Airborne uranium data in support of radon potential mapping in Derbyshire, Central England.

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Abstract

In order to assess if uranium (eU) data gathered by airborne survey could support the radon potential mapping process in areas with few indoor radon measurements, the relationship between airborne eU values, ground-based eU measured by *in situ* gamma spectrometry, indoor radon and soil gas radon was investigated for Derbyshire, Central Britain.
Significant correlations between the airborne eU geometric mean and the geometric mean of indoor radon for a single geological unit can be demonstrated in some urban areas (e.g. Buxton, Derbyshire, England) where there are many indoor radon measurements. Significant correlation was also shown in the Buxton area between airborne eU data, soil gas radon measurements and the percentage of houses estimated to exceed the UK Action Level of 200 Bq m^{-3}.
At the regional scale, airborne eU data correlates significantly ($p=0.0005$) with geometric mean indoor radon for data grouped by generalised geology and 1-km grid square when data for all geologies are considered together. Significant correlations for individual geological units are found only when these include a wide range of eU and indoor radon values (e.g. Visean Limestone). Permeability of the parent material (soil, superficial deposits and/or bedrock) is an important controlling factor in the relationship between eU and indoor radon as the same level of uranium generally gives rise to higher indoor radon when the bedrock is permeable and lower indoor radon when the bedrock is impermeable.
Linear regression modelled estimates of indoor radon with K, eTh, eU and permeability as independent predictor variables correlate better with measured indoor radon than when eU is the sole predictor variable.

1- Introduction

Following the first phase of a multi-parameter airborne geophysical survey of Central England conducted by the British Geological Survey (BGS) in collaboration with World Geoscience (UK) in 1998, the Carboniferous Limestone of Derbyshire was further investigated due to the elevated eU values found and high radon potential of the area. This investigation intended to verify the airborne survey measurements and assess whether airborne eU, with support from ground-based eU and soil gas radon measurements, could give an indication of radon potential and inform the radon potential mapping process in areas with few indoor radon measurements.

This study required assessment of data in a GIS environment, statistical analysis of data and a ground follow-up survey that included ground based gamma spectrometry and soil gas radon measurements in areas corresponding to locations where airborne measurements were taken. Further to this, sites were chosen close to housing in an effort to link soil gas radon, ground based eU and the airborne eU data to the indoor radon concentration data supplied by the Health Protection Agency (HPA). Ground follow-up sites were in areas with differing percentages of houses over the UK radon Action Level (AL) of 200 Bq m^{-3}.

2- Methodology

2.1- Airborne gamma spectrometry

Gamma spectrometry data was gathered by airborne survey in 1998 over 14 000 km^2 of Central England. The aircraft flew at a height of 90 m but this increased to 240 m over developed areas. Flight line separation was generally 400 m with tie line spacing at 1,200 m except over three infill areas of special interest where flight line and tie line separations were effectively reduced to 200 m and 600 m respectively. Potassium, equivalent uranium (eU, determined from ^{214}Bi) and equivalent thorium (eTh, determined from ^{208}Tl) data was acquired and processed to produce equivalent ground concentrations in % K, ppm eU and ppm eTh. Each airborne point represents a one-second measurement, which equates to a travelling distance of approximately 70 m over the ground. The area of view of the detector for each measurement is more than 10, 000 m^2 (Peart *et al*., 2004).

2.2- Ground based gamma spectrometry

Gamma spectrometry was carried out using an Exploranium GR-320 with a 76 x 76 mm NaI (Tl) detector. Ten-minute counts were obtained at a height of 1m by mounting the detector on a tripod. A detector at this height detects gamma rays from an area within a 10-metre radius to a depth of approximately 30 cm (Atomic Energy Commission, USA, 1972). Once again K (%), eU (ppm) and eTh (ppm) were recorded. Measurements were made along traverses directly below the aircraft's known flight path at a spacing of approximately 70 m.

2.3- Soil gas radon

Soil gas radon, measured at selected 70 m traverse sites outlined above, was analysed from a depth of 60-80 cm using a Pylon AB-5 portable radiation monitor with attached Lucas cell (Ball *et al*., 1991). After a background count to confirm that the Lucas cell had a low enough background, a known volume of air was pumped via a hand pump from the ground into the Lucas cell and three consecutive one-minute counts (C1, C2, C3) were made. Radon in counts per minute (cpm) was calculated using the following formula that corrects for the contribution from Thoron, which has a shorter half-life than that of Radon.

$$^{222}Rn\ (cpm) = (0.87*(C3-Background))+(0.32*(C2-Background))-(0.34*(C1-Background))$$

A calibration factor, or coefficient, was calculated for each Pylon monitor and each Lucas cell based on an annual calibration done at the HPA in the 'Fast Radon Exposure Device' in which radon in generated at a known concentration. Using this coefficient, the radon concentration in Bql^{-1} was calculated using the following formula:

$$Radon\ (Bql^{-1}) = {}^{222}Rn\ CPM \times Coefficient$$

2.4- Indoor radon

The HPA has carried out various surveys of radon in houses since the early 1980s, most of them funded by the Department of the Environment, Food and Rural Affairs. This has resulted in a database of radon levels in more than 430,000 homes in England and Wales. Measurements of radon in houses were carried out using small closed passive etched-track detectors over 3 or 6 months. Since indoor radon levels are usually higher in cold weather, the annual average radon concentrations in houses used in this study were calculated using temperature corrections (Miles and Appleton, 2005).

2.5- Permeability

A limited field assessment of soil gas permeability using a 'RADON-JOK' permeameter (Neznal et al., 2004) was carried out at four sites underlain by limestone. From this restricted field trial there was relatively little variation in permeability and no correlation could be detected between soil gas permeability, soil gas radon and indoor radon concentrations (Table 1) so it appears in this case that the concentration of uranium in bedrock and superficial cover and radon in soil gas are the dominant factors controlling indoor radon, rather than permeability. Studies covering a wider range of superficial and bedrock types are planned.

Table 1 Soil gas permeability, soil gas radon, airborne eU and indoor radon at four sites on limestone in the Buxton area, Derbyshire (%>AL = proportion of houses with radon exceeding the Action Level estimated by lognormal modelling, Miles and Appleton, 2005)

Site	*Average Permeability* m^2 (range)	*GM soil gas radon Bq/L (n)*	*eU (ppm)*	*GM indoor radon Bq m^{-3} (n)*	*%>AL*
Buxton 1	*$2.3E^{-12}$ ($1.0E^{-13}$-$7.0E^{-12}$)*	*342 (11)*	*3.47*	*333 (136)*	*70*
Buxton 2	*$8.8E^{-12}$ ($2.3E^{-14}$-$2.4E^{-11}$)*	*147 (7)*	*2.04*	*169 (969)*	*40*
Buxton 3	*$6.2E^{-12}$ ($3.5E^{-14}$-$2.9E^{-11}$)*	*158 (15)*	*1.03*	*130 (270)*	*33*
Buxton 4	*$1.4E^{-11}$ ($5.2E^{-14}$-$2.7E^{-11}$)*	*35 (22)*	*0.88*	*73 (264)*	*11*

In order to determine the influence of permeability over a much larger area, all bedrock and superficial geological units were assigned permeability codes based on known properties of the bedrock and superficial geological units, rather than on direct field tests. The permeability code allocated consisted of a predominant permeability type (intergranular, fracture, or a mixture of intergranular and fracture), and a maximum and minimum permeability class. The five classes are: very high, high, moderate, low and very low and these equate broadly to a range of hydraulic conductivity of 10^{-1} to 10^{-13} m/sec. In the majority of cases the minimum and maximum permeability classes are the same or similar, indicating that the range in potential permeability values for that geological unit is relatively small. In other cases, the range could span 2, 3 or even 4 classes due to lithological variation or secondary permeability caused by fracturing. In order to include the permeability in numerical models, a continuous range from 1 to 5 (very low to very high permeability) was attributed to each minimum and maximum permeability class, and a numerical average was calculated.

2.6- Integration and analysis of airborne eU, indoor radon and permeability data
In a GIS, each airborne data point was attributed with 1: 50,000 scale bedrock and superficial geology codes, and permeability codes. Indoor radon measurement locations were attributed with bedrock and superficial geology codes.
Geometric mean values for bedrock/superficial geology combinations within 1–km grid squares for which there are 10 or more airborne gamma spectrometry data points and more than 30 indoor radon measurements were calculated. A total of 189 1-km grid square/geology combinations fulfilled these criteria in the study area. The average number of airborne eU measurements for a 1-km grid square- bedrock-superficial geology combination is 33 (range 10-93) and the average number of indoor radon measurements is 91 (range 31- 968).

3- Results and discussion

3.1- Ground-based verification of the airborne survey eU data
Airborne and ground-based gamma spectrometry eU measurements showed a significant positive correlation (p=0.0005) and profiles revealed a 'smoothed' airborne profile relative to the more detailed ground profile reflecting the larger sampling area (Figure 1).

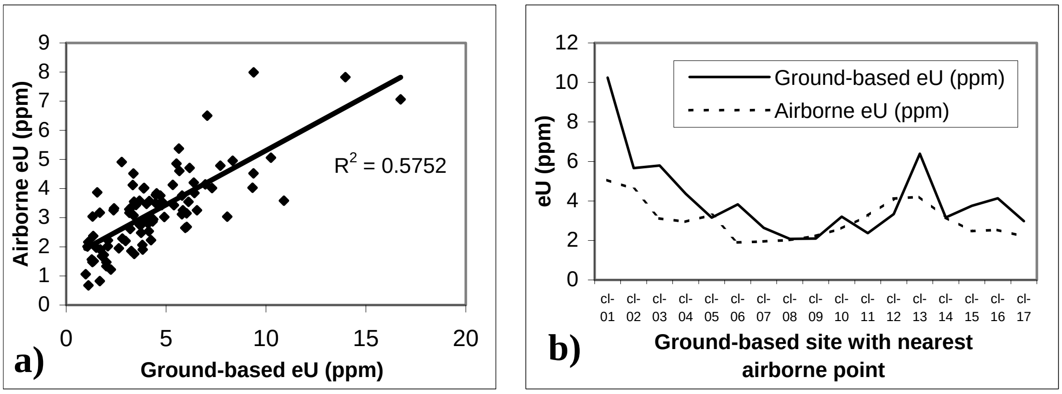

Figure 1 a) Airborne equivalent eU vs. ground-based equivalent eU (ppm); b) An example profile of ground-based and airborne equivalent eU (ppm) on the Carboniferous Monsal Dale Limestone at Chelmorton, Derbyshire.

One factor in the airborne survey that may complicate using airborne eU measurements to inform radon potential mapping is that airborne eU appears to be reduced in those areas where most of the ground is covered with buildings. This can be illustrated to the south of Buxton (Figure 2) where the Monsal Dale Limestone Dark Lithofacies (MODK-LMST) is covered with dwellings and roads. The eU geometric mean of 0.07 ppm for the MODK-LMST in this grid square (2.1 ppm over the whole study area) is very low compared with the geometric mean indoor radon of 190 Bqm^{-3}. For comparison, most of Bee Low Limestone (BLL-LMST) in this grid square is not covered with buildings and has a higher geometric mean eU of 1.2 ppm in comparison with the geometric mean indoor radon of 124 Bq m^{-3}.

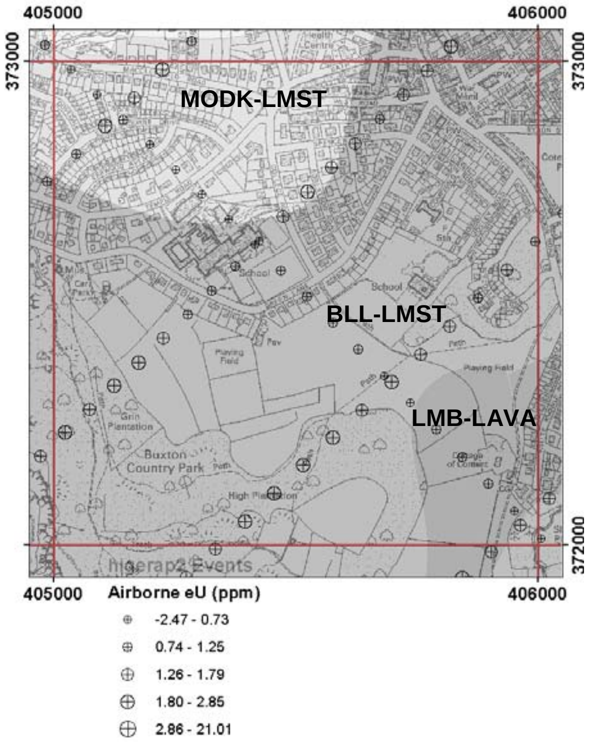

Figure 2 Distribution of airborne eU (ppm) measurements in a 1- km grid square to the south of Buxton, Derbyshire (MODK-LMST: Monsal Dale Limestone Dark Lithofacies, pale grey; BLL-LMST: Bee Low Limestone, medium grey, LMB-LAVA: Lower Miller's Dale Lava Member, dark grey) (Topography © Crown copyright. All rights reserved).

3.2- Airborne survey eU measurements and radon

Significant correlation between airborne eU and indoor radon for a single geological unit (Bee Low Limestone) can be demonstrated in some urban areas (e.g. Buxton) where there are many indoor radon measurements (p=0.01, Figure 3).

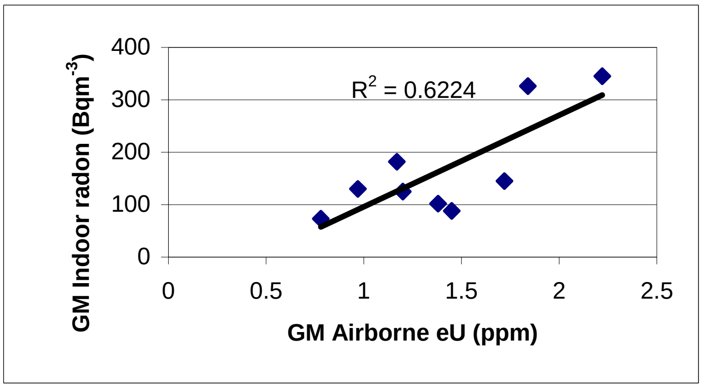

Figure 3 Correlation of geometric mean airborne eU (ppm) with geometric mean indoor radon (Bqm^{-3}) for the Bee Low Limestone (no superficial cover) in the Buxton Area (data grouped by 1-km grid square).

In the four 1-km grid squares in which soil gas radon concentrations, indoor radon and airborne eU data are available for the Buxton area, these all correlate closely (Figure 4).

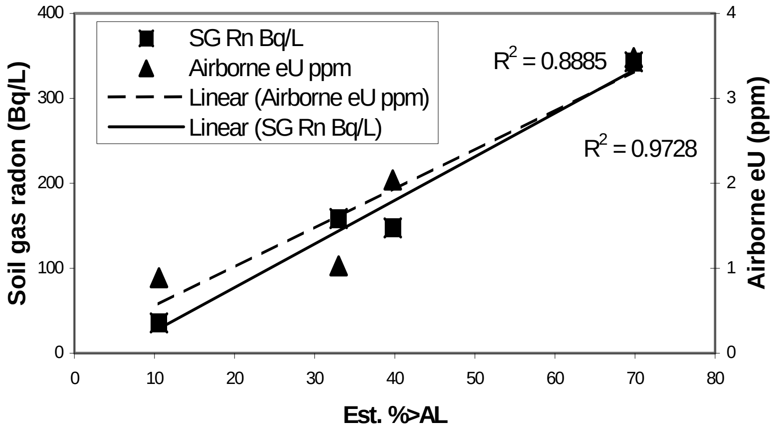

Figure 4 Relationship between soil gas radon concentrations (Bq/l), percentage of houses estimated to exceed the Action Level (Est. %>AL) and airborne eU (ppm) for the Bee Low Limestone, Buxton area.

When airborne eU and indoor radon data are grouped by the more generalised geological unit, Visean Limestone (VIS-LMST) over a larger area (9 km^2), the correlation is less significant (p=0.025, Figure 5).

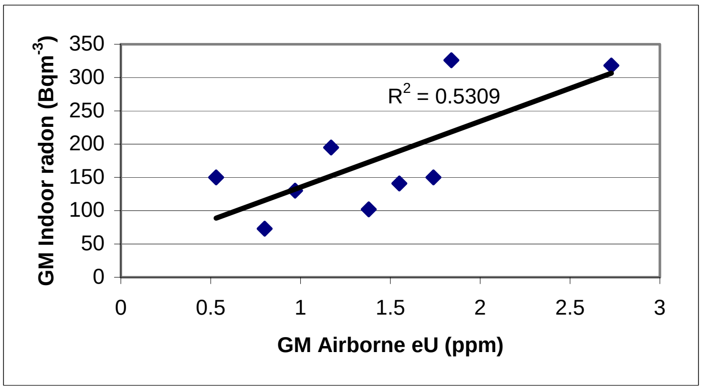

Figure 5 Correlation of geometric mean airborne eU (ppm) with geometric mean indoor radon (Bqm^{-3}) for the Visean Limestone (no superficial cover) in the Buxton Area (data grouped by 1-km grid square).

Over the whole of the study area, airborne eU correlates significantly (p=0.0005) with geometric mean indoor radon for data grouped by generalised bedrock/superficial geology combination and 1-km grid square when data from all geologies are considered together (Figure 6). Significant (p=0.005) correlations for individual geological units are found only when these include a wide range of eU and indoor radon values (e.g. Dinantian Limestone DINLM and Dinantian mudstone-siltstone units DINMDMIX, Figure 7).

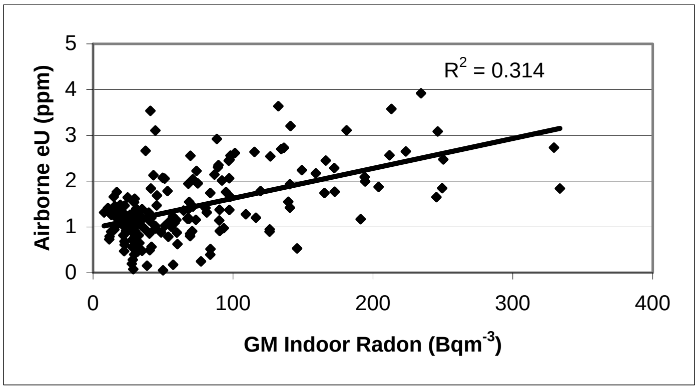

Figure 6 Relationship between geometric mean airborne eU (ppm) and geometric mean indoor radon (Bq m^{-3}) for the Derbyshire area (British National Grid 400000-440000/345000-385000, data grouped by 1-km grid square, generalised bedrock and superficial geology).

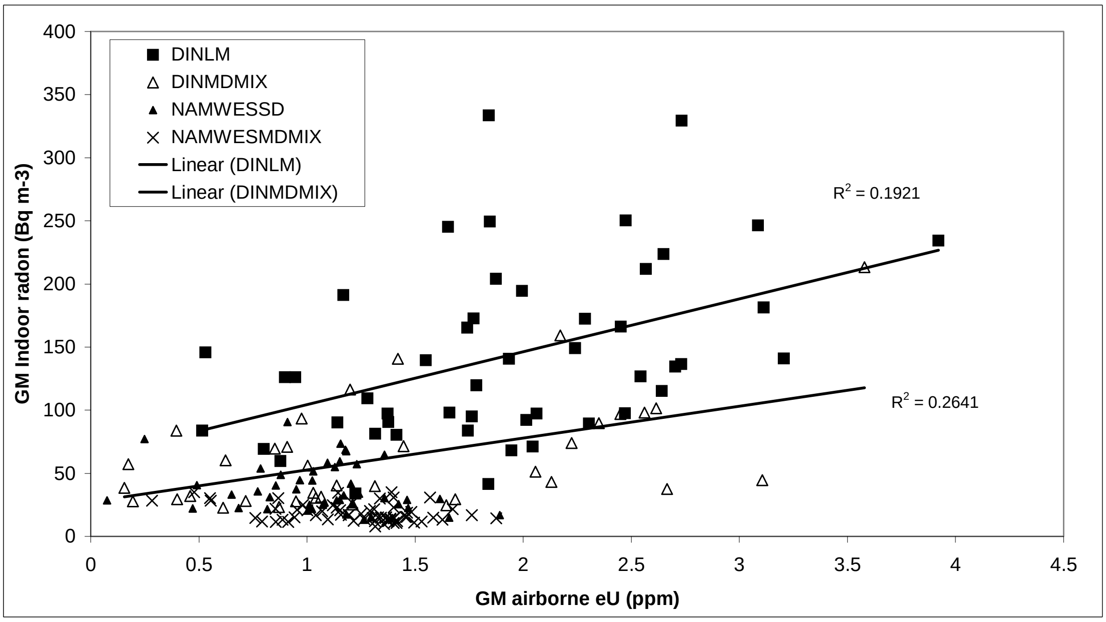

Figure 7 Relationship between geometric mean airborne eU (ppm) and geometric mean indoor radon (Bq m^{-3}) for the Derbyshire area (British National Grid 400000-440000/345000-385000, data grouped by 1-km grid square, generalised bedrock and superficial geology). DINLM: Dinantian Limestone, DINMDMIX: Dinantian Mudstone-Siltstone, NAMWESSD: Namurian and Westphalian Sandstone, NAMWESMDMIX: Namurian and Westphalian Mudstone-Siltstone.

3.3- Permeability and indoor radon

Permeability of the parent material (soil, superficial deposits and/or bedrock) is an important controlling factor in the relationship between eU and indoor radon as the same level of eU generally gives rise to higher indoor radon when the bedrock is permeable (e.g. sandstone and limestone) and lower indoor radon when the bedrock is impermeable (argillaceous rocks). Namurian and Westphalian mudstone-siltstone bedrocks produce lower indoor radon than Namurian and Westphalian sandstones over a similar range of eU (Figure 7). The average permeability of the mudstone-siltstones bedrocks is 2.5 (on the scale of 1 to 5, very low to very high) compared with 3 to 3.5 for the sandstones. The Lower Carboniferous (Dinantian) mudstone-siltstone bedrocks have an average permeability of 2.5 compared with 4.5 for the Dinantian Limestones. Whereas the range of eU for these two bedrock groups is about the same, higher indoor radon characterises the limestone compared with the mudstone-siltstone bedrock (Figure 7). Correlations between indoor radon and eU for both geological groups are significant (p=0.005).

The impact of permeability can also be illustrated on the scale of a single kilometre square for example to the north-west of Matlock, Derbyshire (Figure 8), where the eU geometric mean for the relatively impermeable argillaceous Bowland Shale Group (BSG-MDSS) is 3.1 ppm and the indoor radon geometric mean is relatively low at 49 Bq m^{-3} compared with the permeable Eyam Limestone (EYL-LMST) which has a slightly higher geometric mean eU of 4.2 ppm, but a much higher indoor radon geometric mean of 228 Bq m^{-3}.

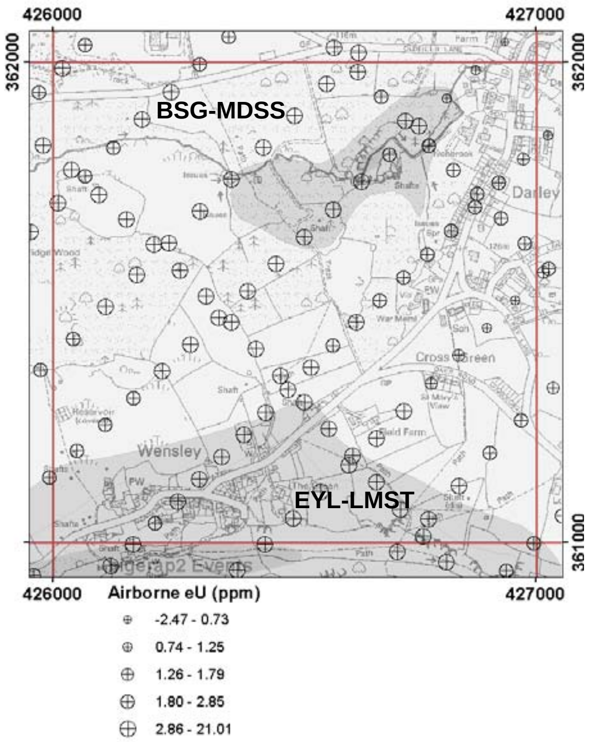

Figure 8: Distribution of airborne eU (ppm) measurements in a 1- km grid square to the north-west of Matlock, Derbyshire (BSG-MDSS: Bowland Shale Formation- mudstone, siltstone and sandstone, pale grey; EYL-LMST: Eyam Limestone Formation, medium grey) (Topography © Crown copyright. All rights reserved).

3.4- Modelling indoor radon

Geometric mean indoor radon, eU, K, eTh and average permeability for data grouped by generalised bedrock/superficial geology combination and 1-km grid square correlate significantly (p=0.0005; Table 2; indoor radon and eU plotted in Figure 6). In the study area, which is characterised by limestones, mudstones, siltstones and sandstones, K is a good indicator of the clay content and permeability of bedrock at each measurement site. The average permeability, although still significantly correlated, is an average permeability over a larger area and so evidently does not provide such a good indication of permeability/clay content at the local scale.

Table 2 Correlation coefficients of geometric mean eU, K, eTh, and average permeability with geometric mean indoor radon

	GM Indoor Radon
GM eU	0.55
GM K	-0.55
GM eTh	-0.39
GM Average Permeability	0.45

Multiple linear regression analysis was used to model geometric mean indoor radon using geometric mean eU, K, eTh and average permeability. Estimated geometric mean indoor radon correlates significantly with measured indoor radon (Figure 9, R^2=0.5356). Estimated indoor radon correlates less well with measured indoor radon when average permeability is not included in the model (R^2=0.4929) or when only geometric mean eU is used in the model (R^2=0.2978).

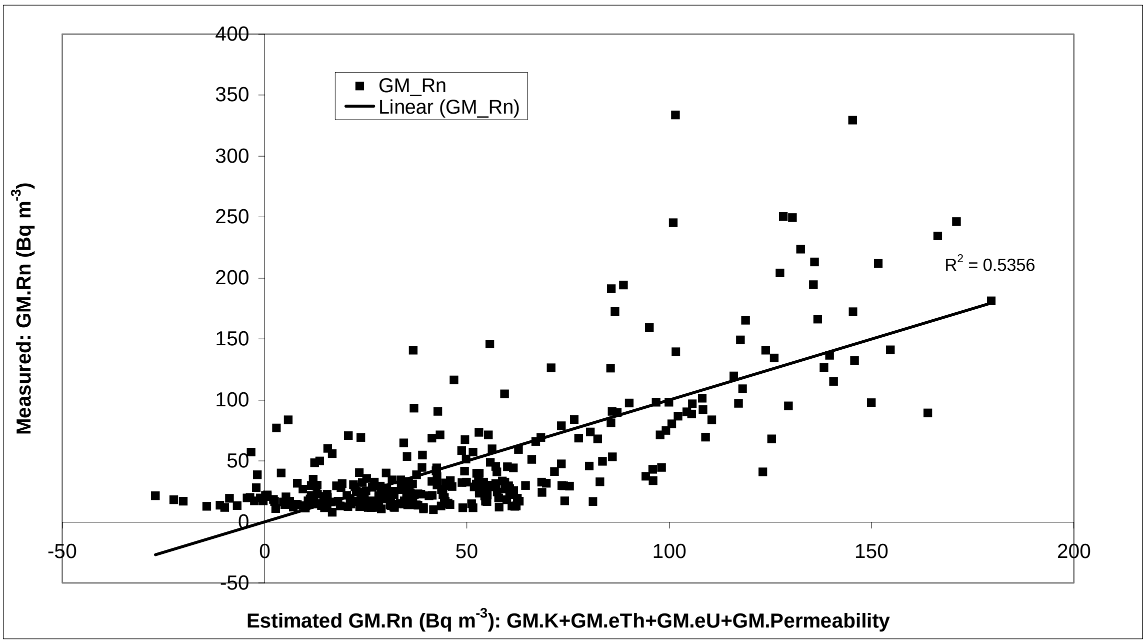

Figure 9 Correlation of measured geometric mean indoor radon (Bqm^{-3}) with estimated geometric mean indoor radon where geometric mean K, eTh, eU and average permeability were included.

4- Conclusions

1. Airborne and ground-based gamma spectrometry eU measurements correlated significantly (p=0.0005). Airborne eU profiles appeared 'smoothed' relative to the more detailed ground profile reflecting the larger sampling area. Airborne eU appears to be reduced in those areas where most of the ground is covered with buildings and roads.
2. Airborne eU, K, eTh and average permeability correlate significantly (p=0.0005) with geometric mean indoor radon for data grouped by generalised bedrock/superficial geology combination and 1-km grid square when data

from all geologies are considered together. It was shown in the case of airborne eU that significant correlations (p=0.005) for individual geological units are found only when these include a wide range of eU and indoor radon values.

3. Permeability has been shown to be an influencing factor, but airborne K data may provide better site-specific clay content/permeability information than average bedrock permeability derived for a larger area. Further field investigation is required to understand the influence of soil gas permeability in the area.
4. Modelled estimates of indoor radon were most significant when eU, K, eTh and average permeability were all taken into account rather than eU alone. Further investigation, taking into account soil geochemical data such as Fe, Ca, La, Y, Zr, Al, Mg and Ca distributions, would be likely to improve estimated radon.

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