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Volume 28, numéro 2, juin 2001

URI : https://id.erudit.org/iderudit/geocan28_2art04

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Éditeur(s)

The Geological Association of Canada

ISSN

0315-0941 (imprimé)
1911-4850 (numérique)

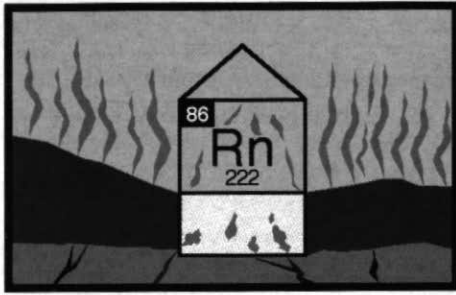
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Citer cet article

Ford, K. L., Savard, M., Dessau, J.-C., Pellerin, E., Charbonneau, B. W. & Shives, B. K. (2001). The Role of Gamma-ray Spectrometry in Radon Risk Evaluation: A Case History from Oka, Quebec. *Geoscience Canada*, 28(2), 59–64.

Résumé de l'article

Une augmentation des concentrations U mesurées lors d'un levé de spectrométrie gamma aéroporté, montre qu'il existe un lien clair et progressif avec l'augmentation des concentrations intérieures de radon, dans une région à proximité de la localité Oka au Québec. Les plus faibles concentrations moyennes intérieures en radon (106 Bq/m^3) sont associées aux concentrations U (1 ppm) les plus faibles, les plus fortes concentrations intérieures en radon ($1\,075 \text{ Bq/m}^3$) sont associées aux plus fortes concentrations U (6 ppm). Les résultats du levé de spectrométrie gamma aéroporté ont été utilisés par les autorités en santé publique pour repérer les endroits pouvant présenter des risques de surexposition au radon à l'intérieur d'aires habitées situées au droit et à proximité d'une intrusion de carbonate. Ce lien clairement établi entre les concentrations U et les concentrations intérieures élevées en radon dans les habitations a constitué une information de première importance dans bon nombre de projets d'affectation des terres ou ayant une composante en santé publique. Ce lien indéniable entre les fortes concentrations U mesurées par levé de spectrométrie gamma aéroporté et les fortes concentrations en radon montre que le levé de spectrométrie gamma aéroporté constitue un outil de repérage très efficace des zones présentant des risques de surexposition aux concentrations intérieures en radon, incluant les endroits sans projets de développement domiciliaire.



The Role of Gamma-ray Spectrometry in Radon Risk Evaluation: A Case History from Oka, Quebec

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SUMMARY

Increasing eU concentrations, as measured by an airborne gamma-ray spectrometry survey, show a progressive and clear association with increasing indoor radon concentrations for an area near Oka, Quebec. The lowest average indoor radon concentrations (106 Bq/m^3) are associated with the lowest average eU concentrations (1 ppm), and the highest average indoor radon concentrations (1075 Bq/m^3) are associated with the highest eU concentrations (6 ppm). The results of the airborne gamma-ray spectrometry survey were used by public health officials to identify specific areas within and near a carbonatite

intrusion where there is a risk of overexposure to indoor radon. The clear association between high eU concentrations and high radon in homes provided invaluable information for a number of land use and public health initiatives. The irrefutable association between high eU concentrations measured by airborne gamma-ray spectrometry and high radon concentrations makes airborne gamma-ray spectrometry a very effective predictive tool for the identification of areas with potential risk of overexposure to indoor radon, including areas without residential development.

RÉSUMÉ

Une augmentation des concentrations éU , mesurées lors d'un levé de spectrométrie gamma aéroporté, montre qu'il existe un lien clair et progressif avec l'augmentation des concentrations intérieures de radon, dans une région à proximité de la localité de Oka au Québec. Les plus faibles concentrations moyennes intérieures en radon (106 Bq/m^3) sont associées aux concentrations éU (1 ppm) les plus faibles et, les plus fortes concentrations intérieures en radon (1075 Bq/m^3) sont associées aux plus fortes concentrations éU (6 ppm). Les résultats du levé de spectrométrie gamma aéroporté ont été utilisés par les autorités en santé publique pour repérer les endroits pouvant présenter des risques de surexposition au radon à l'intérieur d'aires habitées situées au droit et à proximité d'une intrusion de carbonatite. Ce lien clairement établi entre les concentrations éU et les concentrations intérieures élevées en radon dans les habitations a constitué une information de première importance dans bon nombre de projets d'affectation des terres ou ayant une composante en santé publique. Ce lien indéniable entre les fortes concentrations éU mesurées par levé de spectrométrie gamma aéroporté et les fortes concentrations en radon montre que le levé de spectrométrie gamma aéroporté constitue un outils de repérage très efficace des zones présentant des risques de surexposition aux concentrations intérieures en radon, incluant les endroits sans projets de développement domiciliaire.

INTRODUCTION

Since 1967, through its National Gamma-Ray Spectrometry Program (NATGAM),

the Geological Survey of Canada (GSC) has been mapping natural and anthropogenic radioactivity, using aerial and field-portable gamma-ray spectrometers. Data from this program accurately depict variations in concentrations of potassium, uranium, thorium, and other radioactive elements in the ground, as an aid to geological mapping, mineral exploration, environmental radiation monitoring, and land use planning.

Radon (Rn^{222}) is a naturally occurring colourless, odourless, and tasteless radioactive gas produced by the radioactive decay of uranium (U^{238}) found as a trace element in most rocks, soil, and water. Studies in Canada (Letourneau *et al.*, 1984; Cocksedge *et al.*, 1993; Jackson 1992; Doyle *et al.*, 1990), the United States (Otton *et al.*, 1995), Sweden (Akerblom 1995), and Great Britain (Ball *et al.*, 1995) have shown that the ground concentration of uranium determined using an airborne gamma-ray spectrometer provides a qualitative, first-order approximation of regional variation in indoor radon levels and can be used to identify and outline high-risk areas.

Airborne gamma-ray spectrometry (AGRS) data from NATGAM archives have been used to evaluate risk of overexposure to radon at national (Cocksedge *et al.*, 1993), regional (Jackson, 1992), and local (Doyle *et al.*, 1990) scales. Cocksedge *et al.* (1993) reported results of a Canada-wide study conducted for the Department of Health and Welfare Canada, to assess the potential risks from radon in homes within aboriginal communities. To test the usefulness of regional geoscience data in this context, the GSC used airborne gamma-ray spectrometry, bedrock and surficial geology, and geochemistry to evaluate radon potential. This resulted in the identification of 41 aboriginal communities that were likely to have high radon potential. Of the remaining communities, 16 were selected as representing those with low potential. Subsequent testing revealed that no homes in communities with low radon potential exceeded 400 Bq/m^3 or half of the Health Canada guideline of 800 Bq/m^3 above which remediation actions are recommended; 42 out of 740 homes (5.6%) in high-potential communities exceeded this level. In communities with high radon potential, 1% of the homes measured

exceeded 800 Bq/m³. Based on these results Health and Welfare Canada initiated a follow-up program to measure radon concentrations in all aboriginal communities where homes were likely to exceed 800 Bq/m³.

In the Province of Nova Scotia, Jackson (1992) demonstrated good correlation between the percentage of homes in selected communities with average radon concentrations above 74, 148, and 370 Bq/m³ (2, 4, and 10 pCi/L) and corresponding average equivalent uranium (eU) concentrations determined by airborne gamma-ray spectrometry. The term "equivalent" or its abbreviation "e" is used to indicate that equilibrium is assumed between the radioactive daughter isotope monitored by the spectrometer, and its respective parent isotope; uranium²³⁸ is estimated indirectly by measuring gamma rays emitted by bismuth²¹⁴ with an energy of 1.76 MeV. Jackson (1992) concluded that the airborne gamma-ray spectrometry data would be of value to both government agencies and land developers.

Doyle *et al.* (1990) selected two communities in Quebec with different eU characteristics measured by airborne gamma-ray spectrometry for comparison of their indoor radon concentrations. They concluded that indoor radon variations essentially paralleled the eU patterns, such that the lowest mean radon concentrations were associated with the lowest mean eU values, and highest mean radon concentrations were associated with

the highest mean eU values.

This paper describes similar relationships between eU concentrations determined by airborne gamma-ray spectrometry and indoor radon levels for an area near Oka, Quebec. This further demonstrates the value of the airborne data as a predictive tool for identifying potential indoor radon problem areas.

FACTORS CONTROLLING RADON DISTRIBUTION

Three factors that should be considered during the evaluation of residential radon levels include: 1) the source (material producing the radon), 2) the transport mechanism (means by which radon travels from source into a dwelling) and 3) the trap (type of home construction and restricted ventilation that allows radon accumulation, Fig. 1). Airborne gamma-ray spectrometry can be used to evaluate the first factor, by measuring variations in the concentration of uranium at the earth's surface. The technique provides a positive test, whereby high U values may indicate an increased risk of overexposure to radon. Rocks and soils, such as certain types of clays, with low to moderate U concentrations may still produce high residential radon if factors controlling the transport or collection of radon are dominant (Grasty, 1994). The airborne data are best applied to groups of homes or areas, rather than to individual sites, because the second and third factors influence the actual radon levels within a given building. These factors include soil

porosity and permeability, moisture content, and the type and quality of home construction. Although home-specific information is not provided by an airborne survey, it offers a systematic and rapid determination of the radon source potential of large areas, and can be conducted prior to new housing development.

OKA, QUEBEC – A CASE HISTORY Description of Area

The Oka carbonatite and alkaline complex (Gold *et al.*, 1967) is located approximately 32 km west of Montreal, Canada (Fig. 2). Carbonatite and associated alkaline rocks of ijolite and okaite suites occur in a double ring-dyke structure that measures 7.2 km by 2.4 km. Most of the carbonate rocks are coarse grained and layered, with calcite as the dominant mineral. Glacial till and Holocene-age Champlain Sea sediments composed predominantly of sand, silt, and clay cover most of the complex, to a maximum thickness of 120 m. Niobium was mined at the St. Lawrence property in the southern part of the intrusion (Fig. 3) in the 1960s and 1970s. The outline of the Oka intrusion is shown in Figure 3.

1995-1996 Radon Survey

In 1995-1996 the Direction régionale de la santé publique des Laurentides (DRSP) (Savard *et al.*, 1998) conducted a radon measurement program in homes located on and near the Oka carbonatite. Geological information and the results of two

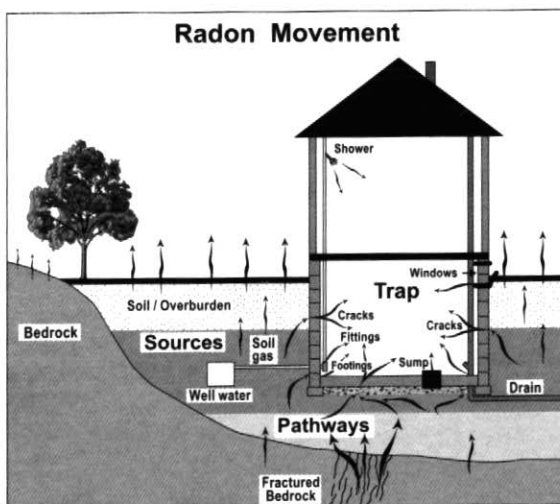


Figure 1 Factors that control the distribution and movement of radon, and typical entry routes into a home for the radon.



Figure 2 Location map.

earlier radon studies were used to define three zones of decreasing risk based on proximity to the known extent of the carbonatite intrusion. Zone 1 encompassed a residential development south of the main mineralized area (St. Lawrence Niobium mine, shown on Fig. 3) and included a 1 km buffer around it. Based on earlier radon studies, Zone 1 was thought to be the area with the most risk for overexposure to residential radon. Zone 2 was defined as the area encompassing the remainder of the carbonatite intrusion, and Zone 3 was defined as a buffer zone 1 km in width around the intrusion.

Radon measurements were taken initially in 176 of approximately 310 homes located within the three zones,

using E-PERM type electrostatic cumulative dosimeters (Savard *et al.*, 1998). The objective of this study was to assess the risk of human exposure to radon. For that reason, the dosimeters were installed in the lowest normally occupied level of each house, either the basement or first floor living area. The final location of each dosimeter was determined on a case by case basis for each individual household after an evaluation of the layout of the house and the living habits of its inhabitants. Had all dosimeters been installed in basements, higher radon concentrations would have been measured, resulting in higher average concentrations.

Savard *et al.* (1998) stated that, based on previous studies, they expected

to find radon concentrations above 150 Bq/m³ in 5-8% of basements of homes and about 3% in the first floor level. A very small percentage, 2-4 homes in 1000, were expected to be above 800 Bq/m³. However, analysis of the radon measurements showed that approximately 41% of homes in Zone 3 and 38% of homes in Zone 2 exceeded 150 Bq/m³, and 8% of homes in Zone 3 and 10% of homes in Zone 2 exceeded 800 Bq/m³. DRSP officials felt that because of the lack of a clear distinction between average radon concentrations in homes located within the buffer zone (Zone 3) around the carbonatite, and concentrations in homes situated on the carbonatite (Zone 2) (excluding the residential area outlined by Zone 1), they were unable to adequately define the geographic extent of the zones of high risk (Savard *et al.*, 1998).

1996 Airborne Gamma-ray Spectrometry Survey

DRSP decided that additional data were required to more accurately delineate the zones of risk of overexposure to indoor radon. While additional radon measurements would provide a direct indication of the desired parameter, they would not allow for an assessment of radon risk in areas where no residential development currently exists. As well, to properly define the extent of the buffer zone around the carbonatite, a much larger area would have to be included in any additional radon measurement program. This would result in a significant increase in the number of homes to be measured, along with a significantly larger population inconvenienced by an additional direct radon measurement survey in their homes.

In 1996 the GSC and the DRSP jointly funded a detailed, 200-m line spacing airborne gamma-ray spectrometry survey (Geological Survey of Canada, 1996) to determine spatial relationships between eU concentrations in surficial geological material and indoor radon concentrations. The objective of this survey was to systematically define the geographic extent of areas of risk of overexposure to indoor radon, including areas without residential development, and to do this with minimum impact on residents of the region.

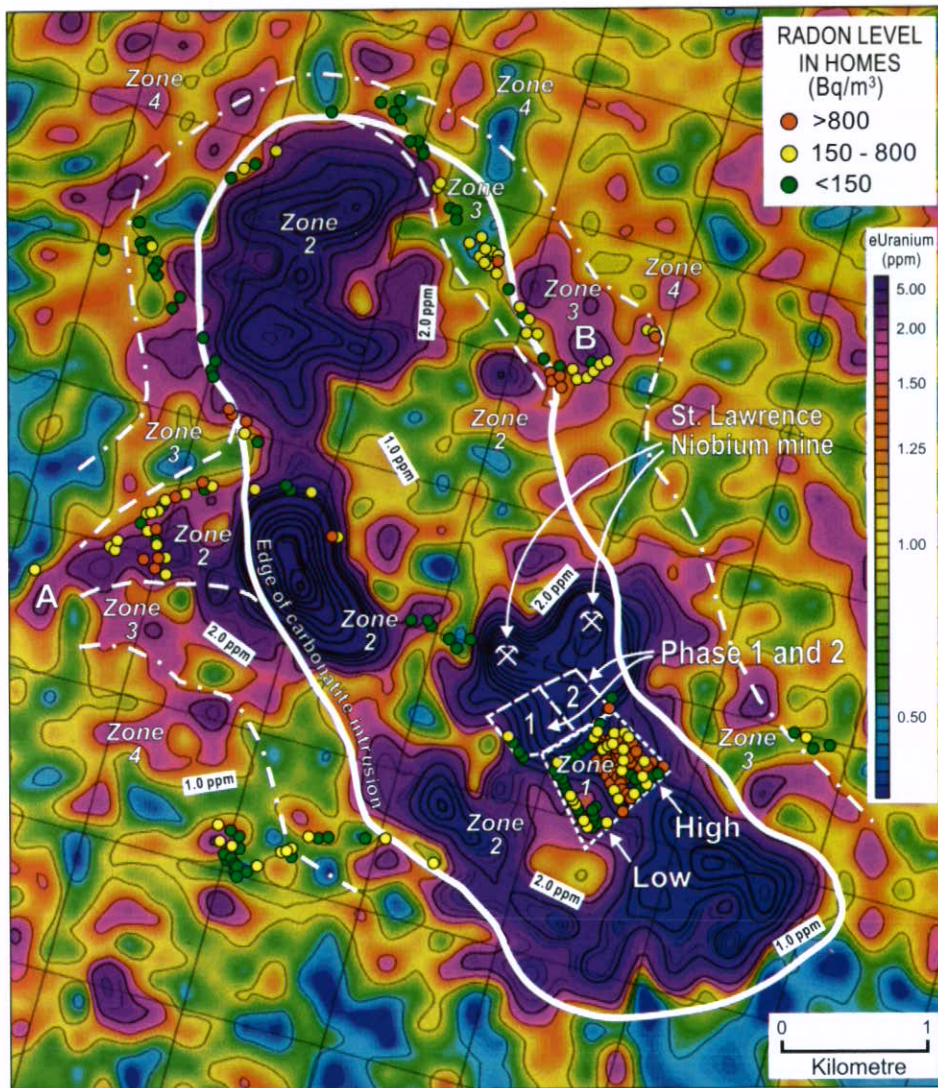


Figure 3 Equivalent uranium patterns from a 200-m line spaced airborne gamma-ray spectrometry survey of the Oka, Quebec area. Scale provided by 1 km UTM grid.

Part of the eU map from the 1996 airborne gamma-ray spectrometry survey (Geological Survey of Canada, 1996) is presented in Figure 3. Symbols depict three levels of measured indoor radon concentrations: less than 150 Bq/m³, (the United States Environmental Protection Agency (U.S. EPA) guideline), above which remediation is recommended; 150-800 Bq/m³; and above 800 Bq/m³, (the Health Canada guideline). The known extent of the carbonatite intrusion, and revised zones of radon risk based on a reanalysis of the radon measurements with new information provided by the airborne survey results, are also indicated in Figure 3.

High eU and eTh concentrations (maximum 65 ppm eU, 137 ppm eTh) are localized in three areas where carbonatite bedrock is exposed. These include the Huscreau Hill area (Gold *et al.*, 1967) along the northwest edge of the carbonatite, the Bond Zone near the west central part, and the St. Lawrence property and residential development in the southeast. The intervening areas of low eU and eTh concentrations (less than 2 ppm eU and 8 ppm eTh) correspond to areas predominantly covered by Champlain Sea sediments composed of sand, silt, and clay. These sediments mask the high eU and eTh signature that characterizes exposed parts of the carbonatite. Areas lying outside the intrusion are characterized by eU concentrations averaging about 1.0 ppm and which typically range between 0.45 ppm and 1.5 ppm; eTh concentrations average about 4.0 ppm and range between 0.2 and 13 ppm.

DISCUSSION

Analysis of the airborne gamma-ray spectrometry data and radon measurements reveals a strong association between increasing eU concentrations and the percentage of homes with increasing radon concentrations (Table 1). Following the 1996 airborne survey and reanalysis of the 1995-1996 radon survey results, additional indoor radon measurements were made. These results have been incorporated into Table 1 and Figure 3. Table 1 shows the percentage of homes exceeding established Canadian and United States guidelines for indoor radon concentrations classified by eU concentrations measured by airborne gamma-ray

spectrometry. As expected, none of the homes situated in areas with eU concentrations of less than 1 ppm exceed the Canadian guideline, whereas a high percentage of homes in areas with greater than 6 ppm eU exceed both the Canadian and United States guidelines.

Higher than expected residential radon levels were found in two areas outside the known extent of the carbonatite intrusion (A and B, Fig. 3). In both areas, higher radon values are associated with eU concentrations that are higher than the regional background of 1-2 ppm eU. The maximum eU concentrations in the airborne data are 2.8 ppm eU for area A and 3.7 ppm eU for area B. Both areas are characterized by slightly elevated terrain with thin till cover, no Champlain Sea sediments, and bedrock exposures that contain carbonatite dyke rocks thought to be derived from the main intrusion. This new information provided by the airborne gamma-ray spectrometry data allowed DRSP to better define the boundaries between Zones 2 and 3.

Re-analysis of the radon results confirmed that the residential development covered by Zone 1 is unique in Canada because it represents a concentrated housing development situated on an area of high natural radioactivity. This coincidence has resulted in a strong association between high indoor radon concentrations and high eU concentrations. The eU data shows that Zone 1 consists of two distinct areas that are shown on Figure 3 as "High" and "Low." The low part of Zone 1 contains some of the lowest indoor radon concentrations within the carbonatite intrusion. Equivalent uranium levels decrease from a high of 9.9 ppm in the high part of Zone 1 to a low of 1.8 ppm in the low part. The higher eU concentrations and higher

indoor radon concentrations over the east half of Zone 1 are associated with an area of increased bedrock exposure and thin till cover. The lower eU and indoor radon concentrations over the west side of Zone 1 are associated with an area of marine sand, silt, or clay that characterize other low radioactivity areas within the area of the carbonatite intrusion.

Within Zone 1, median eU concentrations are 3.8 ppm for the low part and 5.6 ppm for the high part (Fig. 3). Within the low part, 36 of 55 homes were measured. Sixty-one percent have radon concentrations of less than 150 Bq/m³, 31% have concentrations greater than 150 Bq/m³, and 8% have concentrations greater than 800 Bq/m³. Within the high part, 54 of 58 homes were measured. Five percent of the homes have radon concentrations of less than 150 Bq/m³, 30% have concentrations greater than 150 Bq/m³, and 65% have concentrations greater than 800 Bq/m³.

The strong association between high eU concentrations and high indoor radon concentrations demonstrates the effectiveness of airborne gamma-ray spectrometry data as a predictive tool for the identification of high radon risk areas. This strong association allowed DRSP to revise the previously determined zone boundaries, and to add a fourth zone representing regional background levels for eU concentrations. DRSP were also able to conduct an evaluation of undeveloped areas with a high potential for excessive radon exposure based on the eU concentrations of these specific areas. One of these areas was a residential development site north of Zone 1, shown as Phase 1 and 2 (Fig. 3), in an area characterized by high eU concentrations.

The DRSP analyzed the relationship between the eU concentrations and

Table 1 Percentage of homes exceeding established Canadian and American indoor radon levels classified by airborne eU concentrations. Parentheses indicate number of homes in each category. AGRS = airborne gamma-ray spectrometry; U.S. EPA = United States Environmental Protection Agency. See text for discussion.

		U.S. EPA Guideline	Health Canada Guideline
AGRS eU	<150 Bq/m ³	>150 Bq/m ³	>800 Bq/m ³
0-1 ppm (35)	54.3 % (19)	45.7 % (16)	0 % (0)
1-2 ppm (78)	48.7 % (38)	51.3 % (33)	9.0 % (7)
2-4 ppm (42)	52.4 % (22)	47.6 % (11)	21.4 % (9)
4-6 ppm (45)	24.4 % (11)	75.6 % (14)	44.4 % (20)
> 6 ppm (42)	19.1 % (8)	80.9 % (15)	45.2 % (19)

the indoor radon concentrations based on the new revised zoning. The results of this analysis are summarized in Figure 4, which clearly shows that higher eU concentrations relate to higher indoor radon concentrations. Average eU concentrations increase from 1.0 ppm for Zone 4 to 11.8 ppm for Phase 2 of the proposed residential housing development. Average residential radon values increase from 106 Bq/m³ in Zone 4 to 1075 Bq/m³ in the high part of Zone 1.

The airborne data show high eU concentrations in the area of the residential development site, with an average of 8.3 ppm for Phase 1 and 11.8 ppm for Phase 2. These average eU concentrations are much higher than in the "High" part of Zone 1. Ground gamma-ray spectrometry verified these higher eU levels with concentrations averaging between one and a half and two times higher than those measured in the high area of Zone 1.

Considering the strong association between eU concentrations and the proportion of homes in which radon concentrations exceed 150 and 800 Bq/m³ DRSP officials expected that the levels of radon in homes to be constructed in the area of the proposed residential development would represent a significant

risk to the health of their inhabitants. DRSP officials recommended that new construction be stopped unless special mitigation measures were taken that minimized the direct contact between the source material of the radon, the bedrock and soil, and the home. These measures required that houses be elevated above the ground to allow free circulation of air at all times, and that no attached garages which may concentrate radon be built.

CONCLUSIONS

Airborne gamma-ray spectrometry surveys have been used at national, regional, and local scales to map high radon risk areas. From previous radon measurements, public health officials for the Oka region knew that some high indoor radon concentrations are related to a carbonatite intrusion, and they defined radon risk zones based on the known extent of the carbonatite. Subsequent radon measurements revealed concentrations higher than expected based on these known geological factors.

The results of the airborne gamma-ray spectrometry survey were used by public health officials to identify specific areas within and in close proximity to the carbonatite intrusion where

there is a risk of overexposure to indoor radon. The clear association between high eU concentrations and high radon concentrations demonstrates the effectiveness of airborne gamma-ray spectrometry as a predictive tool for the identification of areas with potential risk of overexposure to indoor radon, including areas without residential development. This association supported a number of land use and public health initiatives. These included a recommendation by public health officials that the municipality apply, in its construction by-laws, the Canadian Building Code's Addendum regarding radon gas for its territory, and withhold building permits for certain particularly affected areas. Health authorities offered free radon sampling to homeowners in the affected areas not covered in the initial testing. Given the fact that the situation in Oka was extraordinary, a program of financial assistance from the Quebec government was approved recently to help homeowners in the affected areas to apply mitigation techniques to their homes. This program includes additional radon measurements, after the application of mitigation techniques, to confirm their effectiveness.

A second carbonatite complex is located near the community of St-André-d'Argenteuil, located 20 km west of the Oka intrusion. As a result of the Oka study and the public health initiatives that were developed from it, an investigation was initiated around this second intrusion that employed the same successful methodology used in the Oka study. This included an airborne gamma-ray spectrometry survey followed by a program to measure radon concentrations in homes situated on or near this second alkaline intrusion. A program to test well waters for the presence of uranium in Oka and St-André-d'Argenteuil was also initiated. The airborne gamma-ray spectrometry survey results show a small (less than 2 km²) area of high eU concentrations (maximum 9 ppm). Results from the radon measurements are not yet complete.

ACKNOWLEDGMENTS

We thank Pat Killeen and George O'Reilly for their useful comments as critical reviewers.

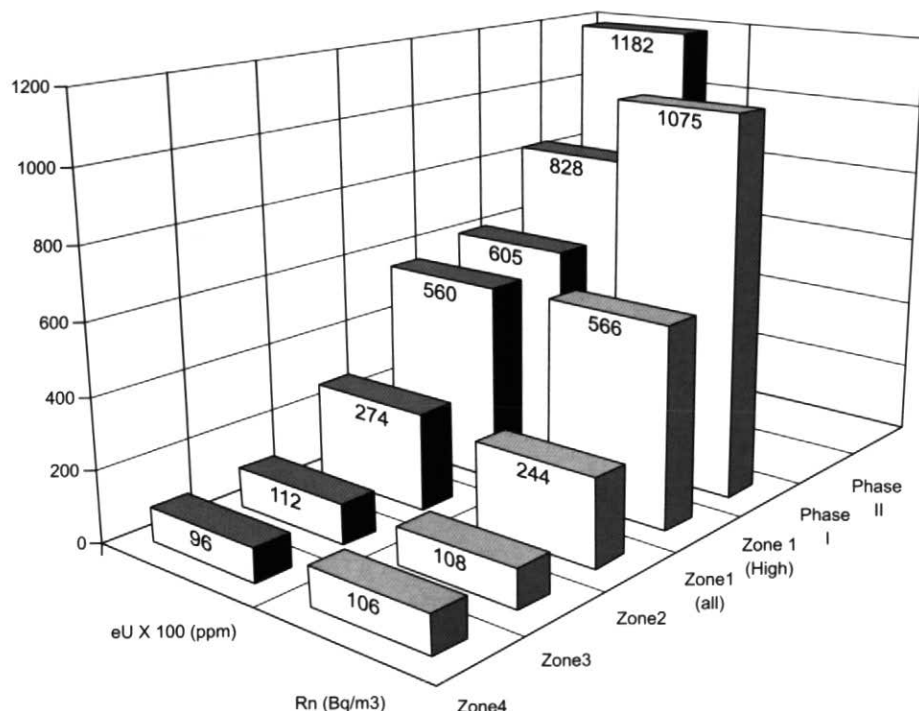


Figure 4 Comparison of average residential radon concentration and average equivalent uranium values by zone. (Rn in Bq/m³ and eU X 100 ppm).

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Accepted as revised 4 April 2001