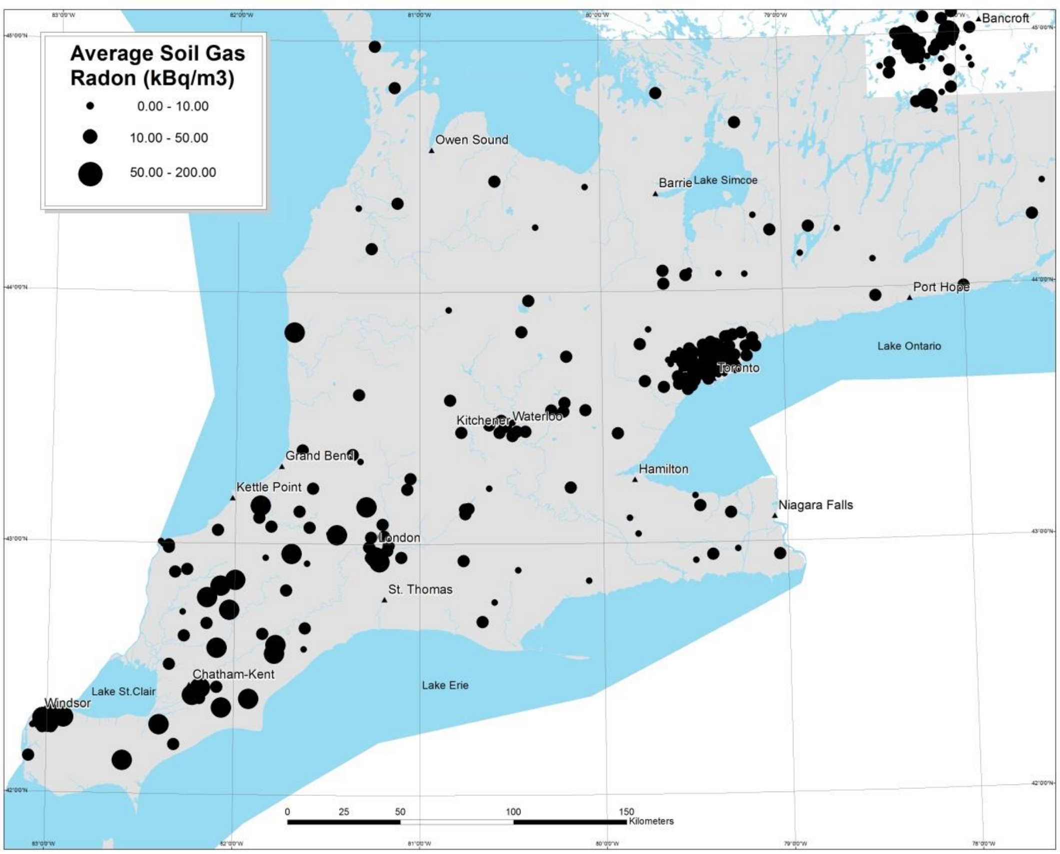

Figure 4: Distribution of average soil gas radon concentrations across southwestern Ontario.

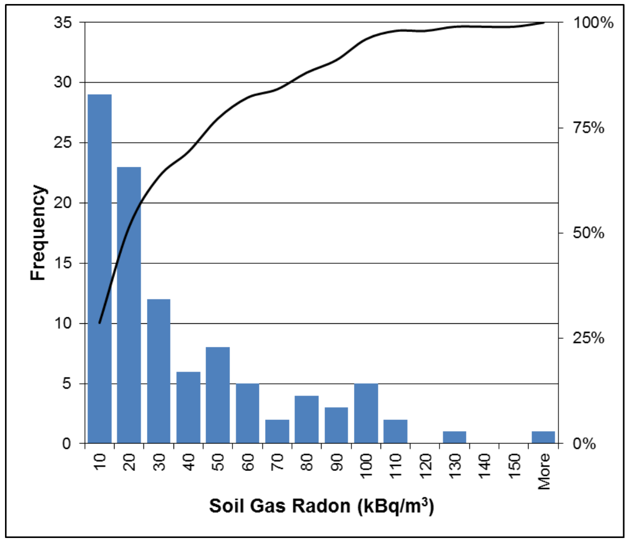

Figure 5: Frequency and cumulative frequency distributions of average soil gas radon measurements across southwestern Ontario.

Soil permeability measurements were also made at each site using a RADON-JOK system (Radon v.o.s., 2007). Generally, for time and field logistical reasons, 2 direct in-situ permeability measurements were made at each site from 2 of the 5 soil gas radon probes prior to the soil gas measurement. Estimates of the relative (low, moderate, high) permeability were made for the remaining 3 probes based on the relative resistance encountered during collection of the soil gas sample using a 150mL syringe. An average permeability value was assigned to these estimated measurements following a comparison of over 1200 probes where both a direct and estimated permeability measurement was made (Friske et al, 2012). A soil radon potential (SRP) index (Neznal et al, 2004) value was determined for each probe. The SRP index is defined as,

$$SRP = (C - C_0) / (-\log(P) + \log(P_0))$$

where C is the radon concentration of the soil gas in kBq/m^3, and P is the soil permeability in m^2. C_0 and P_0 are set to 1 kBq/m^3 and $1*10^{-10}$ m^2, respectively. Figure 6 shows the distribution of average SRP index values across southwestern Ontario. For the 104 sites, average SRP index values range between 0.7 and 74.8 with a mean value of 16.6. Neznal et al (2004) use the SRP index to characterize radon risk at building sites in the Czech Republic. The radon risk is classified as low, moderate or high if the SRP index value is <10, 10-35, and >35 respectively. Based on these classifications 50 (48%) of the 104 sites sampled would be low risk, 39 (37%) would be moderate, and 15 (15%) would be high risk. In general the average SRP index values show a similar distribution to the average soil gas radon values.

2.3 Airborne Gamma Ray Spectrometry

High sensitivity AGRS surveys provide rapid, systematic coverage of large areas including those with no residential development. These surveys acquire data on the distribution of the three most common, naturally occurring radioactive elements, potassium (K, %), equivalent uranium (eU, ppm) and equivalent thorium (eTh, ppm) in the top 30 to 50 cm of the earth's surface. The term "equivalent" or its abbreviation "e" is used to indicate that equilibrium is assumed between the radioactive daughter isotope monitored by the gamma ray spectrometer and its respective parent isotope. Uranium and thorium are estimated indirectly by measuring gamma rays emitted by Bi^{214} and Tl^{208} respectively. This information has applications to bedrock and surficial geological mapping, mineral exploration, environmental radiation monitoring and land-use planning (Shives et al, 1995; IAEA, 2003).

The distribution of uranium measured by AGRS surveys is considered an important geoscience dataset that provides first-order information useful for assessing geographic variations of indoor radon concentrations and for identifying areas or regions prone to elevated indoor radon levels. These data have been used in Canada and elsewhere for radon risk assessment at local (Ford et al, 2001; Doyle et al, 1990), regional (O'Reilly et al, 2013; Smethurst et al, 2008) and national scales (Otten et al, 1995; Ball et al, 1995; Cocksedge et al, 1993). In 2008 and 2009 the Geological Survey of Canada acquired AGRS data across southwestern Ontario (Figure 7) to determine the geographic distribution of K, eU and eTh in the surficial geological material, and to further assess its usefulness for identifying areas prone to elevated indoor radon levels (Carson et al, 2009; 2010a, 2010b).

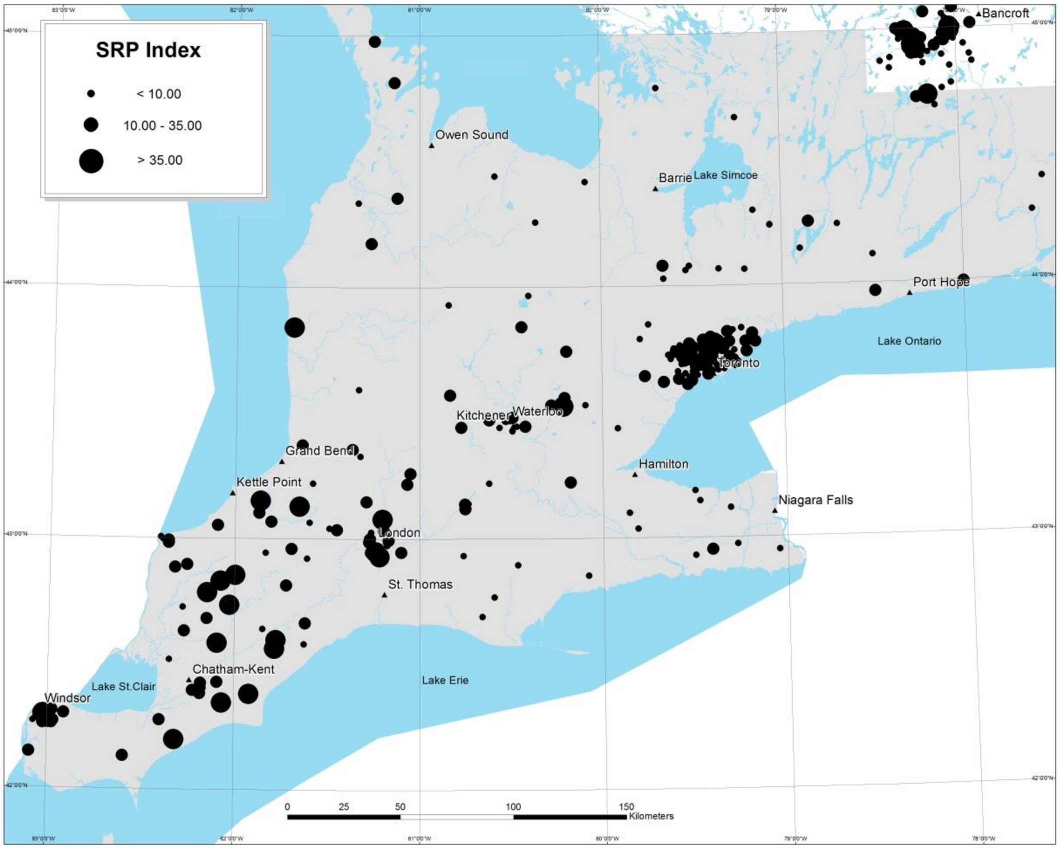

Figure 6: Distribution of average soil radon potential (SRP) index values across southwestern Ontario.

surficial geological material, and to further assess its usefulness for identifying areas prone to elevated indoor radon levels (Carson et al, 2009; 2010a, 2010b).

The AGRS data acquired in 2008 and 2009 covers approximately 52,000 km^2 of southwestern Ontario (Figure 7). The gamma ray spectrometer systems consisted of 50 L of NaI detectors in the main detector array and 8 L in an upward-looking array for real-time monitoring of atmospheric radon variations. Flight lines were flown at 1000 metre spacing, at a nominal terrain clearance of 150 metres that was increased to approximately 300 metres over heavily populated urban areas, and with an air speed of between 200 and 270 kph.

Figure 7 shows 4 maps that depict the distribution of total radioactivity (Natural Air Absorbed Dose Rate (NADR), nGy/h), potassium (K, %), equivalent uranium (eU, ppm) and equivalent thorium (eTh, ppm) for southwestern Ontario. Additional data for the area north of 44^0 30’N has been included from the digital archives of NRCan’s Geoscience Data Repository. Areas west of 79^{0}W and north of 44^0 30’N were flown with a flight line spacing of 5000 metres. The closer line spacing of 1000 metres for most of southwestern Ontario provides increased spatial resolution that will support more detailed interpretation.

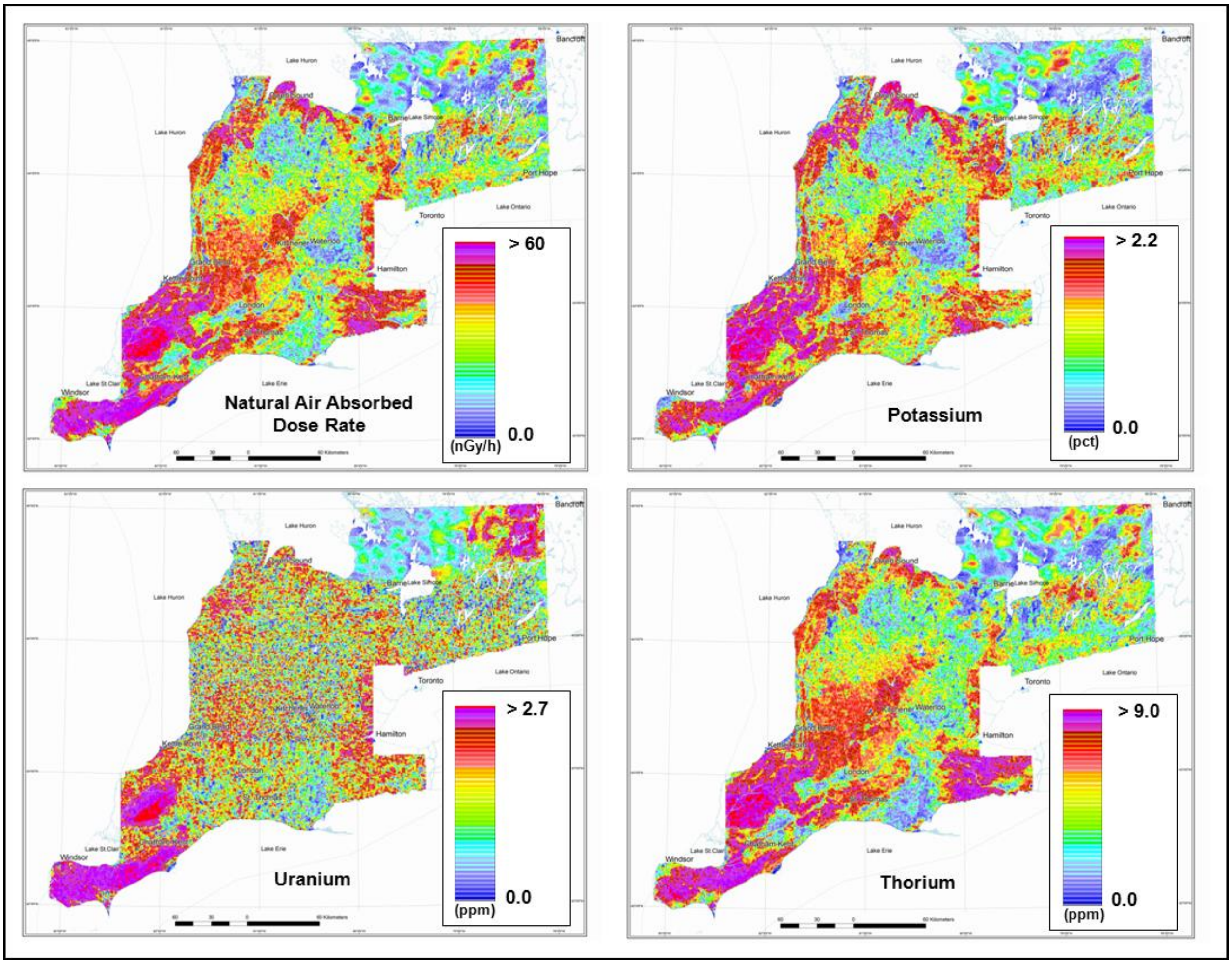

Figure 7: Images of the airborne gamma ray spectrometry data for southwestern Ontario.

In areas with thin or discontinuous drift and soil cover the AGRS patterns provide direct assistance to bedrock geological mapping (Shives et al, 1995). However, in areas covered by thicker till and/or glaciofluvial, glaciolacustrine or other reworked glacial deposits the AGRS patterns may delineate the various types of surficial materials but will reflect local bedrock compositions to a lesser degree or not at all depending on the amount of locally derived bedrock material incorporated in the reworked surficial deposits. This latter situation appears to be the case for most of southwestern Ontario.

A close visual inspection of the AGRS patterns (Figure 7) shows a strong correlation with mapped surficial geology (Figure 17). In general, the coarse predominantly sand and gravel glaciolacustrine, and glaciofluvial outwash and ice-contact deposits (Units 6, 7 and 9 on Figure 17) are characterized by relatively low NADR, K and eTh signatures. Some coarser grained tills (Units 5a and b, Figure 17) exhibit similar signatures. This is well illustrated by large areas that extend from just west of Long Point on Lake Erie, north through the Kitchener and Guelph areas, towards Barrie and then west to Goderich, and smaller areas near London that trend southwest to Chatham. The fine textured, predominantly silt and clay glaciolacustrine deposits (Unit 8, Figure 17) are characterized by moderate to elevated NADR, K and eTh signatures. This is well illustrated by the Niagara Peninsula area south of Hamilton and areas west of London. Some of the highest total radioactivity, K and eTh signatures occur in extreme southwestern Ontario over thinner, locally derived tills and glaciolacustrine deposits, and along the south shore of Georgian Bay between Collingwood and Owen Sound where surficial deposits are again relatively thin and bedrock exposures of shale dominated sequences of the Queenston, Georgian Bay, Blue Mountain and Lindsay formations are more prevalent.

Over most of southwestern Ontario AGRS eU concentrations exhibit a very narrow range of values, generally between 0.25 and 1.25 ppm (Figure 8). Within this narrow range subtle variations reflect a similar distribution to the K and eTh patterns. The highest eU concentrations occur in the Bancroft area with concentrations in excess of 15 ppm associated with zones of uranium-bearing pegmatites, some of which were mined from the 1950's to early 1980's. Outside the Bancroft area, high eU concentrations with values between 2.5 and 4 ppm occur in areas north and south of Chatham associated with black shales of the Kettle Point formation. Reichenback (1993) reports that black shales of the Kettle Point formation have average uranium concentrations in excess of 30 ppm, with some lithotypes in excess of 50 ppm. Outcrops of the Kettle Point formation are rare and generally restricted to the type-locality at Kettle Point on the shore of Lake Huron. The high eU concentrations north and south of Chatham are associated with lobes of the Rannoch and Tavistock tills respectively (Barnett et al, 1991) and likely contain more abundant, locally derived black shale clasts from the Kettle Point formation than similar tills elsewhere. Elevated eU concentrations that extend westward towards Windsor suggest surficial deposits similar to the Tavistock till or reworked equivalents may be more extensive.

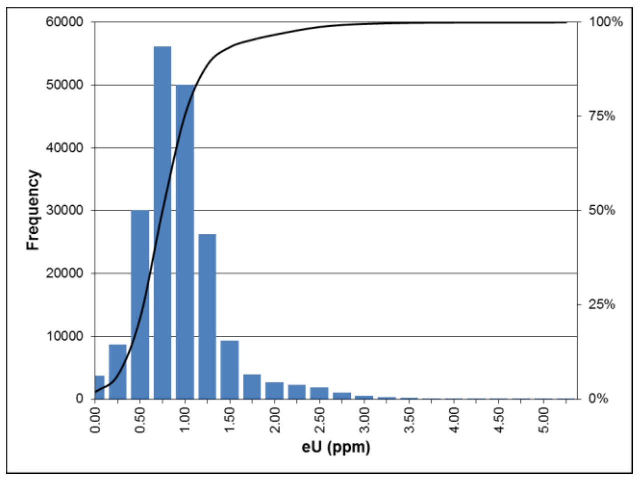

Figure 8: Frequency and cumulative frequency distributions of AGRS eU grid values across southwestern Ontario.

Figure 9 provides a visual comparison between average soil gas radon concentrations and AGRS eU concentrations. An inspection of this figure shows a clear association between areas of high eU concentrations and most of the high average soil gas radon concentrations with the highest soil gas radon and eU concentrations associated with or occurring in close proximity to black shales of the Kettle Point formation. Figure 10 shows this same eU data grouped into contour intervals of 0.5 ppm and labelled with an estimated AGRS radon potential of low (<0.5 ppm), low-moderate (0.51 – 1.00 ppm), moderate (1.01 – 1.50 ppm), moderate-high (1.51 – 2.00 ppm) and high (>2.01 ppm). Indoor radon concentrations are plotted on Figure 10 as three proportionally scaled symbols (<200, 200-400 and >400 Bq/m^3). Results of an analysis of the indoor radon concentrations versus the estimated AGRS eU radon potential are presented in Table 1 and Figure 11. There is little difference in the percentage of homes with indoor radon concentrations greater than 200 Bq/m^3 for the low and low-moderate categories, those with AGRS eU concentrations less than 1.0 ppm eU. There is however a clear positive association between increasing radon potential estimated from the AGRS eU data and an increasing percentage of homes with indoor radon concentrations above 200 Bq/m^3 for the low/low-moderate and the remaining 3 categories. The average indoor radon concentrations for each category do show a progressive increase. Median indoor radon concentrations however show little difference between the low and low-moderate categories, or between the moderate-high and high categories.

To assess the statistical separability of the 5 categories of estimated AGRS eU radon potential, simple box and whisker plots were prepared and are presented in Figure 12. The range indicated by the 2 horizontal lines correspond to the 95% confidence interval of the median for the lowest estimated radon potential category. These lines were added to enable a visual comparison with adjacent categories. This figure suggests that there is little statistical difference between the low and low-moderate categories, and between the moderate-high and high categories.

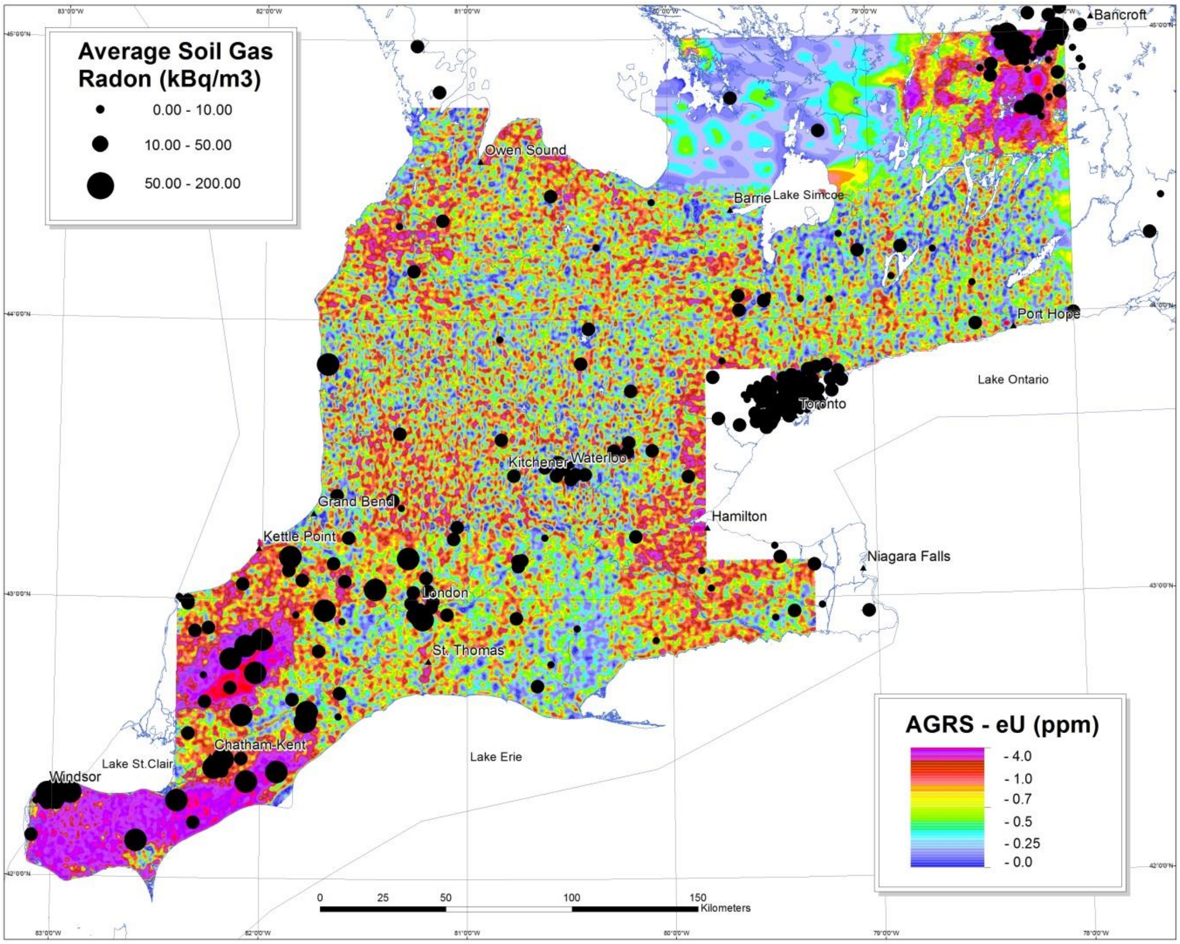

Figure 9: Equivalent uranium (ppm) data from AGRS surveys with average soil gas radon concentrations (kBq/m^3) presented as 3 proportionally scaled symbols (<10; 10-50 and >50 kBq/m^3).

Table 1: Comparison of estimated radon potential derived from AGRS eU data with indoor radon data (Bq/m^3) for southwestern Ontario.

Rn Pot (Est)	eU (ppm)	% Total Area	# of Homes	# > 200 (Bq/m^3)	% > 200 (Bq/m^3)	Mean Indoor Rn (Bq/m^3)	Median Indoor Rn (Bq/m^3)
1 (Low)	< 0.5	21.4	369	27	7.3	71.9	39.0
2 (Low-Mod)	0.5 - 1.0	53.9	1110	79	7.1	76.5	39.5
3 (Mod)	1.0 - 1.5	18.1	460	48	10.4	91.9	59.0
4 (Mod-High)	1.5 - 2.0	3.3	99	14	14.1	126.2	85.0
5 (High)	> 2.0	3.3	75	13	17.3	138.6	82.0

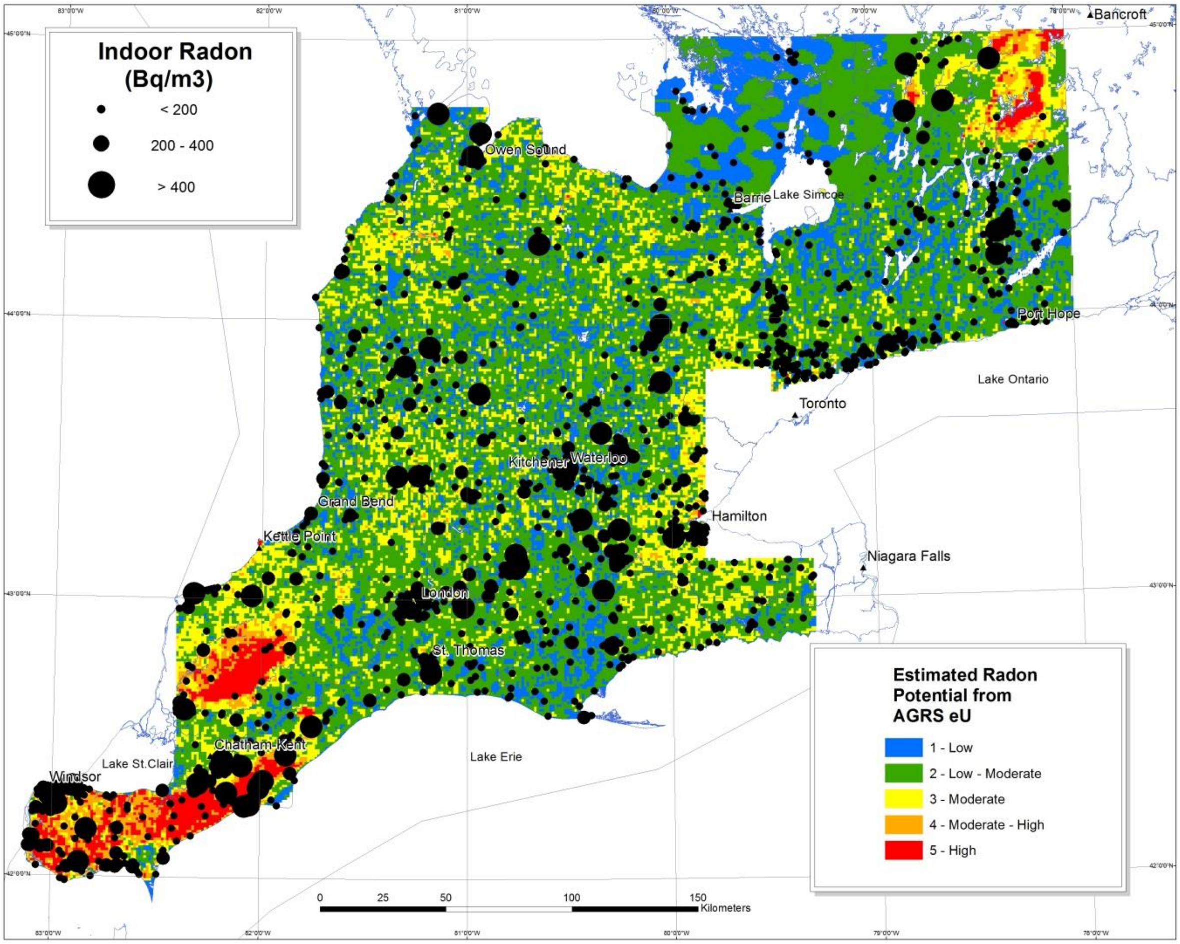

Figure 10: Estimated radon potential map derived from AGRS eU data for southwestern Ontario. Radon potential classified into 5 categories of increasing potential with scores of 1 to 5 (1 - low (<0.5 ppm), 2 - low-moderate (0.51 – 1.00 ppm), 3 - moderate (1.01 – 1.50 ppm), 4 - moderate-high (1.51 – 2.00 ppm) and 5 - high (>2.01 ppm)). Indoor radon concentrations presented as 3 proportionally scaled symbols (<200; 200-400 and >400 Bq/m^3).

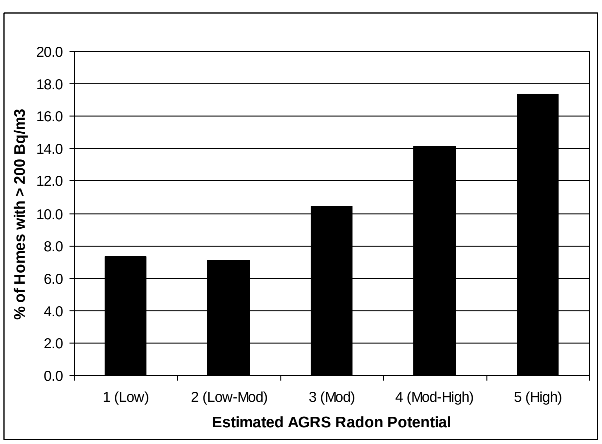

Figure 11: Percentage of homes with greater than 200 Bq/m^3 compared with the estimated radon potential derived from the AGRS eU data.

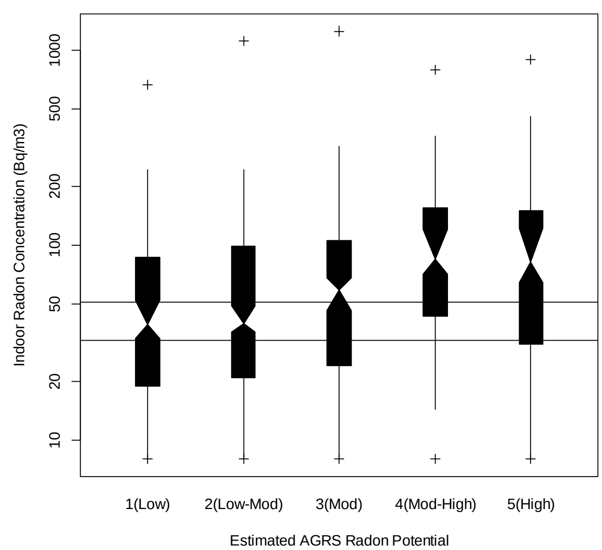

Figure 12: Box and whisker plots comparing the statistical distribution of indoor radon concentrations (Bq/m^3) with the estimated radon potential derived from the AGRS eU data.

2.4 Bedrock Geology

Figure 13 shows the bedrock geology of southwestern Ontario compiled by Armstrong and Dodge (2007) and available in digital format from the Ontario Geological Survey at http://www.geologyontario.mndm.gov.on.ca/mndmaccess/mndm_dir.asp?type=pub&id=MRD219. Excluding the Precambrian terrain north of Lake Simcoe the bedrock geology of southwestern Ontario is dominated by a sequence of Paleozoic sedimentary rocks ranging in age from Ordovician in the east to Devonian in the southwest. Primary lithologies include limestone, dolostone and shale with some sandstone and evaporite sequences.

Apart from the black shales of the Kettle Point and Marcellus formations little is known about the uranium concentrations and by extension the radon concentrations of the sedimentary rocks of southwestern Ontario. The Kettle Point formation is reported to have average U concentrations in excess of 30 ppm (Reichenbach, 1993), while the Marcellus formation is reported to have U concentrations that range between 8 and 53 ppm with some studies reporting concentrations in excess of 100 ppm (Banks, 2010a, b). In the absence of uranium data for individual formations other ancillary information was used to assign a relative and somewhat subjective score to each formation that reflected its estimated radon potential. This information included AGRS eU data from areas with relatively thin drift cover. It also

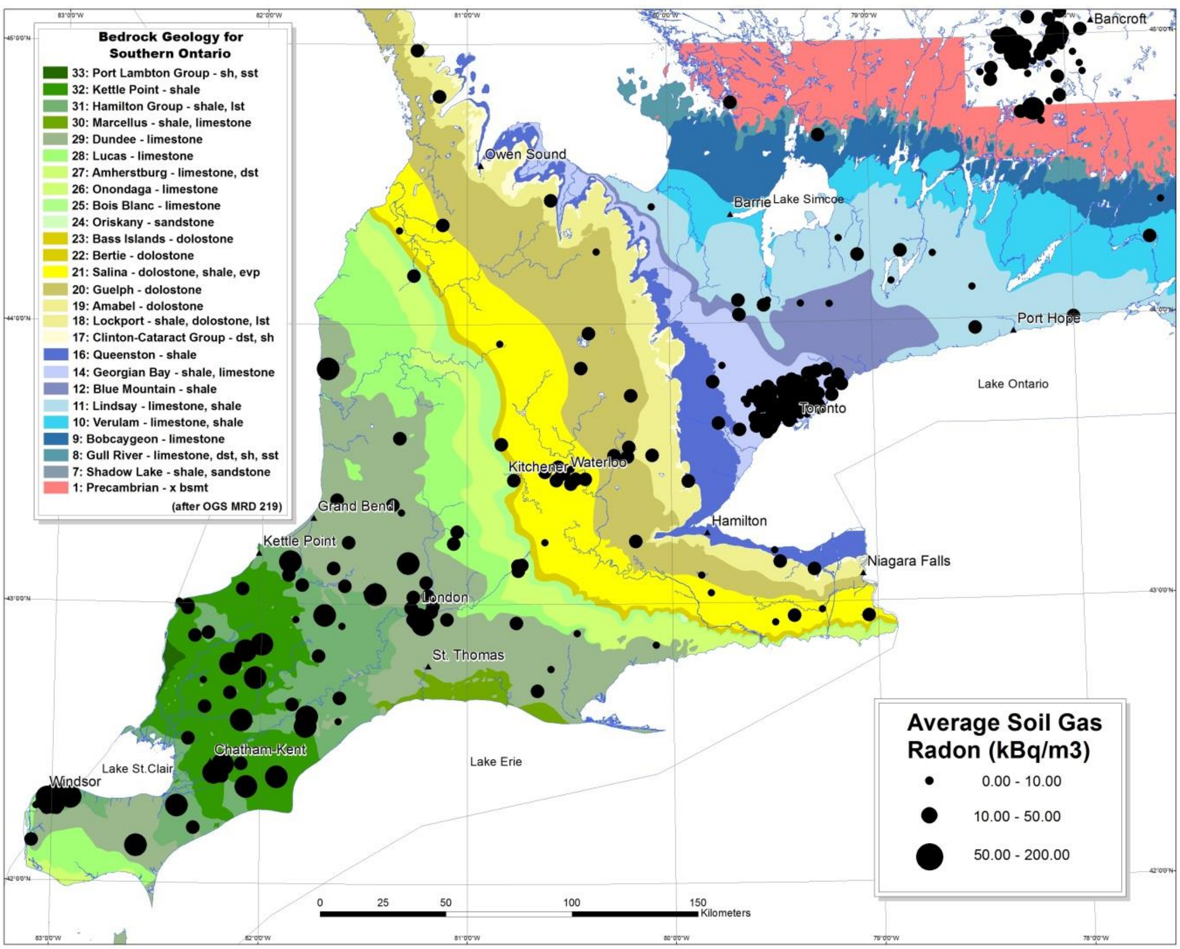

Figure 13: Bedrock geology of southwestern Ontario after Armstrong and Dodge (2007) with average soil gas radon concentrations (kBq/m^3) presented as 3 proportionally scaled symbols (<10; 10-50 and >50 kBq/m^3).

included a review of detailed lithological descriptions of each formation with a focus on attributes that might suggest an increased uranium content. Harrell et al (1991) showed a strong, positive, linear correlation between uranium and organic carbon contents for Ohio Shale samples from Ohio. Banks (2010a, b) showed a similar positive association between increasing U concentrations and increasing total organic content for the Marcellus formation. Therefore formations that had lithological descriptions which indicated an elevated organic content were assigned a slightly higher relative radon potential score than adjacent formations with no indication of organic content. Proximity to U-rich black shale sequences would also result in a slightly higher relative radon potential score.

Figure 13 shows the bedrock geology of southwestern Ontario along with average soil gas radon concentrations. Excluding the Bancroft area where high soil gas radon concentrations are likely associated with zones of uranium mineralization, the majority of high soil gas radon concentrations in the rest of southwestern Ontario are associated with or occur in close proximity to the black shales of the Kettle Point formation. Figure 14 shows the bedrock geology of southwestern Ontario grouped into 5 categories of relative estimated radon potential from Low (1) to High (5). Indoor radon concentrations are plotted on Figure 14 as three proportionally scaled symbols (<200, 200-400 and >400 Bq/m^3). Results of the comparison of indoor radon measurements with the estimated bedrock radon potential are shown in Table 2 and Figure 15. While not as clear of an association as is evident between the AGRS eU radon potential and indoor radon concentrations there still exists a generally positive association between estimated bedrock radon potential and an increasing percentage of homes with indoor radon concentrations in excess of 200 Bq/m^3. Figure 16 shows the box and whisker plots for the 5 categories of estimated bedrock radon potential.

2.5 Surficial Geology

Figure 17 shows the distribution of surficial deposits in southwestern Ontario compiled by the Ontario Geological Survey (2010). This figure was simplified from digital files available at http://www.geologyontario.mndm.gov.on.ca/mndmaccess/mndm_dir.asp?type=pub&id=MRD128-REV. The surficial geology is dominated by a variety of sand, silt and clay-rich tills (Barnett, 1992) shown by the various shades of green on Figure 17. In addition to these till deposits, various coarse textured glaciofluvial ice-contact and outwash deposits, and coarse and fine-textured glaciolacustrine deposits are also prevalent. The majority of high soil gas radon sites, shown by the larger dots on Figure 17, are associated with lobes of the Tavistock and Rannoch tills (Barnett, 1992) deposited over or in close proximity to the black shales of the Kettle Point formation. This may indicate that a significant component of these tills is locally derived. Several other high soil gas radon sites occur in coarse and fine-textured glaciolacustrine deposits that also occur over or near the Kettle Point formation. These high concentrations may reflect incorporation of black shale clasts and/or finer grained material into these reworked deposits. By comparison, soil gas radon concentrations at sites from the St. Joseph till, deposited over the Kettle Point formation (Barnett, 1992) between Sarnia and Kettle Point are lower compared to most similarly situated sites from the Tavistock and Rannoch tills. AGRS eU concentrations are also lower in this same area which may reflect lower amounts of Kettle Point black shale material incorporated into these tills or dilution with material transported from other, low uranium sources.

Studies have shown (Neznal et al, 2004, Chen et al, 2008) that soil permeability is an important factor in the assessment of indoor radon potential as it influences the flux of radon from the soil into the atmosphere, and from the soil into homes. The OGS compilation of the surficial geology for southwestern Ontario includes estimates of the relative permeability for the various deposit types. Figure 18 shows the distribution of this estimated permeability grouped into 5 categories of increasing radon potential from Low that was assigned a score of 1 to High that was assigned a score of 5. Indoor radon concentrations are plotted on Figure 18 as three proportionally scaled symbols (<200, 200-400 and >400 Bq/m^3). The majority of tills and the fine-textured glaciolacustrine deposits were assigned an estimated

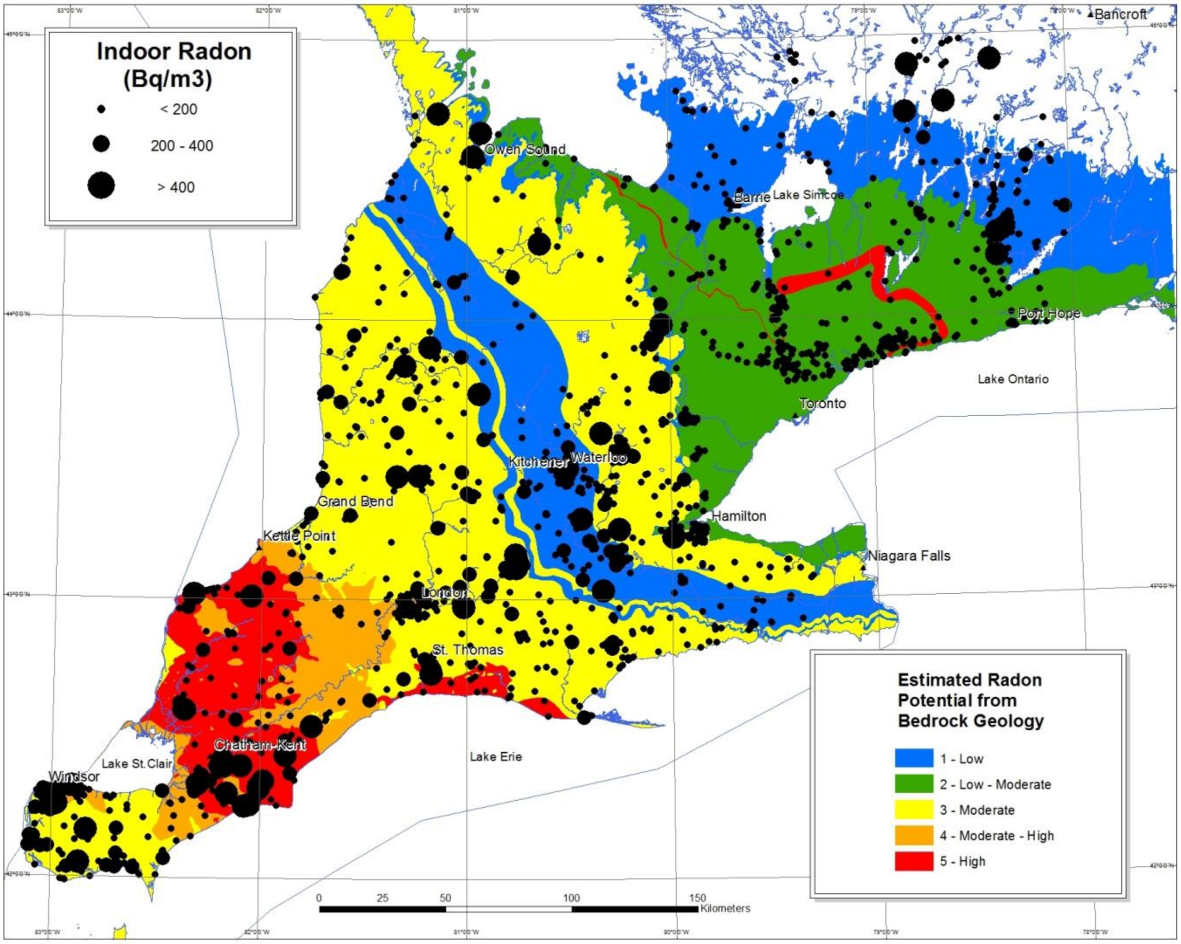

Figure 14: Estimated radon potential map derived from the bedrock geology for southwestern Ontario. Radon potential classified into 5 categories of increasing relative potential with scores of 1 to 5 (1 - low, 2 - low-moderate, 3 - moderate, 4 - moderate-high, and 5 - high). Indoor radon concentrations presented as 3 proportionally scaled symbols (<200; 200-400 and >400 Bq/m^3).

Table 2: Comparison of estimated radon potential derived from bedrock geology with indoor radon data (Bq/m^3) for southwestern Ontario.

Rn Pot (Est)	% Total Area	# of Homes	# > 200 (Bq/m^3)	% > 200 (Bq/m^3)	Mean Indoor Rn (Bq/m^3)	Median Indoor Rn (Bq/m^3)
1 (Low)	24.1	404	25	6.2	72.8	37
2 (Low-Mod)	17.4	344	4	1.2	43.3	26
3 (Mod)	43.1	941	95	10.1	88.9	60
4 (Mod-High)	6.1	139	14	10.1	107.9	72
5 (High)	9.1	285	43	15.1	117.7	78

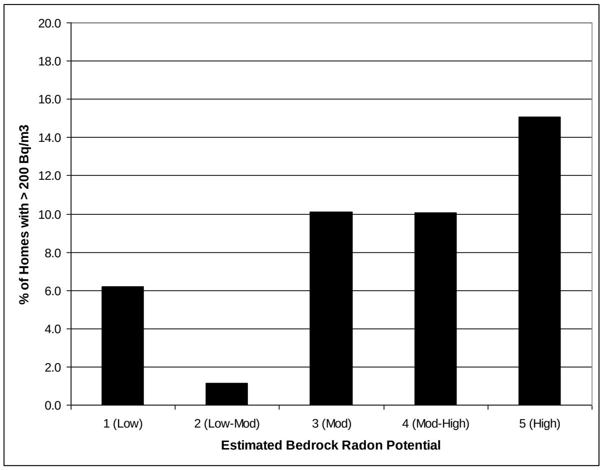

Figure 15: Percentage of homes with greater than 200 Bq/m^3 compared with the estimated radon potential derived from the bedrock geology for southwestern Ontario.

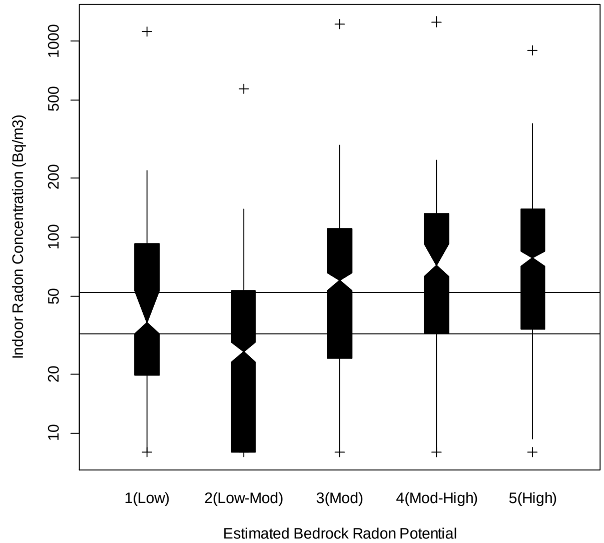

Figure 16: Box and whisker plots comparing indoor radon concentrations with the estimated radon potential derived from the bedrock geology for southwestern Ontario.

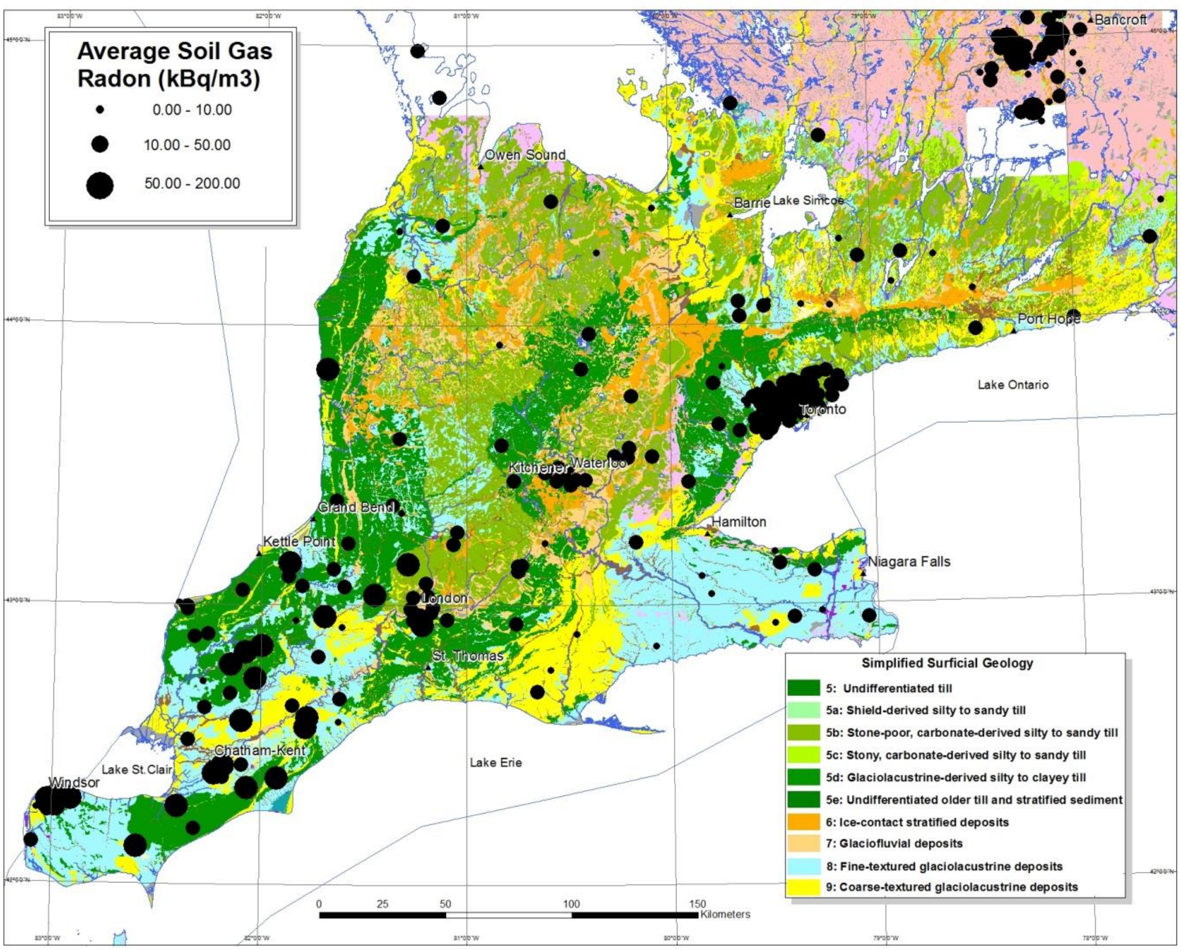

Figure 17: Surficial geology of southwestern Ontario derived from the Ontario Geological Survey (2010) with average soil gas radon concentrations (kBq/m^3) presented as 3 proportionally scaled symbols (<10; 10-50 and >50 kBq/m^3).

permeability of either low or low-moderate. The ice-contact, glaciofluvial and coarse-textured glaciolacustrine deposits were assigned a high permeability. The OGS compilation included a 6th category of estimated relative permeability classified as variable. Most of this category occurs over the Precambrian terrain north of Lake Simcoe and was arbitrarily assigned a moderate permeability score of 3. In areas south and west of Lake Simcoe deposits with this variable ranking were reclassified according to the primary material type. Deposits with clay as the primary material were reclassified with a low permeability, and deposits with sand as the primary material were reclassified with high permeability.

Results of the comparison of indoor radon measurements with the radon potential estimated from increasing relative permeability are shown in Table 3 and Figure 19. The majority of surficial deposits in southwestern Ontario are classified with either low or low-moderate, or high permeability. This is reflected in the percentage of the total area shown in Table 3. Due to the low number of homes located in areas with moderate or moderate-high permeability no further calculations were made. The percentage of homes with greater than 200 Bq/m^3 is only slightly higher in areas of high permeability than that for areas with low permeability. Figure 20 indicates that there is little statistical difference between the 3 categories with sufficient sample populations.

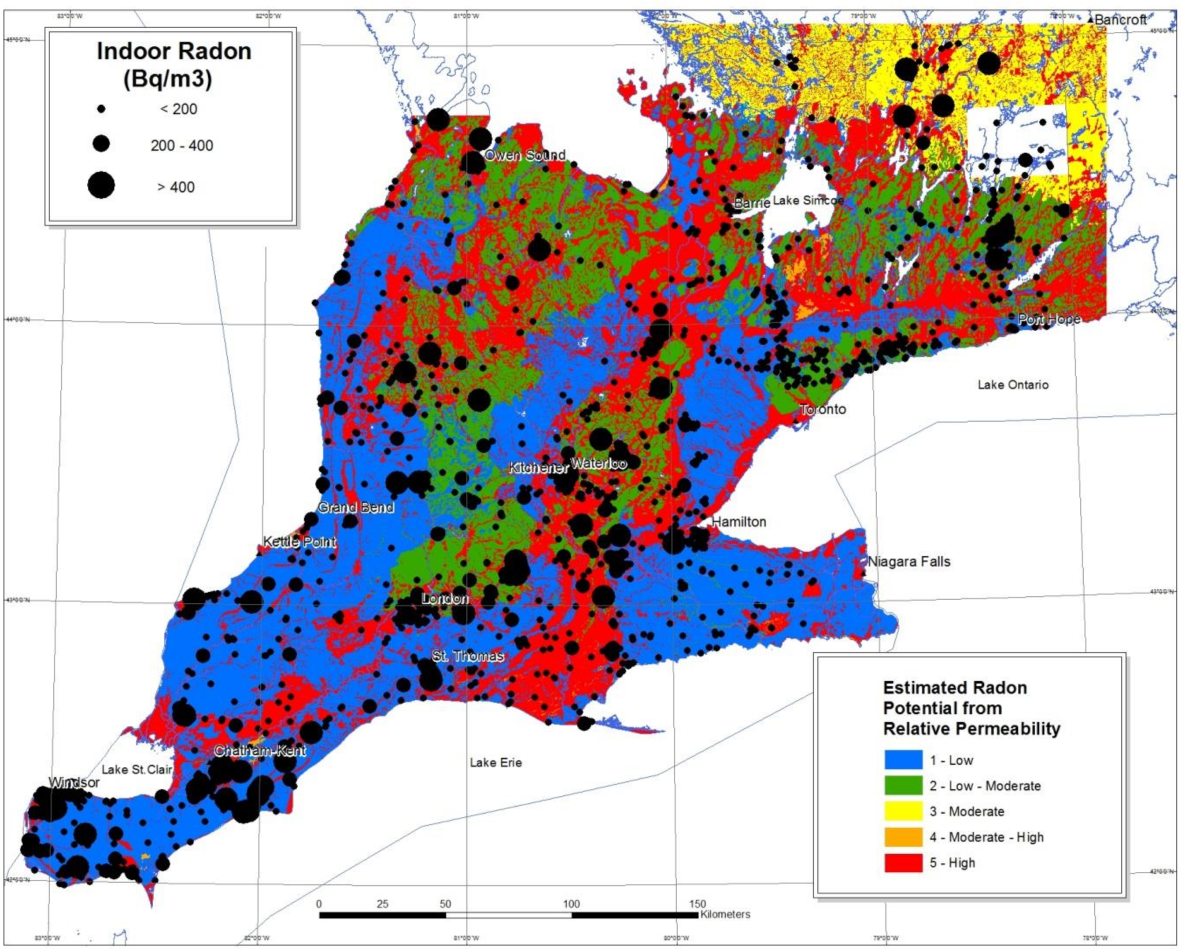

Figure 18: Estimated radon potential derived from the relative permeability of the different surficial geology units for southwestern Ontario. Radon potential was classified into 5 categories of increasing relative potential with scores of 1 to 5 (1 - low, 2 - low-moderate, 3 - moderate, 4 - moderate-high, and 5 - high). Indoor radon concentrations presented as 3 proportionally scaled symbols (<200; 200-400 and >400 Bq/m^3).

Table 3: Comparison of estimated radon potential derived from the relative permeability of the different surficial geology units with indoor radon data (Bq/m^3) for southwestern Ontario.

Rn Pot (Est)	% Total Area	# of Homes	# > 200 (Bq/m^3)	% > 200 (Bq/m^3)	Mean Indoor Rn (Bq/m^3)	Median Indoor Rn (Bq/m^3)
1 (Low)	36.3	825	71	8.6	82.7	47
2 (Low-Mod)	18.7	447	26	5.8	76.1	42
3 (Mod)*	8.3**	3	1			
4 (Mod-High)*	0.4	13	1			
5 (High)	36.4	845	85	10.1	93.0	56

* Insufficient sample population to calculate percentages.
** Includes variable ranking from Precambrian terrain north of Lake Simcoe.

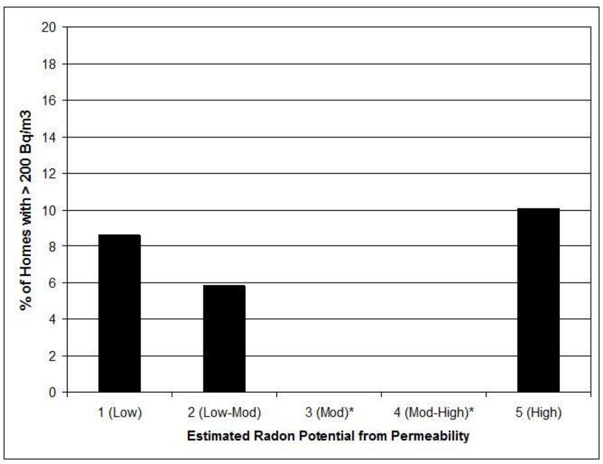

Figure 19: Percentage of homes with greater than 200 Bq/m^3 compared with the estimated radon potential derived from the relative permeability of the different surficial geology units for southwestern Ontario. * Insufficient sample population to calculate percentages.

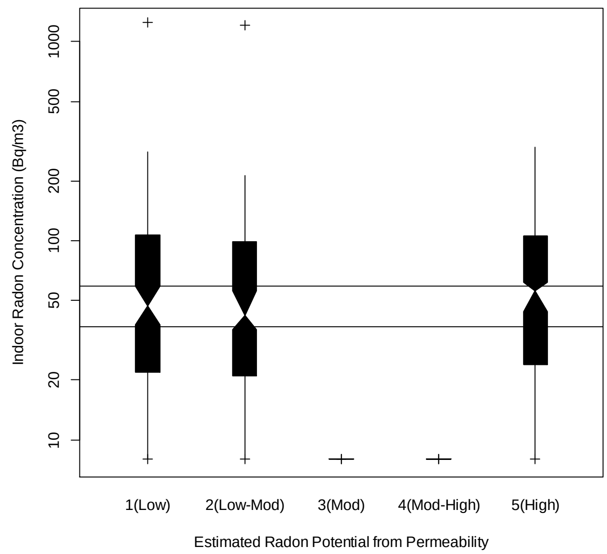

Figure 20: Box and whisker plots comparing indoor radon concentrations with the estimated radon potential derived from the relative permeability of the different surficial geology units for southwestern Ontario.

3. Combined Radon Potential Map using AGRS eU, Bedrock and Relative Permeability Data

A GIS-based approach was used to integrate and model digital information for the AGRS eU, bedrock and surficial (relative permeability) geology datasets, and to produce a combined radon potential map for southwestern Ontario. Similar approaches have recently been used to produce radon potential maps of the Oslofjord region in southern Norway (Smethurst et al, 2008) and for the Province of Nova Scotia (O'Reilly et al, 2013). The southwestern Ontario region is ideally suited for using this GIS approach as it has available recent seamless compilations of bedrock and surficial geology available from the Ontario Geological Survey and complete coverage with recently acquired AGRS and indoor radon data.

Each input dataset was ranked individually into 5 categories, from low to high, of estimated radon potential. The bedrock and surficial geology information was rasterized with the same origin and cell size as the AGRS eU data. The estimated radon potential score for each cell from each dataset was summed to produce a cumulative score from 3 to 15. Cells that returned summed scores less than 3 were considered to include a null value from one of the three input datasets and were ignored. Table 4 and Figure 21 show the results of the summation of the individual cell scores from each of the input datasets compared with the indoor radon measurements. Due to an insufficient number of indoor measurements, scores for categories 3, 14 and 15 were included with adjacent categories.

Other radon potential studies (Smethurst et al, 2008; O'Reilly et al, 2013) have utilized 3 categories of estimated potential, generally low, moderate and high. For clarity, the 10 categories of radon potential presented in Table 4 and Figure 21 were regrouped into 3 categories of low, moderate and high potential that corresponds to a percentage of homes with greater than 200 Bq/m^3 of less than 5%, 5% to 10%, and the first occurrence of a category with greater than 10%. Table 5 and Figure 22 show results of this clarified regrouping and comparison with indoor radon measurements. Figure 23 shows a simple box and whisker plot for the 3 categories of estimated radon potential and indicates that each category is statistically distinct. Figure 24 shows the radon potential map for southwestern Ontario using the 3 regrouped categories of low, moderate and high.

Table 4: Cumulative Radon Potential Score derived from addition of individual cell scores for 3 input datasets (AGRS eU, Bedrock and Relative Permeability) vs Indoor Radon (Bq/m^3). Colour coding for "Rn Pot (Est)" corresponds to regrouped categories in Table 5 and Figure 19.

Rn Pot (Est)	% Total Area	# of Homes	# > 200 (Bq/m^3)	% > 200 (Bq/m^3)	Mean Indoor Rn (Bq/m^3)	Median Indoor Rn (Bq/m^3)
3-4 (Low)	6.8	122	4	3.3	55	30
5 (Low)	10.9	213	8	3.8	58	33
6 (Mod)	17.5	349	23	6.6	66	32
7 (Mod)	18.4	345	28	8.1	84	57
8 (Mod)	14.1	321	22	6.9	90	59
9 (High)	13.0	246	32	13.0	100	70
10 (High)	11.8	236	24	10.2	91	60
11 (High)	4.8	102	15	14.7	100	64
12 (High)	1.7	82	7	8.5	87	72
13-15 (High)	1.0	99	18	18.2	135	79

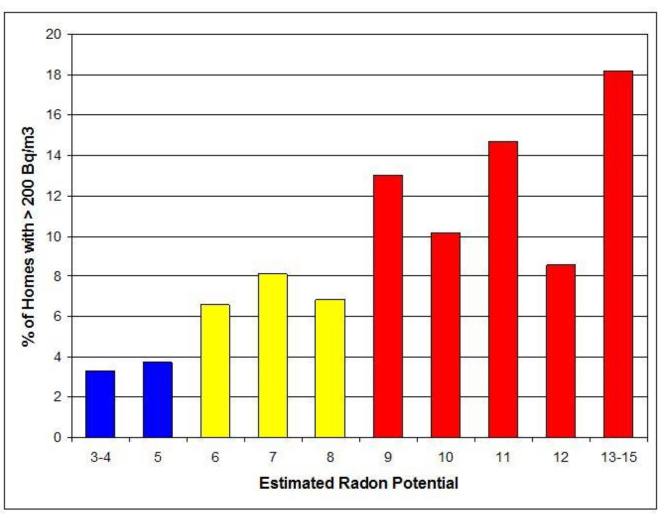

Figure 21: Percentage of homes with greater than 200 Bq/m^3 compared with the estimated radon potential derived from addition of individual cell scores for the 3 input datasets (AGRS eU, Bedrock and Relative Permeability) for southwestern Ontario.

Table 5: Cumulative Radon Potential Score regrouped into 3 categories of radon potential derived from addition of individual cell scores for the 3 input datasets (AGRS eU, Bedrock and Relative Permeability) vs Indoor Radon (Bq/m^3). Colour coding for "Rn Pot (Est)" corresponds to categories in Table 4 and Figure 18.

Rn Pot (Est)	% Total Area	# of Homes	# > 200 (Bq/m^3)	% > 200 (Bq/m^3)	Mean Indoor Rn (Bq/m^3)	Median Indoor Rn (Bq/m^3)
Low	17.7	335	12	3.6	57	32
Moderate	50.0	1015	73	7.2	80	43
High	32.3	765	96	12.5	101	69

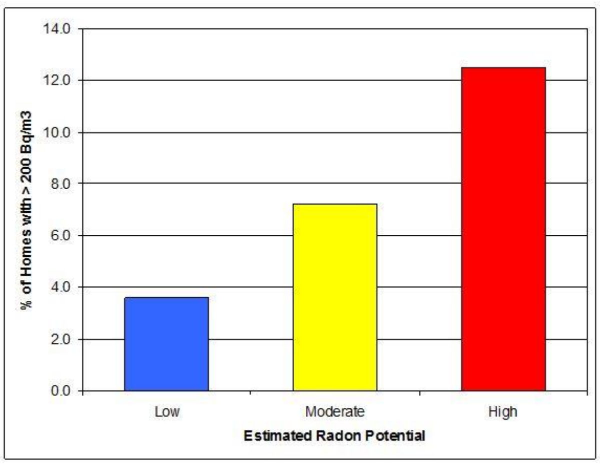

Figure 22: Percentage of homes with greater than 200 Bq/m^3 compared with the estimated radon potential derived from addition of individual cell scores for the 3 input datasets (AGRS eU, Bedrock and Relative Permeability) regrouped into 3 categories.

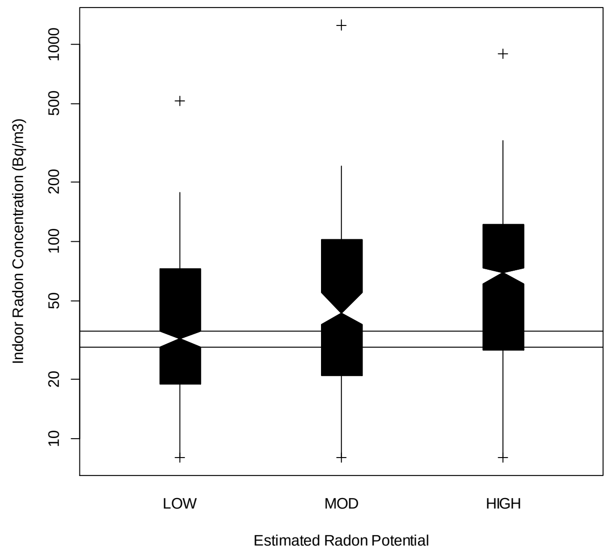

Figure 23: Box and whisker plots comparing indoor radon concentrations with the 3 categories of regrouped estimated radon potential derived from addition of individual cell scores for the 3 input datasets (AGRS eU, Bedrock and Relative Permeability) for southwestern Ontario.

4. Combined Radon Potential Map using AGRS eU and Bedrock Geology

While permeability is an important factor to consider when assessing the radon potential of a particular site (Neznal et al, 2004), results of the comparison of indoor radon values with the estimated radon potential derived from the relative permeability of surficial materials for southwestern Ontario are unclear (see Table 3 and Figure 20). Because of this a second radon potential or radon risk map was prepared using only the estimated radon potential scores for the AGRS eU and bedrock geology datasets. Results of the comparison of indoor radon measurements with this second estimated radon potential are shown in Table 6 and Figure 25. Using only 2 input datasets results in radon potential scores that range between 2 and 10. Again for clarity these 9 categories were regrouped into 3 categories of low, moderate and high radon potential. Based on a simple visual examination of the percentage of homes with greater than 200 Bq/m^3 of indoor radon categories 2, 3 and 4 were assigned a low radon potential, categories 5, 6 and 7 were assigned a moderate radon potential, and categories 8, 9 and 10 were assigned a high radon potential. Table 7 and Figure 26 show the results of regrouping of the 9 categories of radon potential derived from using only the AGRS eU and bedrock geology into 3 categories. Figure 27 shows a simple box and whisker plot for the 3 categories of estimated radon potential and indicates again that each category is statistically distinct. Figure 28 shows this second radon potential map for southwestern Ontario as low, moderate or high.

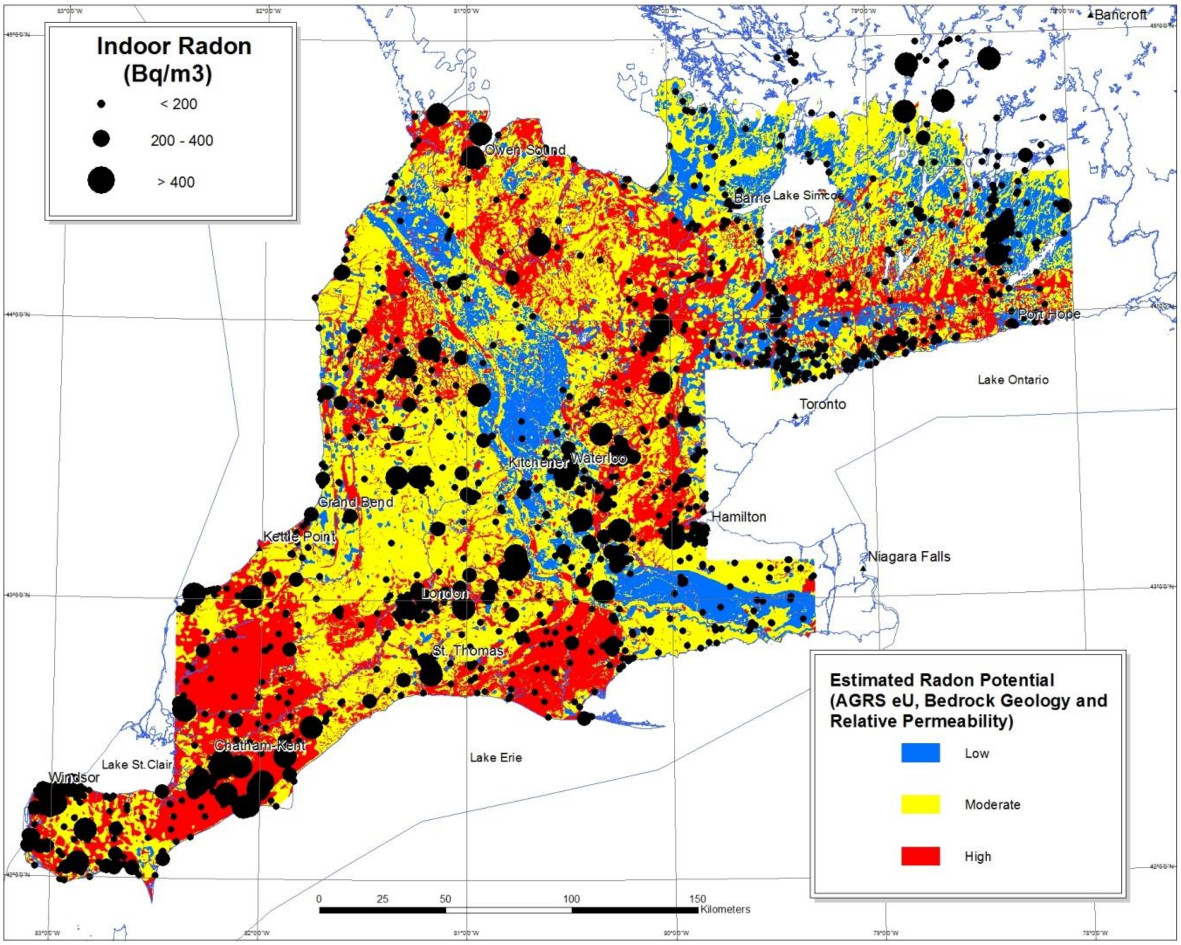

Figure 24: Estimated radon potential map for southwestern Ontario derived from addition of individual cell scores for 3 input datasets (AGRS eU, Bedrock and Relative Permeability) with indoor radon (Bq/m^3) concentrations presented as 3 proportionally scaled symbols (<200; 200-400 and >400 Bq/m^3).

Table 6: Cumulative Radon Potential Score derived from addition of individual cell scores for 2 input datasets (AGRS eU and Bedrock Geology) vs Indoor Radon (Bq/m^3). Colour coding for "Rn Pot (Est)" corresponds to regrouped categories in Table 7 and Figures 22.

Rn Pot (Est)	% Total Area	# of Homes	# > 200 (Bq/m^3)	% > 200 (Bq/m^3)	Mean Indoor Rn (Bq/m^3)	Median Indoor Rn (Bq/m^3)
2	7.2	105	6	5.7	62	32
3	17.7	310	17	5.5	72	34
4	21.1	421	21	5.0	62	33
5	28.8	569	51	9.0	82	43
6	12.7	283	27	9.5	90	61
7	5.6	206	15	7.3	95	74
8	3.9	172	30	17.4	117	82
9	1.7	33	8	24.2	190	119
10	1.4	21	6	28.6	202	134

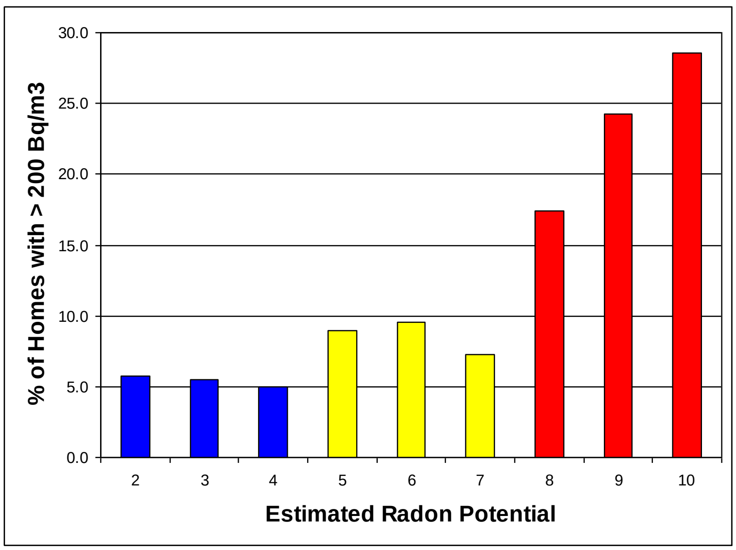

Figure 25: Percentage of homes with greater than 200 Bq/m^3 compared with the estimated radon potential derived from addition of individual cell scores for 2 input datasets (AGRS eU and Bedrock Geology) for southwestern Ontario.

Table 7: Cumulative Radon Potential Score derived from addition of individual cell scores for 2 input datasets (AGRS eU and Bedrock Geology) regrouped into 3 categories of radon potential vs Indoor Radon (Bq/m^3). Colour coding for "Rn Pot (Est)" corresponds to categories in Table 6 and Figure 22.

Rn Pot (Est)	% Total Area	# of Homes	# > 200 (Bq/m^3)	% > 200 (Bq/m^3)	Mean Indoor Rn (Bq/m^3)	Median Indoor Rn (Bq/m^3)
Low	46.0	836	44	5.3	66	34
Moderate	47.1	1073	93	8.7	87	59
High	7.0	226	44	19.5	136	85

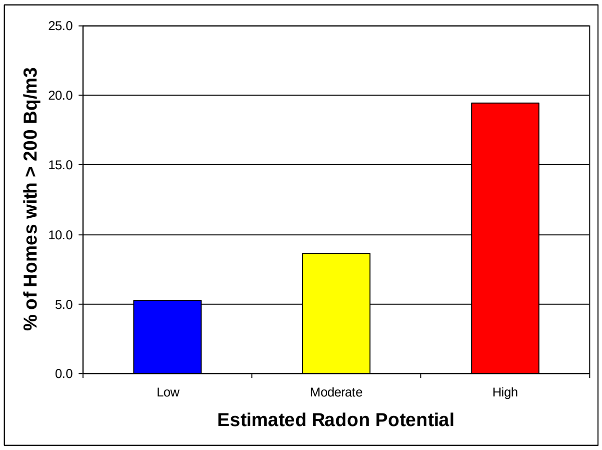

Figure 26: Percentage of homes with greater than 200 Bq/m^3 compared with the estimated radon potential derived from addition of individual cell scores for 2 input datasets (AGRS eU and Bedrock Geology) for southwestern Ontario regrouped into 3 categories.

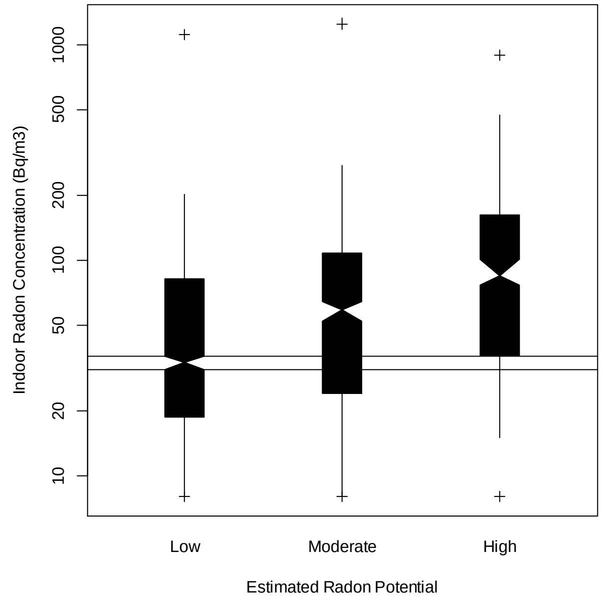

Figure 27: Box and whisker plots comparing indoor radon concentrations with the 3 categories of regrouped estimated radon potential derived from addition of individual cell scores for 2 input datasets (AGRS eU and Bedrock Geology) for southwestern Ontario.

5. Discussion

Analysis of regional AGRS, bedrock and surficial geoscience data shows varying degrees of association from strongly positive to inconclusive, between an increasing estimated radon potential for each dataset and an increasing percentage of homes with elevated indoor radon concentrations.

Analysis of the AGRS eU data and the indoor radon measurements for southwestern Ontario reveals a strong positive association between increasing eU concentrations and the percentage of homes with increasing radon concentrations. Areas with AGRS eU concentrations of 2 ppm and above were assigned a “High” ranking. These areas encompass only slightly more than 3% of the study area yet over 17% of homes in these areas had indoor radon concentrations above 200 Bq/m^3, the highest of any category. Areas with AGRS eU concentrations of 1 ppm and above (moderate to high) encompass almost 25% of the study area. Almost 12% of homes in these areas have indoor radon concentrations that exceed 200 Bq/m^3. As expected, the lowest percentage of homes with indoor radon concentrations that exceed 200 Bq/m^3 at 7.2%, occurs in areas where the AGRS eU concentrations are less than 1 ppm. These results are generally consistent with results reported by Doyle et al, (1990) for the Maniwaki area in western Quebec where they found that trends for increasing radon in homes essentially paralleled those for increasing AGRS eU concentrations.

AGRS measurements can vary significantly from region to region due predominantly to variations in rock types and variations in types and composition of glacial deposits. Other factors that will contribute to variations in radioelement signatures include soil moisture and vegetation cover. For these reasons the actual AGRS eU concentrations utilized for estimating indoor radon potential will also vary from region to region. For example, Smethurst et al, (2008) reported that in the Oslo area of Norway, 20-40% of homes had indoor radon concentrations above 200 Bq/m^3 for AGRS eU concentrations between 3.5 and 6 ppm. This increased to greater than 40% for areas with AGRS eU concentrations greater than 6

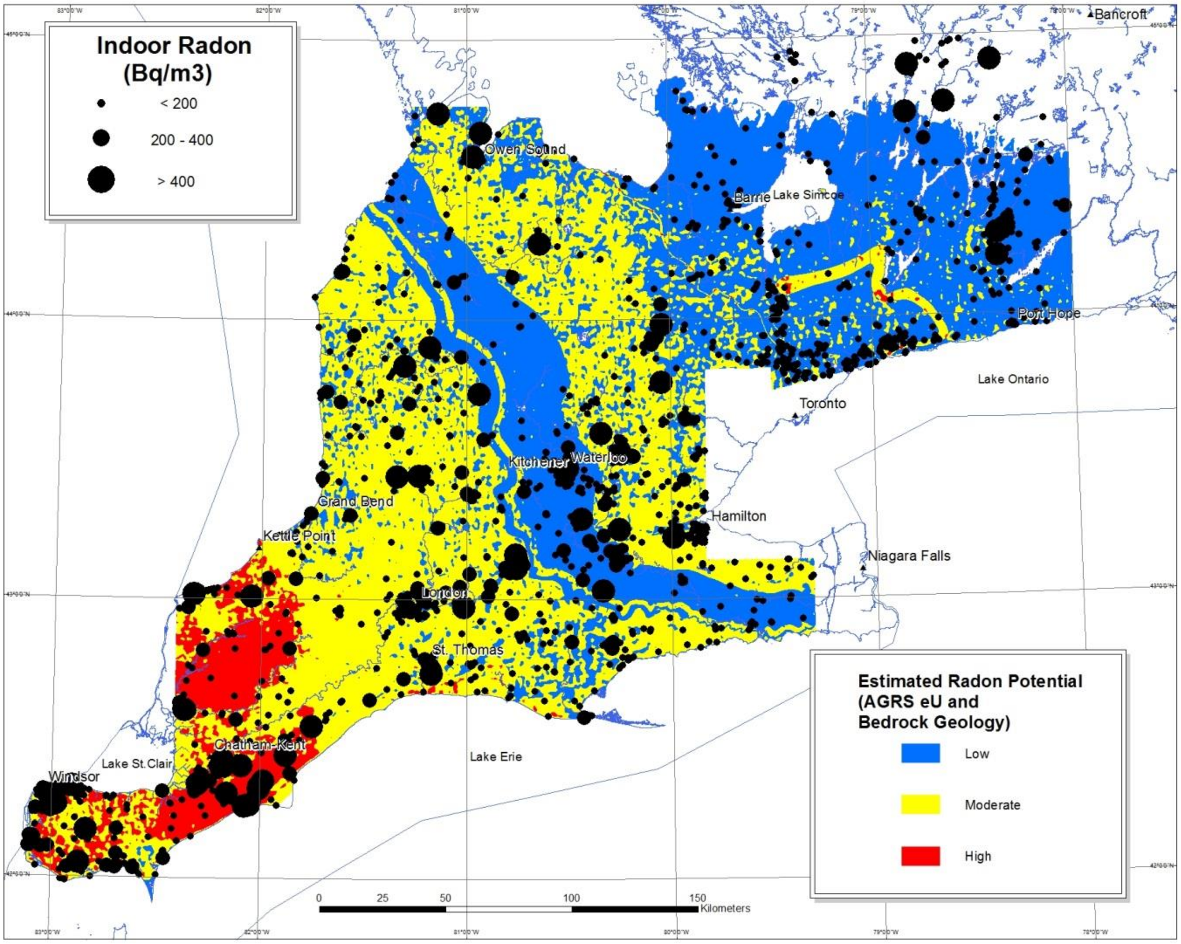

Figure 28: Estimated radon potential map for southwestern Ontario derived from addition of individual cell scores for 2 input datasets (AGRS eU and Bedrock Geology) with indoor radon (Bq/m^3) concentrations presented as 3 proportionally scaled symbols (<200; 200-400 and >400 Bq/m^3).

ppm. If available, AGRS data is a valuable dataset to estimate the indoor radon potential of any given region. However, its application might be considered an indirect one (IAEA, 2003). This is because the majority of the gamma radiation measured originates in the top 25 to 30 cm of the surface. Most radon that enters homes is likely sourced from depths greater than these shallow depths encountered for sources of gamma radiation measured by an AGRS survey. Despite this limitation regional indoor radon evaluations often show a good positive association between AGRS eU data and a higher proportion of homes with elevated indoor radon concentrations greater than 200 Bq/m^3.

The distribution of indoor measurements may also play a role in the actual AGRS eU concentration values utilized. An uneven distribution of indoor measurements may result in much higher percentages of homes occurring at higher eU concentrations if the indoor measurements were targeted to specific areas (Ford et al, 2001) or the distribution of homes is naturally uneven. The Health Canada indoor radon measurements included a significant number of measurements from urban areas. AGRS measurements from urban areas often trend to lower concentrations due to the larger amounts of low radioactivity construction and road material and the subsequent masking effects of this material. Such an effect may decrease the relative percentage of homes with greater than 200 Bq/m3 in high AGRS eU areas and increase the percentage in low AGRS eU areas.

Black shales are often high in uranium (Reichenbach, 1993) and therefore would usually be assigned a high estimated radon potential. In southwestern Ontario black shales of the Kettle Point and Marcellus formations are both confirmed in published reports (Reichenbach, 1993; Banks, 2010a, b) to have elevated uranium concentrations and were therefore assigned a high radon potential score. Black shales of the Collingwood member of the Lindsay formation were also assigned a high estimated radon potential score. However no direct uranium analysis could be found to confirm this. All other rock types were assigned lower relative rankings based on proximity to the black shale formations, AGRS eU concentrations in thinly drift covered areas or other, somewhat subjective, indicators of radon potential such as organic content (Banks, 2010a, b).

Analysis of the estimated radon potential derived from the bedrock geology and the indoor radon measurements (Table 2, Figures 15 and 16) show a generally positive association. Of the three black shale units that were assigned a high estimated radon potential only the Kettle Point formation encompasses a large enough area to have a significant number of indoor measurements (256). The Marcellus formation and Collingwood member cover much smaller areas and have an insufficient number of indoor measurements, 14 and 15 respectively, to properly verify their estimated radon potential separately. Only one of the 29 indoor measurements over the Marcellus and Collingwood units exceeded 200 Bq/m^3. A contributing factor for the low number of elevated indoor radon concentrations include very thick drift cover (Gao et al, 2006), in excess of 200 metres over the Marcellus formation and parts of the Collingwood member. Such a thickness of drift cover would act as a barrier to direct radon migration from the underlying bedrock units. Total gamma well logs suggest indirectly that the Collingwood member of the Lindsay formation may not have similar, elevated uranium concentrations as the Kettle Point and Marcellus formations. These logs show no increase in total radioactivity that might suggest higher uranium concentrations compared to the overlying shales of the Blue Mountain formation or the underlying limestone and shales of the Lindsay formation. Most logs show a decrease in total gamma activity as they progress from the shales of the overlying Blue Mountain formation, through the black shales of the Collingwood member and into the shales and limestones of the Lindsay formation (Johnson et al, 1983; Churcher et al, 1991).

Areas with an estimated high radon potential, derived from the bedrock geology, encompass over 9% of southwestern Ontario. Over 15% of homes in these areas had indoor radon concentrations above 200 Bq/m^3. Areas with an estimated radon potential of moderate or higher encompass 58% of southwestern Ontario and have almost 84% of the homes (152 of 181 homes) that exceed 200 Bq/m^3. Areas that were assigned an estimated radon potential of moderate or higher occur west of the Niagara Escarpment in Paleozoic rocks that are Silurian in age or younger. Compared to other recent regionally-scaled radon evaluations (Smethurst et al, 2008; O'Reilly et al, 2013) southwestern Ontario exhibits a limited range of geological diversity and only one rock type (black shale) with confirmed elevated uranium concentrations. Despite this limitation results show that estimating the radon potential from bedrock geology still provides important information. Additional analysis of uranium concentrations from bedrock formations other than the Kettle Point and Marcellus formations, either from type localities and/or diamond drill holes would likely refine and improve these analytical results.

Surficial deposits with a high permeability are generally associated with a high indoor radon potential (Neznal et al, 2004; Smethurst et al, 2008). Surficial deposits that were assigned a high relative permeability in the surficial geology of Southern Ontario (OGS, 2010) were assigned a high estimated radon potential for this study. Other surficial deposits were assigned scores that matched their relative permeability rankings in the OGS dataset. Results of the comparison (Table 3, Figures 19 and 20) of the estimated radon potential derived from relative permeability with the indoor radon concentrations for southwestern Ontario suggest that variations in relative permeability have little effect on the regional indoor radon distribution patterns. This is consistent with results reported by Doyle et al, (1990). Locally however this may not always be the case. For example, in southwestern Ontario south of Kitchener-Waterloo there is a cluster of indoor radon measurements that exceed 200 Bq/m^3. This cluster occurs in an area with generally low or low-moderate AGRS eU concentrations and is associated with dolostones, shales and evaporites of the Salina formation that were assigned a low estimated bedrock radon potential. However, this cluster of elevated indoor radon concentrations is coincident with an area of highly permeable glaciofluvial deposits. Grasty (1989) also links high indoor radon concentrations to local enhancement of permeability caused by fracturing of glaciolacustrine clays in the Winnipeg area.

Harrell et al, (1991) and Tilsley and Baker (1992) suggest that factors other than permeability, including thickness and composition play an important role in estimating the radon potential of a particular area. Harrell et al, (1991) state that overburden will act as a barrier to radon migration if it is thick or of low permeability. Locally this appears to be the case in southwestern Ontario. For example, a visual comparison of the drift thickness map (OGS, 2010) for southwestern Ontario with the indoor radon distribution patterns indicates that several of the areas with consistently low indoor radon concentrations occur in areas with particularly thick yet permeable overburden. These include the area south of London along the shore of Lake Erie, and an area from Barrie, south to Markham and east towards the Kingston/Napanee area north of the shore of Lake Ontario. In some areas where other indicators would suggest there should be a higher number of homes with elevated indoor radon concentrations such as over the uranium-bearing black shales of the Marcellus formation south of London, there are very few homes with indoor radon concentrations that exceed 200 Bq/m^3. This is likely the result of the very thick, in excess of 200m, deposits of coarse and fine textured glaciolacustrine material. Harrell et al, (1991) also suggests that the overburden can also act as a source of radon if it contains an abundance of uranium bearing material. Again, locally in southwestern Ontario this appears to be the case. For example, over the poorly exposed uranium-bearing black shale of the Kettle Point formation north and south of Chatham. Material derived from the Kettle Point formation and incorporated into the glacially derived tills and reworked glaciolacustrine deposits may also explain the distribution of elevated indoor radon concentrations southwest of Chatham towards Windsor. Tilsley and Baker (1992), note that some strong soil gas radon anomalies occur above or in close proximity to known oil and gas fields in southwestern Ontario. This may explain some of the isolated high indoor radon concentrations that occur away from known or expected areas of high soil gas concentrations.

Combining the estimated radon potential scores from the individual datasets into a single radon potential map provides clarity. Smethurst et al (2008) noted that while each dataset may have its own shortfalls or limitations, combining the information into a single map may mitigate each dataset's individual weaknesses. They use the model that if any one of the input datasets indicates a high radon potential then that point on the combined map is assigned a high potential. Combining the estimated radon potentials from AGRS eU, bedrock geology and relative permeability for southwestern Ontario into a single radon potential map (Figure 24) results in 32% of the area having a combined radon potential of "High" (Table 5). Of the 765 indoor measurements in these "high" areas only 96 or 12.5% had indoor concentrations that exceeded 200 Bq/m^3. Validating the individual input datasets separately to assess their relative significance may indicate that some datasets add little to the regional radon potential assessment. This appears to be the case in southwestern Ontario. Given the generally poor association between relative permeability and the percentage of indoor radon values that exceed 200 Bq/m^3 a second combined radon potential map was made using the estimated radon potentials from only AGRS eU and bedrock geology (Figure 28). Using only the AGRS eU and bedrock geology as input datasets for a combined radon potential map results in a smaller area having a "High" radon potential (7%) compared to that using the 3 input datasets (32%). However, the percentage of homes with indoor radon concentrations in excess of 200 Bq/m^3 increases from 12.5% to almost 20% if you remove relative permeability as an input dataset (Table 6).

6. Conclusion

Analysis of the AGRS, bedrock and surficial geology (relative permeability) data for southwestern Ontario with indoor radon measurements reveal associations that range from strongly positive in the case of AGRS eU data to weak in the case of relative permeability. The positive associations between the estimated radon potential and a higher percentage of homes with indoor radon concentrations that exceed 200 Bq/m^3 demonstrates the effectiveness of some regional geoscience datasets as a predictive tool for the identification of areas prone to elevated indoor radon concentrations. These positive associations may allow public health officials to better evaluate areas or regions with elevated radon potential including areas with little or no residential development thereby supporting more detailed studies and future land-use planning decisions and make more effective use of limited resources.

Results show that the estimated radon potential from different geoscience datasets can be combined to produce a single radon potential map. This single map shows a positive association between increasing estimated radon potential and a higher proportion of homes with elevated indoor radon concentrations. However to properly assess the contributions from each dataset it is important to evaluate them independently of each other before combining into a single map. If one of the datasets provides little or no improvement, as appears to be the case for relative permeability in southwestern Ontario, including it in further analysis may unnecessarily increase the size of the area of high potential and/or lower the percentage of homes in excess of 200 Bq/m^3 making these areas statistically less distinct from other lower potential areas. If the intent is to use these assessments to guide additional follow-up studies then having a more reliable assessment of the areas with high potential should result in more effective use of limited resources.

Despite the restricted range of AGRS eU concentrations and limited bedrock variability analysis showed that areas with increased radon potential could be delineated and verified by existing indoor radon data. Results suggest that some, regionally consistent datasets are of value in predicting regional variations in indoor radon concentrations. Care however may be warranted when using such datasets at more local scales where other factors may limit effectiveness. Estimating radon potential from geoscience data can be used to support future land-use planning decisions and to guide future targeted follow-up studies by making more effective use of limited resources. However no areas should be excluded from indoor radon testing even if they receive a low estimated potential, since indoor radon levels cannot be predicted prior to home construction.

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