Geological controls on radon potential in Northern Ireland

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Abstract

Moderate and high radon potential in Northern Ireland is associated mainly with (i) the Neoproterozoic psammites, semipelites, meta-limestones, volcanics and mafic intrusives of Counties Londonderry and Tyrone; (ii) Silurian Hawick Group greywackes and, to a much more limited extent Gala Group greywackes, in the southern sector of Counties Armagh and Down; (iii) Ordovician and Silurian acid intrusives and volcanics in eastern Counties Londonderry and Tyrone; (iv) Middle-Late Devonian conglomerates in County Tyrone; (v) Lower Carboniferous (Dinantian) limestone in the western sector of Northern Ireland, especially in County Fermanagh; (vi) Palaeogene and Late Caledonian acid intrusive rocks of the Mourne Mountains Complex, Slieve Gullion Complex and Newry Granodiorite Complex in the SE sector in County Down and County Armagh.

Moderate to high radon potential is sometimes associated with glacio-fluvial sand and gravel deposits where these overlie a range of bedrocks, some of which have relatively low radon potential. In this latter case the enhanced radon potential is probably caused by the high permeability of superficial deposits. Radon potential tends to be lower when bedrocks characterised by moderate or high radon potential are overlain by relatively impermeable silt-clay alluvium, glaciolacustrine, and lacustrine deposits; peat; and glacial till and moraine. Redistribution of rock debris derived from uranium-rich bedrocks, such as the Mourne Mountains granites, through glacial, alluvial and other processes can also result in higher radon potential being associated with superficial deposits relative to underlying bedrocks.

Keywords

Geology, Northern Ireland, Radon

1. Introduction

Radon (^{222}Rn) is produced by the radioactive decay of radium (^{226}Ra), which in turn is derived from the radioactive decay of uranium. Uranium is found at variable concentrations in all soils and rocks. The most important factors controlling the migration and accumulation of radon in buildings include: (i) characteristics of the bedrock and soils that affect fluid transport, including porosity and permeability; (ii) the construction of the building and its use which includes the level of ventilation and heating; and (iii) environmental factors such as temperature (increased heating in buildings during the colder months causes a stack effect which draws soil gases including radon into the property), plus wind speed and direction which can increase the stack effect. Radon in soil air can be drawn into buildings through gaps and cracks in solid floors, walls and service pipes below construction level; through the voids in suspended floors and crawl spaces, and via small cracks or pores in hollow-block walls or wall cavities.

Radon can accumulate in buildings and provides about 50% of the total radiation dose to the average person in the UK (Watson et al., 2005). Radon gas decays to form short-lived solid radioactive decay particles that can enter the body by inhalation and has been linked to an increase in the risk of developing lung cancer. Radon is responsible for an estimated 1,100 lung cancer deaths a year in the UK (McColl et al., 2010) and is the second largest cause of lung cancer deaths after smoking (HPA, 2009). Radon concentrations in outdoor air in the UK are generally low, on average 4 Bq m^{-3} (becquerels per cubic metre) whilst radon in indoor air in UK dwellings ranges from less than 10 Bq m^{-3} to over 17 000 Bq m^{-3} (Rees et al., 2011) with a population-weighted average of 20 Bq m^{-3}. PHE (Public Health England) recommends that radon levels should be reduced in homes where the annual average is at or above 200 Bq m^{-3}. This is termed the Action Level. PHE defines radon Affected Areas as those with 1% chance or more of a house having a radon concentration at or above the Action Level. PHE advises that homes in radon Affected Areas should be tested for radon.

Geology is usually one of the most important factors controlling the distribution and level of indoor radon and the radon hazard. A previous study (Appleton and Miles, 2010) demonstrated that mapped bedrock geology explains on average 25% of the variation of indoor radon in England and Wales, 17% in Scotland and 11 % in Northern Ireland. Mapped superficial geology explains, on average, an additional 1 to2% (Appleton and Miles, 2010). In England, the proportion of the total variation controlled by geology is lower (14%) where the influence of confounding geological controls, such as uranium mineralisation, cut across mapped geological boundaries (Appleton and Miles, 2010).

Published data for Northern Ireland indicate that the geological units associated with the highest levels of naturally occurring radon are: (i) Late Caledonian and Palaeogene acid intrusive rocks of the Mourne Mountains, (ii) Carboniferous limestones and some Carboniferous shales (iii) Silurian Hawick Group greywackes, and (iv) Neoproterozoic psammites, semipelites and meta-limestones in the western sector of Northern Ireland (Appleton et al., 2011). This paper describes in greater detail the geological control on radon potential in Northern Ireland based on a new geological radon potential map compiled using recently published 1:10,000 scale digital geological map data and 23,000 radon measurements in homes held by Public Health England (PHE). It replaces the current maps presented as radon potential in 1-km squares on the Irish grid (Green et al., 2009).

Access to accurate radon maps is essential to enable preventative (protective) measures to be installed in new buildings (Radon: guidance on protective measures for new buildings in Northern Ireland; BR-413); to help identify houses and workplaces that are at elevated risk of having radon above the Action Level which should be measured for radon and have high levels remediated; and to allow measurement campaigns and public awareness to be targeted on areas at greatest risk. The radon map data helps local authorities to communicate quickly and effectively with existing homeowners or developers planning to build new homes in radon Affected Areas.

However, it is important to remember that a wide range of indoor radon levels is likely to be found in any particular area. This is because there is a long chain of factors that influence the radon level found in a building, such as radium content and permeability of the ground below it, and construction details of the building (Miles & Appleton, 2000). Radon potential does not indicate whether a building constructed on a particular site will have a radon concentration that exceeds the Action Level. This can only be established through measuring radon in the building. Radon potential indicates the probability that homes in a locality will have radon above the Action Level. This informs decisions about whether to test specific premises for radon.

This paper is the last of a series that describes the radon potential of geological units in the UK (Appleton and Miles, 2005; Scheib et al, 2009; Scheib et al., 2013). Reference is made to the Tellus airborne gamma spectrometry eU (equivalent uranium) and soil total U data (Appleton et al., 2008, 2011).

2. Materials and methods

2.1 Radon mapping

The factors that influence radon concentrations in buildings are largely independent and multiplicative so the distribution of radon concentrations is usually lognormal. Therefore lognormal modelling was used to produce accurate estimates of the proportion of homes above the Action Level in the UK (Miles, 1998; Miles et al., 2007). When indoor radon measurements are grouped by geology and 1-km squares of the national grid, the cumulative percentage of the variation between and within mapped geological units is shown to be 34–40% (Appleton and Miles, 2010). Combining the grid square and geological mapping methods gives more accurate maps than either method can provide separately (Appleton and Miles, 2002; Miles and Appleton, 2005). The integrated mapping method allows significant variations in radon potential within bedrock geological units to be identified.

The reliability and spatial precision of the mapping method is, in general, proportional to the indoor radon measurement density and the accuracy of the geological boundaries. Other uncertainties in the mapping process relate to house-specific factors, proximity to geological boundaries and measurement error (Hunter et al., 2009, 2011; Miles and Appleton, 2005).

The radon mapping method has been used to produce the current radon maps and indicative atlases for England and Wales (Appleton and Miles, 2005; Miles et al., 2007; Scheib et al., 2013) and Scotland (Scheib et al., 2009; Miles et al., 2011).

The radon potential map described here for Northern Ireland is based on 23, 000 indoor radon measurements made by PHE and 1: 10 000 scale digital geology information provided by the Geological Survey of Northern Ireland (GSNI), or 1: 250 000 scale digital geology in those areas where the 1 : 10 000 data is not yet available (Figure 1). The indoor radon measurements were made using two passive integrating detectors placed in each dwelling for 3 months (Green et al., 2009).

The land area is first divided up using a combination of bedrock and superficial geological characteristics derived from GSNI 1: 10 000 DiGMap and 1: 250 000 scale digital geological map data (Figure 1; GSNI 1991, 1997; http://www.bgs.ac.uk/gsni/geology/status/index.html). Each different combination of geological characteristics may appear at the land surface in many discontinuous locations across the country.

In order to facilitate the seamless 1-km interpolation of radon potential within major geological units, simplified bedrock and superficial geology classification systems were developed. These ensure continuity and also group some geological units with similar characteristics. Grouping similar geological units ensured that there were a sufficient number of indoor radon measurements for intra-geological unit grid square mapping to be carried out over a greater proportion of Northern Ireland. There are 360 named 1: 10 000 scale bedrock geological units in Northern Ireland and 44 bedrock units in the area with only 1: 250 000 scale bedrock geology. These were grouped using a simplified bedrock classification comprising 69 units. The geological map in Figure 2 was produced after additional grouping of bedrock units on the basis of age. There are 12 individually named 1: 250 000 scale superficial geological units and 27 1: 10 0000 scale superficial geology units. A simplified superficial geology classification comprising 13 units was used in the radon mapping procedure (Table 1; Figure 3). Once the superficial geology has been unioned (combined) with bedrock geology there are a total of 466 bedrock/superficial (BS) geology combinations. The geology of Northern Ireland is summarised in Mitchell (2004).

Table 1 Simplified superficial geology classsification

Description	Code	Permeability[a]
ALLUVIUM (SILT-CLAY)	ALV	Low
BEACH DEPOSITS (SAND-GRAVEL)	BEA	Medium
BLOWN SAND	BSD	Medium
CALCAREOUS TUFA	CAL	Medium
GLACIOFLUVIAL &-LACUSTRINE (SAND-GRAVEL)	GFL	High
GLACIOLACUSTRINE (SILT-CLAY)	GLA	Low
HEAD	HEA	Medium
LACUSTRINE (SILT-CLAY)	LSC	Low
LACUSTRINE (SAND-GRAVEL)	LSG	Medium
PEAT	PEA	Low
RIVER TERRACE (SAND-GRAVEL)	RTE	High
TILL-MORAINE (DIAMICTON)	TIM	Low-Medium
TIDAL-INTERTIDAL (SILT-CLAY)	TSC	Low

[a] based on information in Ball et al. (2005) as explained in Appleton et al. (2011)

Accurate coordinates for house measurement results are required for the radon mapping method. Of the approximately 24,000 radon measurements for domestic dwellings available in Northern Ireland (Green et al., 2009), 23,000 have precise coordinates obtained from the Land and Property Services (LPS) Pointer® location data (http://maps.osni.gov.uk/CMSPages/moreinfo_address_data.aspx). These results were used for preparing the radon maps. Each of these measurements is allocated to the bedrock–superficial geological combination underlying it. Taking each geological combination in turn, the spatial variation of radon potential is mapped, treating the combination as if it were continuous over the land area. All of the maps of radon potential within different geological combinations are then combined to produce a map of variation in radon potential over the whole land surface.

The simplified bedrock and superficial geology ArcGIS SHP files were unioned and intersected with a 1-km grid, derived from the Irish National grid, using ArcGIS geoprocessing tools. Radon potential estimates were made for each 1km\Bedrock\Superficial (1km-BS) polygon, initially following the methods described in Table 1 in Appleton et al. (2011). In cases where there were too few (in this study <80) house radon results available for a bedrock\superficial (BS) geological combination to allow the spatial variation to be mapped using the combined geology-grid square radon mapping method described by Miles and Appleton (2005), a number of different approaches were taken, dependent on the number of indoor radon measurements and their distribution (Table 2). The uncertainty of the estimated radon potential (RP; %> 200 Bq m^{-3}) increases substantially as the number of measurements used to make the estimate decreases (Miles and Appleton, 2005).

Table 2 **Methods used for calculating the estimated percentage of dwellings above 200 Bq m^{-3} for each 1km bedrock\superficial (1km-BS) polygon for the radon potential (RP) map**

No. of radon measurements in BS group	No. of 1km-BS polygons	Description of method used to estimate RP (%>200 Bq m^{-3})
>79	27361	RP based on geometric mean (GM) and geometric standard deviation (GSD) of all measurements in a polygon if >30 or nearest 30 radon measurements or; Bayesian 1km-BS GSD corrected for measurement uncertainty
25 – 79	12885	RP based on GM of nearest 10 measurements; GSD is average of BS GSD and 1km-BS GSD corrected for measurement uncertainty
10 – 24	10761	RP based on GM of all data in the same BS group in N Ireland; GSD is average of UK national BS GSD and BS GSD, both corrected for measurement uncertainty
3-10	8811	RP based on GM of all data in the same BS group in N Ireland and UK national GSD corrected for measurement uncertainty
0	8592	Assessment of RP based on analogy with similar geological combinations for which radon data are available

Airborne gamma-ray spectrometry and soil geochemistry data from the Tellus Project have been used for predictive modelling of RP in Northern Ireland (Appleton et al., 2008, 2011). The data are used here to help explain the association of relatively high RP with glacial and alluvial deposits outside areas where high RP is associated with bedrock. Gamma spectrometry estimated uranium (eU) is on average only about a third of topsoil U concentration possibly due to (a) dilution caused by high organic content of the top 5 cm of the soil profile, (b) more water in peaty soils which will adsorb ^{214}Bi , and (c) a potential calibration problem with the airborne data (Appleton et al., 2008, 2011).

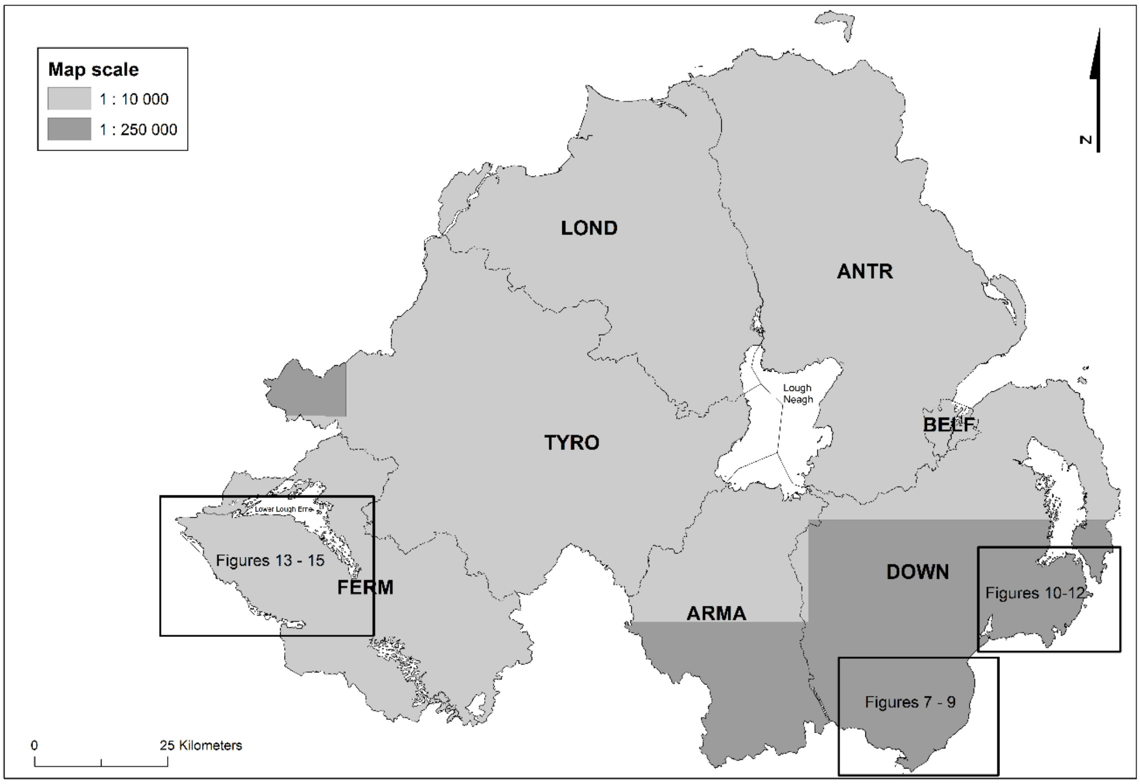

Figure 1 Scale of geological data used to produce radon map (boxes indicate areas covered by Figures 7-15) County Names: ANTR=Antrim, ARMA=Armagh, BELF=Belfast County Borough; DOWN=Down, FERM=Fermanagh, LOND=Londonderry, TYRO=Tyrone. (BGS © NERC 2014. Based on LPS data © Crown Copyright & Database Right 2014, DMOU 205)

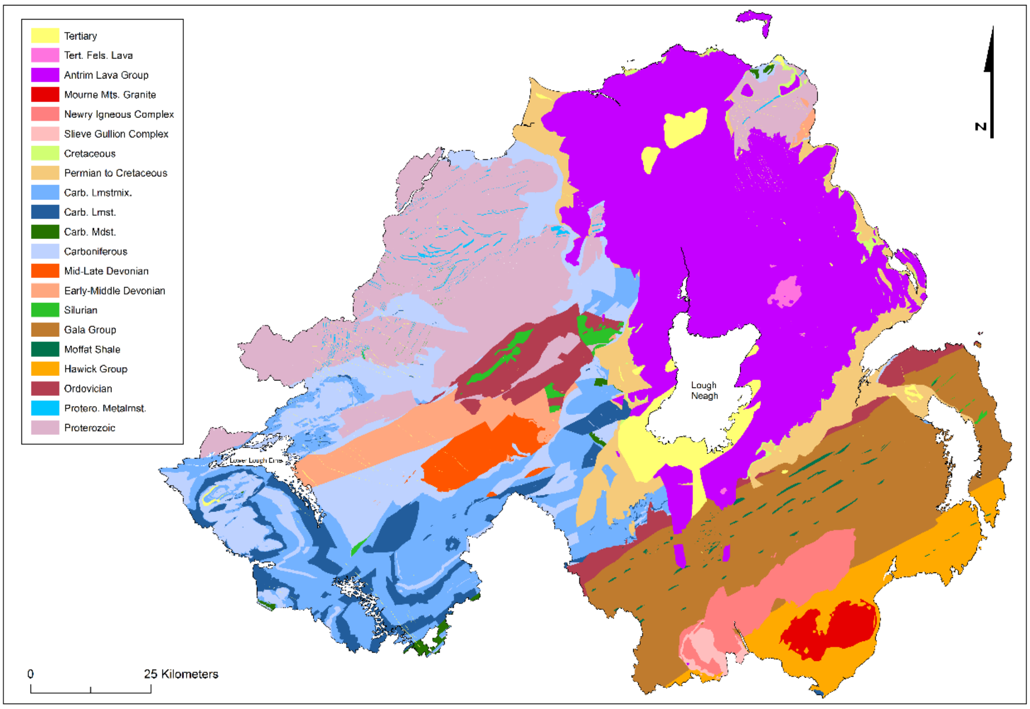

Figure 2 Simplified bedrock geology of Northern Ireland (BGS © NERC 2014. Geological data, GSNI © Crown copyright 2014. Based on LPS data © Crown Copyright & Database Right 2014, DMOU 205)

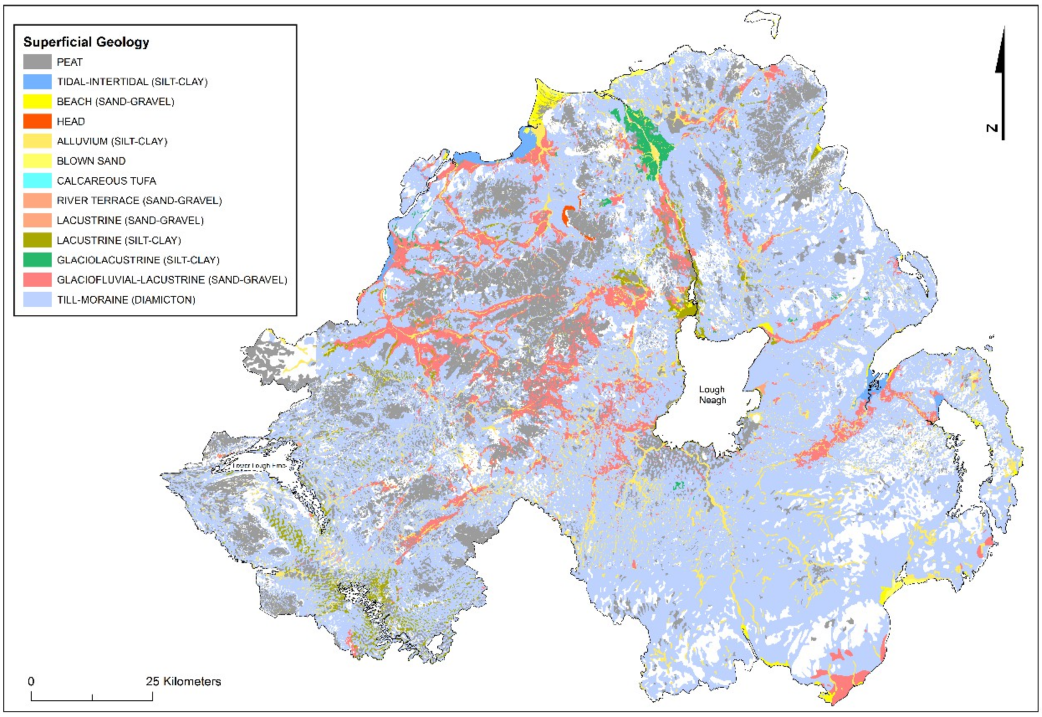

Figure 3 Simplified superficial geology of Northern Ireland (uncoloured = bedrock at surface) (BGS © NERC 2014. Geological data, GSNI © Crown copyright 2014. Based on LPS data © Crown Copyright & Database Right 2014, DMOU 205)

2.2 Analysis of Variance

One way analysis of variance (ANOVA) in MINITAB® 15 was used to calculate the proportion of the variation of indoor radon concentrations explained by geology (bedrock\superficial geology combination) using the sum of squares between group means. The F-statistic was utilised to measure significance level (p-value) and the fraction of the variation related to geology was always significant statistically ($p < 0.0001$). The application of a log-transform in general produces more normal distributions with lower skewness coefficients so indoor radon data were log-transformed (Log_e). ANOVA and non-parametric Kruskal-Wallis statistics (not reported here) for indoor radon data grouped using the simplified geology classification have comparable p values.

3. Results and discussion

3.1 Analysis of variance

Using the indoor radon data for bedrock\superficial geology (BS) combinations with 9 or more LnRn values (22622 of 23040 available radon measurements), 12.1% of the variation is explained by BS (Table 3). The percentage variances are slightly higher when all indoor radon data are included in the ANOVA. When bedrock (B), superficial (S) and 1 km grid square (KM1) are included in the nested ANOVA, the % variances are 9.3, 3.6 and 20.2% respectively.

The percentage variance explained by geology is higher for the 10k sector than the 250k sector (Figure 1 and Table 3).These results could indicate that attribution of geology to indoor radon locations is more accurate at 10k than 250k or that bedrocks and superficial units in 10k area exhibit greater RP contrast between BS combinations than in the 250k area. Most of the bedrocks are different in the two areas and only the Silurian Gala Group (greywackes) occurs in both the 10k and 250k areas in sufficient numbers for ANOVA (10k area: n = 1240; 250k area: n = 2374). For the Gala Group subset of the radon data, superficial geology (S) explains 4.9% (DF=6) and 1.7% (DF=4) of the variance in the 10k and 250k sectors.

Nested ANOVA indicates that 9% of the variance can be attributed to bedrock (B) and 4.7% to superficial (S) geology when all the data are taken whilst the corresponding figures for the 10k sector are 13% for bedrock and 4% for superficial geology (Table 3). In the 250k sector only 3% of the variance can be attributes to bedrock and 6% to superficial geology, both of which are surprisingly low. This could be caused by glacial transport of rock debris with relatively high uranium concentrations, derived from the Palaeogene intrusive rocks, onto surrounding bedrock units with correspondingly lower U concentrations and lower radon potential.

Table 3 One-way (BS) and nested (B, S) analysis of variance for all BS combinations with > 9 measurements; number in brackets is degrees of freedom)

	Number of Rn measurements	Bedrock\superficial (BS)	Bedrock (B)	Superficial (S)
All N Ireland	22621	12.1 (97)	9.0 (31)	4.7 (66)
250k sector	12218	7.0 (22)	2.9 (8)	6.0 (14)
10k sector	10372	14.2 (81)	12.7 (26)	3.8 (55)

Nested ANOVA indicates that the percentage of the variation within bedrocks with more than 500 radon measurements explained by superficial geology (S) is very low or low (<0.1 – 6%, Table 4) whilst lateral variation between 1-km (KM1) grid squares within BS combinations (i.e. intra-unit) explains 8 to 25% of the variance, being highest for the Hawick Group (HWK-SDST; Table 4).

Table 4 Analysis of variance of indoor radon measurement data for selected bedrocks (B) with >500 measurements and >9 measurements for each KM1BS combination (number in brackets is degrees of freedom)

Bedrock (B)	Geological map scale	No. Rn measurements in subset	% variance by superficial geology	% variance by KM1 (intra-BS variance)
Gala Group (greywackes)	10k+250k	1420	2.4 (4)	8.3 (49)
Hawick Group (greywackes)	250k	4969	6.4 (5)	25.1 (111)
Newry Igneous Complex	250k	2259	0.8 (3)	11.5 (49)
Proterozoic (psammites)	10k	1913	<0.1 (4)	17.6 (66)

ANOVA indicates that spatial variation in radon concentrations within BS combinations with more than 500 radon measurements explains 6 to 27% of the total indoor radon variance (Table 5).

Table 5 Analysis of variance of indoor radon measurement data for selected bedrock\superficial combinations with >500 measurements and >9 measurements for KM1BS combinations (number in brackets is degrees of freedom)

Bedrock\superficial combination	Geological map scale	No. Rn measurements in subset	No. KM1 squares with >9 Rn measurements	% variance by KM1
Gala Group\bedrock	10k+250k	527	18	9.6 (17)
Gala Group\till-moraine	10k+250k	828	31	5.7 (36)
Hawick Group\glaciofluvial-lacustrine	250k	1158	21	11.6 (20)
Hawick Group\till-moraine	250k	2309	65	27.4 (64)
Newry Igneous Complex\till-moraine	250k	1912	32	11.6 (42)
Proterozoic psammites\glaciofluvial-lacustrine	10k	990	31	18.2 (32)
Proterozoic psammites\till-moraine	10k	647	27	16.2 (26)

3.2 Summary statistics

Summary statistics (Table 6) for bedrocks not covered with superficial deposits were determined for those bedrock units with two or more radon measurements. Geometric means (GM) were calculated for indoor radon and soil U in preference to arithmetic means (AM) because of their lognormal distributions. Average (AM) eU (gamma ray spectrometry) data are included as eU data are mainly normally distributed (Appleton et al., 2008). The distributions of indoor radon data for bedrock units not covered by superficial deposits and with 10 or more measurements are illustrated in Figure 4.

In the following analysis of the relationship between geology and radon potential, Low, Moderate, High and Very High radon potential are used to describe geological units characterised by <2%, 2-6%, 6-12% and >12% of dwellings estimated to exceed the radon Action Level (200 Bq m^{-3}). These class limits were selected because they help to highlight the contrasting radon potentials of the major geological units in Northern Ireland (Figure 2).

Table 6 Summary statistics for bedrock geological units with 2 or more indoor radon measurements (dom. = dominant; nd = no data)

		Rn Bq m^{-3}				eU mg kg^{-1}		Soil U mg kg^{-1}		
Bedrock Code	Bedrock description	No.	GM	Max	%>AL	Max.	Avg.	No.	Max.	GM
PGU-MADY	Palaeogene, basic dyke	2	48	122	0.89	2.9	0.6	2	3.1	2.2
PGU-MAIN	Palaeogene, mafic intrusive	9	26	191	0.36	4.2	0.3	5	1.8	1.4
ALG-BLAV	Antrim Lava Group, basic lava	108	19	99	<0.01	4.2	0.2	270	2.7	1.1
OLIG-MDMIX	Oligocene, mudstone dom.	3	18	46	0.07	1.2	0.1	nd	nd	nd
MNG-GRAN	Mourne Mountains Granite	2	108	163	21.91	18.2	4.3	38	142.9	7.1
SGD-AGGL	Slieve Gullion Complex, agglomerate	2	59	80	1.7	3.3	1.6	nd	nd	nd
SGD-FEIN	Slieve Gullion Complex, felsic intrusive	15	73	1072	12.61	4.8	1.7	12	46.4	6.0
SGD-MAIN	Slieve Gullion Complex, mafic intrusive	19	54	188	4.69	4.5	1.2	4	6.6	3.1
CRET-SED	Cretaceous, sedimentary rocks	13	28	223	2.05	3.8	0.4	11	2.4	1.1
JUR-SED	Jurassic, sedimentary rocks	7	29	223	1.7	2.3	0.2	1	2.0	2.0
TRI-MDST	Triassic, mudstone dom.	5	19	27	0.08	4.5	0.5	13	3.3	1.5
PER-SDMIX	Permian, sandstone dom.	2	33	60	0.95	4.2	0.4	3	2.9	1.7
DIN-MDST	Dinantian, mudstone	4	169	313	41.66	2.9	1.2	1	2.8	2.8
DIN-MDMIX	Dinantian, mudstone dom.	10	38	84	0.24	2.7	1.0	10	3.4	2.6
DIN-SDMIX	Dinantian, sandstone dom.	71	31	287	1.86	3.3	0.6	42	9.5	2.4
DIN-LMMIX	Dinantian, limestone dom.	87	55	610	6.98	5.0	0.9	36	6.9	3.1
DIN-LMST	Dinantian, limestone	65	53	657	6.85	5.1	0.9	30	10.3	3.1
MLDEV-COMIX	Mid-Late Devonian, conglomerate dom.	66	52	303	6.03	2.5	0.8	25	2.8	2.4
MDEV-SDMIX	Middle Devonian, sandstone dom.	3	28	74	0.54	2.5	0.9	3	2.7	2.5
EDEV-SDMIX	Early Devonian, sandstone dom.	16	24	185	0.43	3.4	1.1	10	5.5	3.1
NEGD-GD	Newry Igneous Complex, granodiorite	200	54	455	5.94	6.8	1.4	27	10.3	3.8
SIL-FEIN	Silurian, felsic intrusive	14	61	425	14.25	2.4	0.8	10	2.5	1.2
GALA-GWMIX	Silurian, Gala Group, greywacke dom.	1265	41	1325	0.91	6.9	1.3	178	6.9	2.9
MFS-MDST	Silurian, Moffat Shale Fm., mudstone	2	34	42	1.05	4.1	1.3	nd	nd	nd
HWK-SDST	Silurian, Hawick Group, greywacke dom.	505	61	1578	4.78	7.9	1.5	55	23.2	3.3
UORD-GWMIX	Upper Ordovician, greywacke dom.	2	36	43	1.31	4.7	1.1	2	2.5	2.5
ORD-FEIN	Ordovician, felsic intrusive	3	79	125	11.96	2.3	0.7	nd	nd	nd
UIIO-FEIN	Ordovician, felsic intrusives	4	17	31	0.05	2.0	0.6	1	2.5	2.5
TPG-MAIN	Ord. Tyrone Plutonic Group, mafic intr.	10	50	114	1.4	2.3	0.4	5	2.8	2.1
TVG-VOLC	Ord. Tyrone Volcanic Group, volcanics	26	75	376	14.56	2.7	0.6	6	22.4	3.1
NE-NEOP-PSP	Proterozoic (NE Antrim), psammite dom.	6	16	20	0.04	3.5	0.7	3	2.1	1.7
NEOP-MAIN	Proterozoic, mafic intrusion	14	37	205	2.91	2.7	0.7	2	2.9	1.9
NEOP-MELS	Proterozoic, metalimestone	17	58	230	5.05	2.7	1.0	3	3.5	2.3
NEOP-PSP	Proterozoic, psammite dom.	479	50	958	5.95	4.0	0.8	79	4.1	2.1
NEOP-VOLC	Proterozoic, volcanics	47	46	275	3.01	2.6	0.6	1	2.3	nd

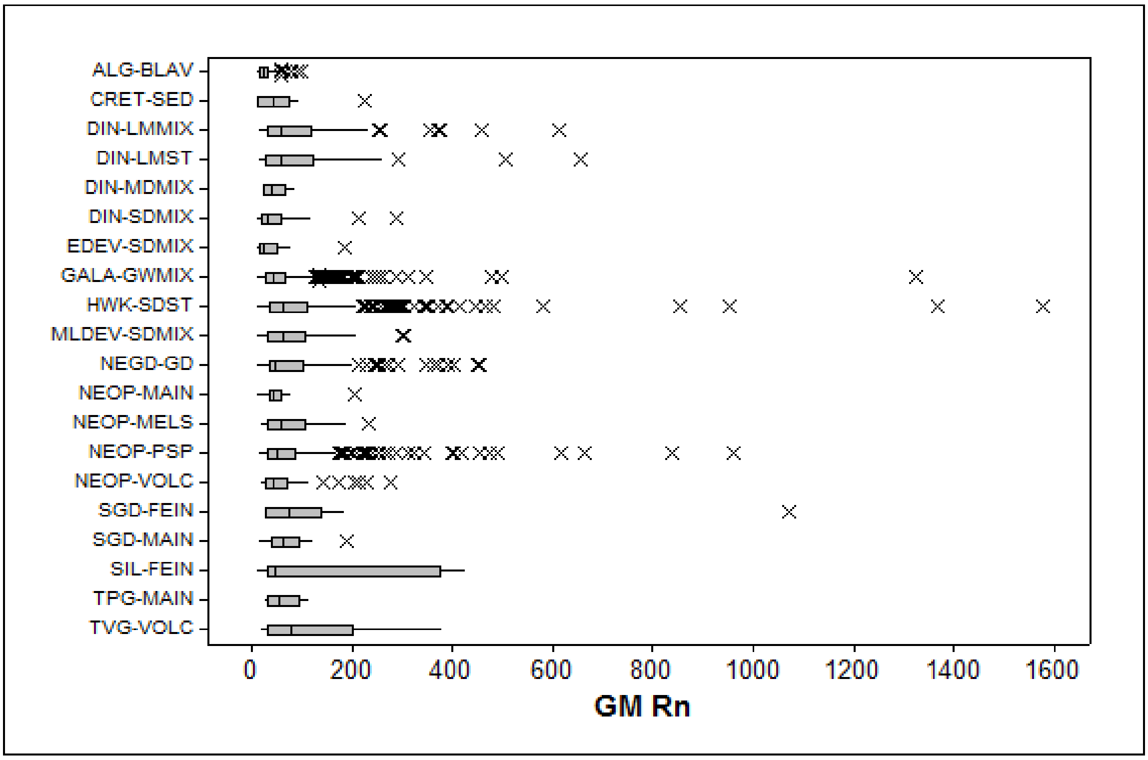

Figure 4 Boxplot of indoor radon (Bq m^{-3}) for bedrock units not covered by superficial deposits and with >9 measurements (boxes = interquartile range; X = outlier)

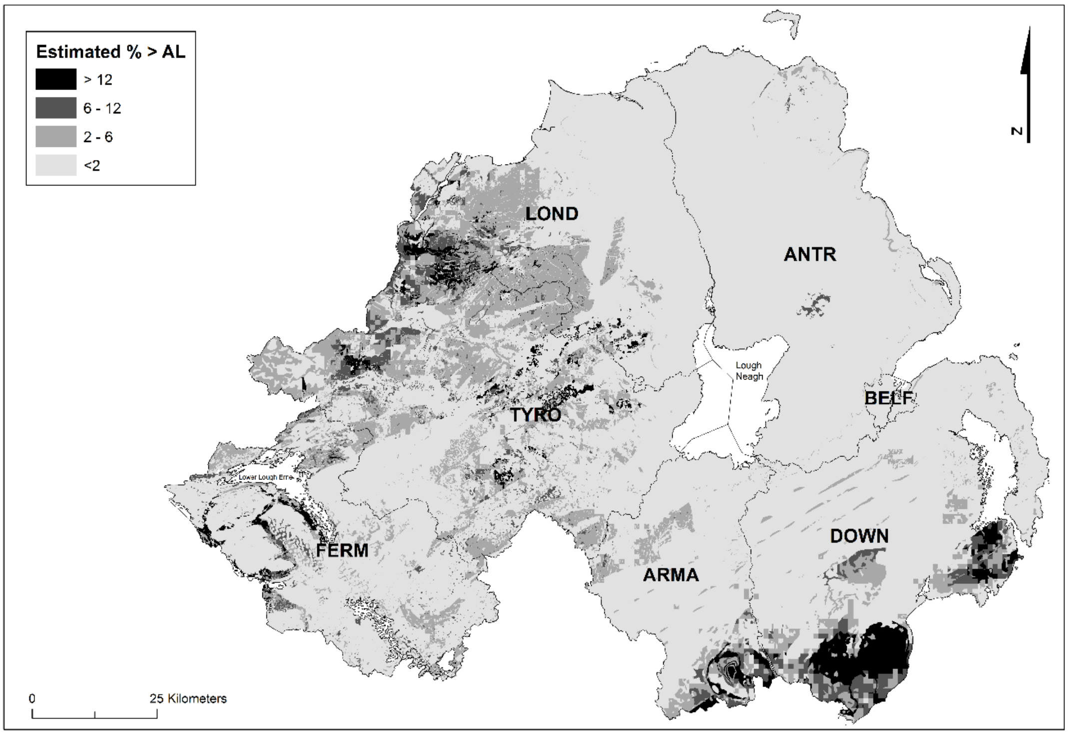

Figure 5 Joint HPE-BGS radon potential map of Northern Ireland showing the percentages of dwellings estimated to exceed the radon Action Level (200 Bq m^{-3}). County Names: ANTR=Antrim, ARMA=Armagh, BELF=Belfast County Borough; DOWN=Down, FERM=Fermanagh, LOND=Londonderry, TYRO=Tyrone. (BGS © NERC 2014. Radon data BGS © NERC 2014/PHE © Crown copyright 2014. Based on LPS data © Crown Copyright & Database Right 2014, DMOU 205)

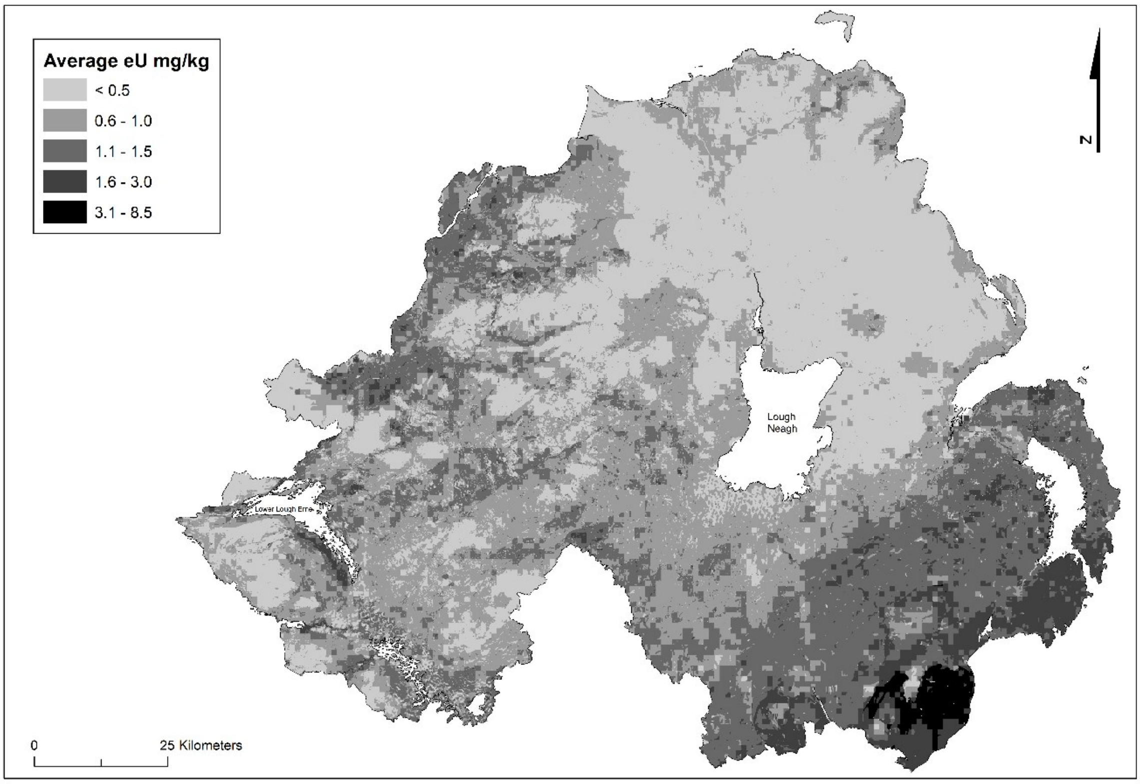

Figure 6 Average eU (mg kg^{-1}) for airborne gamma-ray spectrometry data grouped by 1-km\BS polygons. (BGS © NERC 2014. Tellus and Geological data, GSNI © Crown Copyright 2014. Based on LPS data © Crown Copyright & Database Right 2014, DMOU 205)

3.3 Proterozoic

The metamorphic basement of Northern Ireland mainly comprises Dalradian (Neoproterozoic) age psammites, semi-pelites, and meta-quartzites with subsidiary meta-limestone, graphitic schistose pelites, meta-volcanics and basaltic volcaniclastic rocks. The meta-limestones range up to 100m thick and often comprise limestone beds up to 1 m thick separated by dark grey to black pelite. There are two relatively small areas of Pre-Dalradian psammites in the Lough Derg Inlier and the Central Inlier which have higher metamorphic grade (granulite facies) than the younger Dalradian rocks (greenschist to amphibolite facies). The Dalradian inlier in the northeast of Co. Antrim comprises mainly schistose psammites, semipelites with subsidiary amphibolite and meta-limestone. For radon mapping, the Dalradian and pre-Dalradian have been grouped together and subdivided into psammites (NEOP-PSP), meta-limestones (NEOP-MELS), mafic igneous intrusions (NEOP-MAIN), meta-volcanics (NEOP-VOLC) and felsic meta-igneous (NEOP-FEIN). The psammites (PSP) that underlie most of the western Proterozoic terrain have an average radon potential of 6% (number of radon measurements (n) = 479), being slightly higher than meta-limestones (5%, n = 17) and double that of the mafic intrusives (3%, n=14) and volcanics (3%, n = 47). Where glaciofluvial and lacustrine sand and gravel (GFL) overlies mafic intrusives and meta-limestones, the radon potential is substantially higher (9%), whilst GFL overlying volcanics is much lower (0.9%) and GFL over psammites is only slightly lower than bedrock (5% compared with 6%). In general, radon potential would be expected to be higher for ground underlain by GFL compared with ground underlain by bedrock due to the higher permeability of the GFL. Relatively few radon measurements are available for other superficial units overlying Proterozoic psammites (n = 11 to 47) and these have average radon potentials in the range 2 – 8%. In some cases clay dominant, relatively impermeable superficial deposits (alluvium (ALV) and lacustrine – silt, clay (LSC)) over Proterozoic psammites have lower RP (2-3%), as would be expected, whilst the clay dominant tidal-intertidal deposits (TSC) unexpectedly has higher RP (8%) than the bedrock. Areas with glacial till-moraine (TIM) overlying psammites have on average lower RP (3%) compared with bedrock (6%), which may result from lower ground permeability. However, 1-km grid RP for those bedrock\superficial combinations with >25 – 1795 measurements varies substantially from <1% to 56% (Table 7). Whilst the reason for this lateral variation is not known, it may reflect variations in the source of superficial deposits, soil chemistry, permeability or house construction characteristics.

Indoor radon data for the Proterozoic (Dalradian) inlier in northeast Antrim are mapped separately because they appear, on the basis of relatively few measurements, to be characterised by relatively low radon potential compared with the western Proterozoic terrain in County Tyrone and County Londonderry. For example, the radon potential of the psammites (NE-NEOP-PSP) and psammites overlain by till-moraine (NE-NEOP-PSP\TIM) in Antrim is less than 0.04% and 0.16% respectively compared with 5.95% and 3.25% in the western terrain (Table 7). Dwellings sited on glaciofluvial-lacustrine (sand-gravel; GFL) overlying psammites have higher radon potential (8%; n =5), as in the western terrain, presumably reflecting higher permeability of the ground.

Table 7 Summary radon statistics for Proterozoic (NEOP) bedrock\superficial geology combinations with 5 or more radon measurements in (i) N E Antrim and (ii) County Tyrone and Londonderry

Bedrock\superficial geology code[a]	No. Rn measurements	GM Rn. Bq m^{-3}	Max. Rn Bq m^{-3}	Ave. %>AL[b]	Min. %>AL[b]	Max. %>AL[b]
NE Antrim						
NE-NEOP-PSP\BEA	5	34	144	1.16		
NE-NEOP-PSP\GFL	5	65	135	7.57		
NE-NEOP-PSP	6	16	20	0.04		
NE-NEOP-PSP\TIM	32	29	95	0.16	0.00	1.10
County Tyrone and Londonderry						
NEOP-MAIN\GFL	23	64	584	9.40		
NEOP-MAIN	14	37	205	2.91		
NEOP-MAIN\TIM	36	40	412	3.63	0.00	10.69
NEOP-MELS\GFL	140	70	562	9.30	1.97	21.77
NEOP-MELS\GLA	6	48	152	3.40		
NEOP-MELS	17	58	230	5.05		
NEOP-MELS\TIM	137	42	816	4.33	0.02	9.01
NEOP-PSP\ALV	25	47	278	2.26	0.36	7.29
NEOP-PSP\GFL	1549	55	1460	4.66	0.02	55.96
NEOP-PSP\GLA	47	55	500	5.41	0.12	22.43
NEOP-PSP\LSC	26	59	186	2.95	1.17	3.40
NEOP-PSP\PEA	17	54	242	3.74		
NEOP-PSP	479	50	958	5.95	0.03	21.77
NEOP-PSP\RTE	11	35	4915	8.09		
NEOP-PSP\TIM	1795	48	1556	3.25	0.05	22.36
NEOP-PSP\TSC	41	57	358	8.23	3.81	33.54
NEOP-VOLC\GFL	30	40	124	0.93	0.04	2.61
NEOP-VOLC	47	46	275	3.01	0.02	15.64
NEOP-VOLC\TIM	9	49	640	3.59		

[a]Explanation of superficial and bedrock geology codes in Tables 1 and 6 [b]Estimated by lognormal modelling

3.4 Palaeozoic

Surrounding the Proterozoic central Inlier is the early Palaeozoic Tyrone Igneous Complex comprising the mafic igneous intrusions (gabbro, dolerite, basalt) of the Ordovician Tyrone Plutonic Group (TPG-MAIN) which has low RP (1%, n = 10, Table 6), and the ophiolites, basic to intermediate pillow lavas, volcaniclastic tuffs, rhyolites and banded chert with subsidiary ironstones and graphitic mudstones of the Tyrone Volcanic Group (TVG-VOLC) which has a very high average RP (15%, n = 26). The Pomeroy, Carrickmore and Beragh granite intrusions (UIIO-FEIN) appear, on the basis of only 4 radon measurements, to have low RP (<1%, n = 4) whilst the Silurian Slieve Gallion Granite and Laght Hill tonalite intrusions and rhyolites (SIL-FEIN) have very high RP (14%, n=14, Table 6). Where till-moraine

(TIM) and glacio-fluvial-lacustrine sand and gravel (GFL) overlie SIL-FEIN, the RP is moderate (3%); 1% and 2% respectively where TIM and GFL overlie UIIO-FEIN; 1% and 8% where Tyrone Volcanic Group (TVG-VOLC) is overlain respectively by TIM and GFL; and 1% and 9% when Tyrone Plutonic Group (TPG-MAIN) is overlain by TIM and GFL. This again highlights the enhancement of RP when bedrock is overlain by high permeability glaciofluvial-lacustrine sand and gravel compared with low-medium permeability till-moraine.

Most of the south east of Northern Ireland (Counties Down and Armagh) is underlain by Palaeozoic bedrocks of the Southern Uplands-Down-Longford Terrane. Greywackes of the Leadhills Supergroup (UORD-GWMIX; RP 1% for bedrock and bedrock overlain by TIM) occur along the northern margin of the terrane, followed to the south by greywacke sandstones, siltstones and mudstones of the Gala Group (GALA-GWMIX), intersected with subsidiary bands of the Moffat Shale Group (MFS-MDST), and finally by the greywackes of the Hawick Group (HWK-SDST). The RP of the Gala Group is generally low both where bedrock is at the surface (1%, range <0.1-10%; n=1265) and overlain by till-moraine (0.4%, range <0.1-5%; n=2140), alluvium, beach deposits, blown sand, and glaciofluvial-lacustrine sands and gravels (0.1 – 0.8%; n = 13-97; Table 8). The radon potential of ground mapped as peat overlying Gala Group is slightly higher (2.2%, n=25), which is rather unusual but may be related to uncertainties in the position of geological boundaries at the 1: 250 000 scale leading to incorrect attribution of geological codes to some indoor radon measurement locations. In addition (i) it is likely that peat would be removed before the construction of houses so that building foundations were excavated into older superficial deposits, such as till-moraine; (ii) a relatively low number of radon measurements will result in high uncertainty for the RP estimate; and (iii) different methods used to calculate RP (Table 2) will result in different uncertainties in RP estimates.

Table 8 Summary radon statistics for Gala and Hawick Group bedrock\superficial geology combinations with 5 or more radon measurements

Bedrock\superficial geology	No. Rn measurements	GM. Bq m-3	Max. Bq m-3	Ave. %>AL	Min. %>AL	Max. %>AL
Gala Group\alluvium	97	35	205	0.1	0.0	0.7
Gala Group\beach deposits	55	43	534	0.8	0.2	25.9
Gala Group\blown sand	19	20	55	0.1		
Gala Group\glaciofluvial-lacustrine	13	45	96	0.7		
Gala Group\peat	25	42	168	2.2	0.0	5.8
Gala Group \bedrock	1265	41	1325	0.9	0.0	10.2
Gala Group\till-moraine	2140	34	804	0.4	0.0	4.9
Hawick Group\alluvium	183	37	696	10.6	0.0	42.5
Hawick Group\beach deposits	1046	48	883	6.4	0.0	21.5
Hawick Group\blown sand	91	26	148	0.0	0.0	0.1
Hawick Group\glaciofluvial-lacustrine	1265	77	939	15.9	0.1	45.6
Hawick Group\bedrock	505	61	1578	4.8	0.0	23.0
Hawick Group\till-moraine	3337	50	2504	4.9	0.0	26.4

The Hawick Group bedrock is characterised by moderate radon potential (4.8%, range <0.01 – 23%), being very similar where Hawick Group bedrock is overlain by till-moraine (4.9%; range <0.01 - 26%). Hawick Group overlain by till and moraine immediately to the south of the Mourne Mountains Granite (MNG) has high to very high radon potential (7-24%), being highest (13-24%) on the SE margin of the intrusion (Figures 7 and 8). Figures 9, 12 and 15 show the Tellus airborne gamma-ray spectrometry eU data (integrated over flying distances of about 70m along flight lines 200-m apart) interpolated to the same bedrock\superficial geology-1km framework used for the production of the radon potential maps (Figures 8, 11 and 14). The proportional symbols indicate U concentrations in the Tellus survey topsoil samples (Figure 9, 12 and 15). Very high RP (13-24% and >24% is associated with alluvium in the valleys to the south and south-east of the Mourne Mountains Granite (MNG; Figure 8). The eU and soil U data suggest that this may be related to enrichment of U bearing minerals in alluvial sediments dispersed from the MNG (Figure 7). This supports the conclusions of Moles et al., (1995, 1998) based on a detailed stream sediment geochemistry survey. Small sectors of Beach sand and gravel and glaciofluvial-lacustrine (GFL) sand and gravel also have high radon potential, which may be caused by high permeability of these superficial deposits combined with enhanced U in surficial deposits derived from the Mourne Mountains Complex. In contrast, the radon potential of ground where blown sand (BSD) overlies HWK is <0.1%.

The sector of Hawick Group (HWK) with the highest RP is located on the Lecale peninsula, where very high RP (>24%) is associated with glaciofluvial-lacustrine deposits overlying HWK and very high (13-24%) and high (7-12%) RP is associated with both bedrock and very large sectors where HWK is overlain with till-moraine (Figures 10 and 11). Higher gamma ray spectrometry eU and soil U values are also associated with the HWK on the Lecale peninsula, although the spatial correlation with RP is imprecise (Figures 11 and 12).

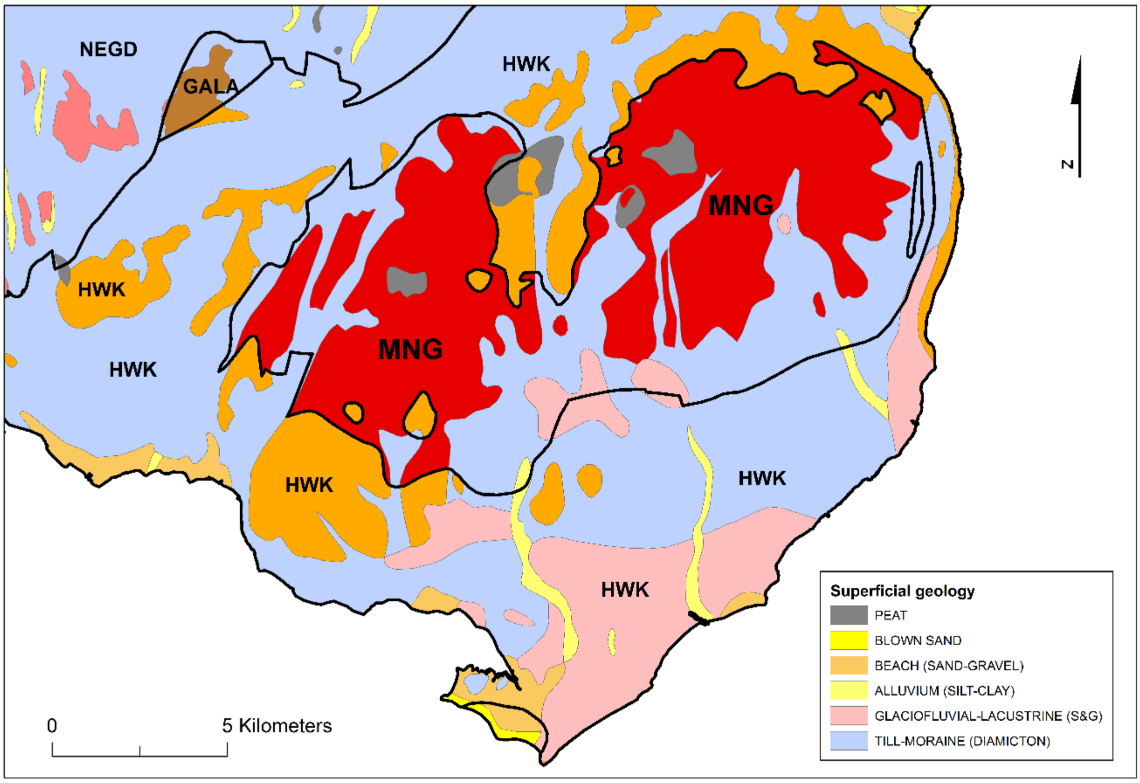

Figure 7 Geology of the Mourne Mountains area (Bedrock underlying superficial deposits (boundaries indicated by thick lines): HWK = Hawick Group; GALA = Gala Group; NEGD = Newry Igneous Complex; MNG = Mourne Mountains Complex) (BGS © NERC 2014. Geological data, GSNI © Crown copyright 2014. Based on LPS data © Crown Copyright & Database Right 2014, DMOU 205)

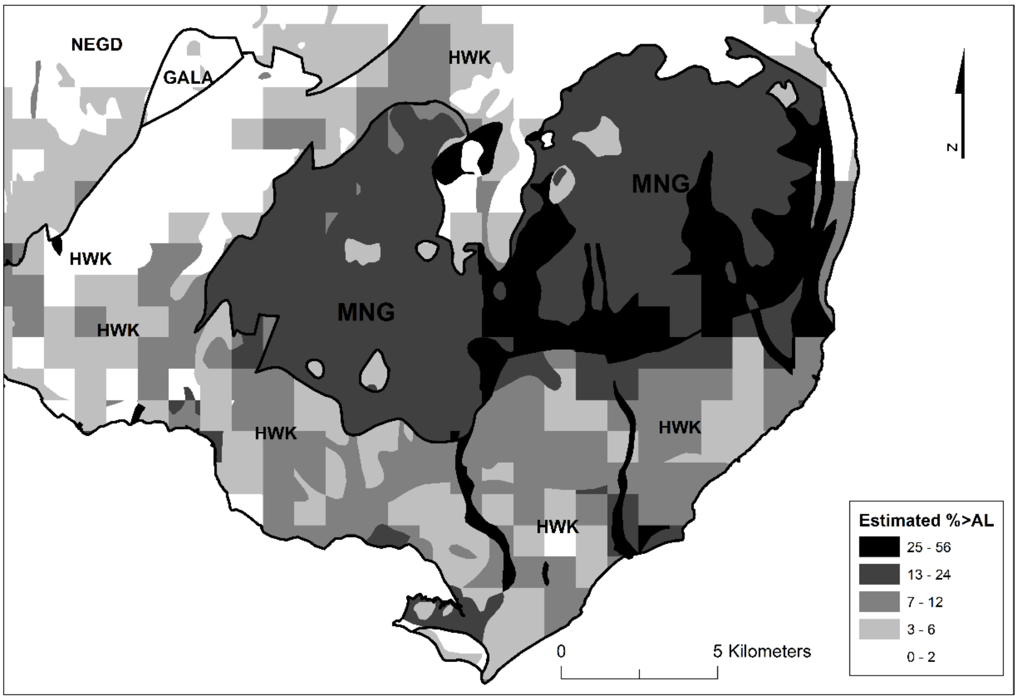

Figure 8 Radon potential of the Mourne Mountains area (bedrock boundaries indicated by thick lines) (BGS © NERC 2014. Radon data BGS © NERC 2014/PHE © Crown copyright 2014. Based on LPS data © Crown Copyright & Database Right 2014, DMOU 205)

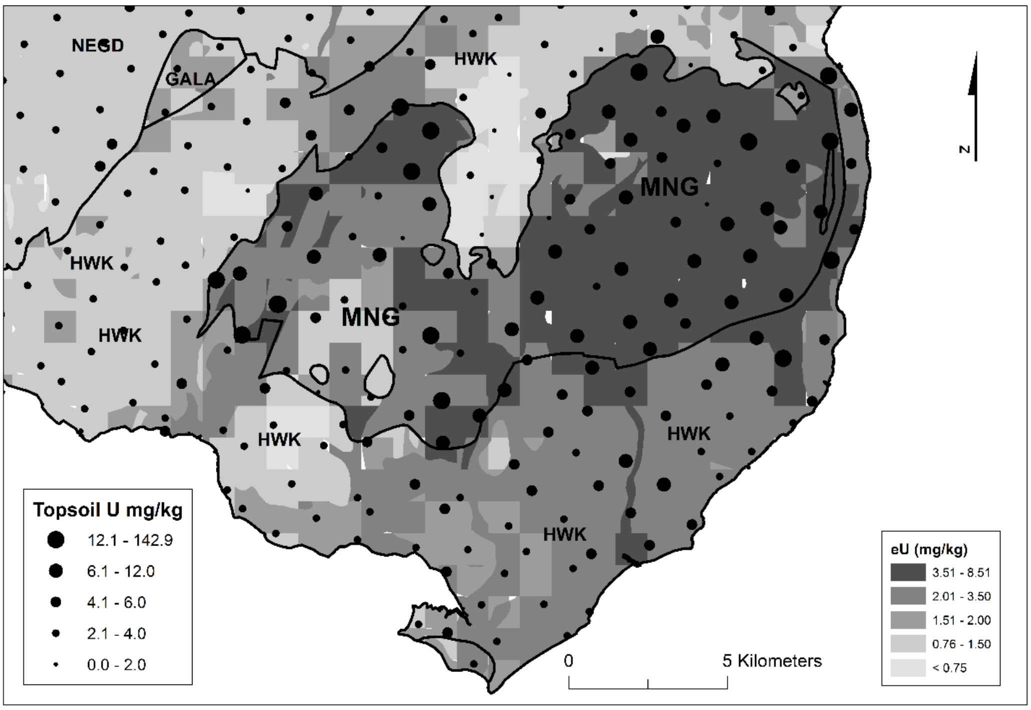

Figure 9 Gamma-ray spectrometry eU for the Mourne Mountains area interpolated by geology and 1-km grid square overlain by proportional symbol U (mg kg^{-1}) in surface soil samples (bedrock boundaries indicated by thick lines) (BGS ©

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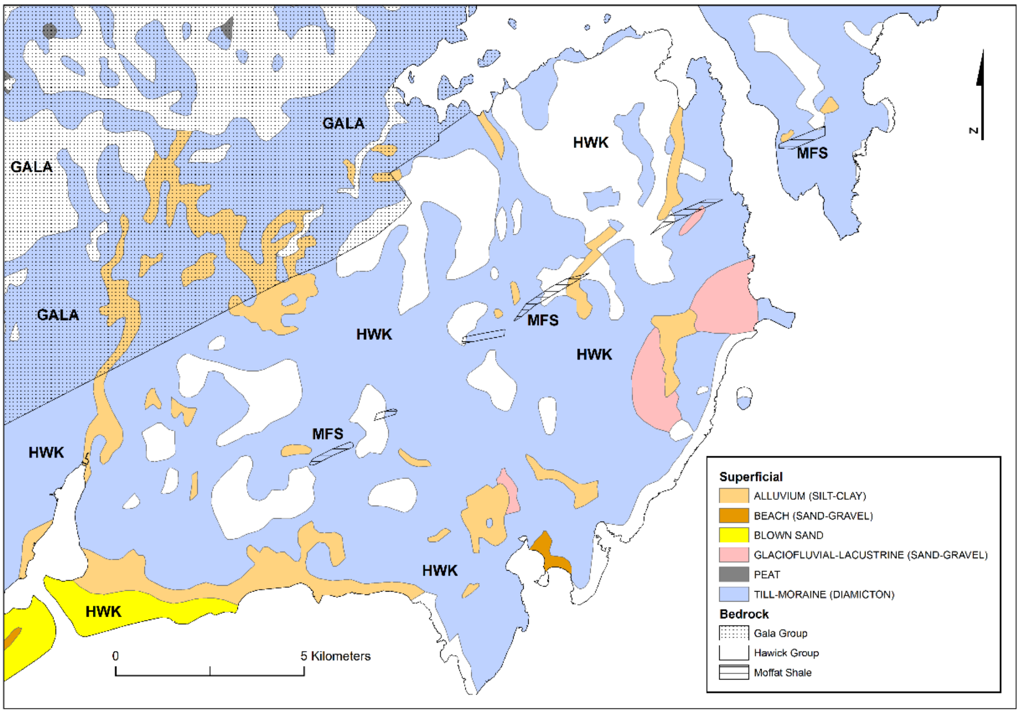

Figure 10 Geology of the Lecale peninsula (Bedrock: HWK - Hawick Group; GALA = Gala Group; MFS = Moffat Shale Formation) (BGS © NERC 2014. Geological data, GSNI © Crown copyright 2014. Based on LPS data © Crown Copyright & Database Right 2014, DMOU 205)

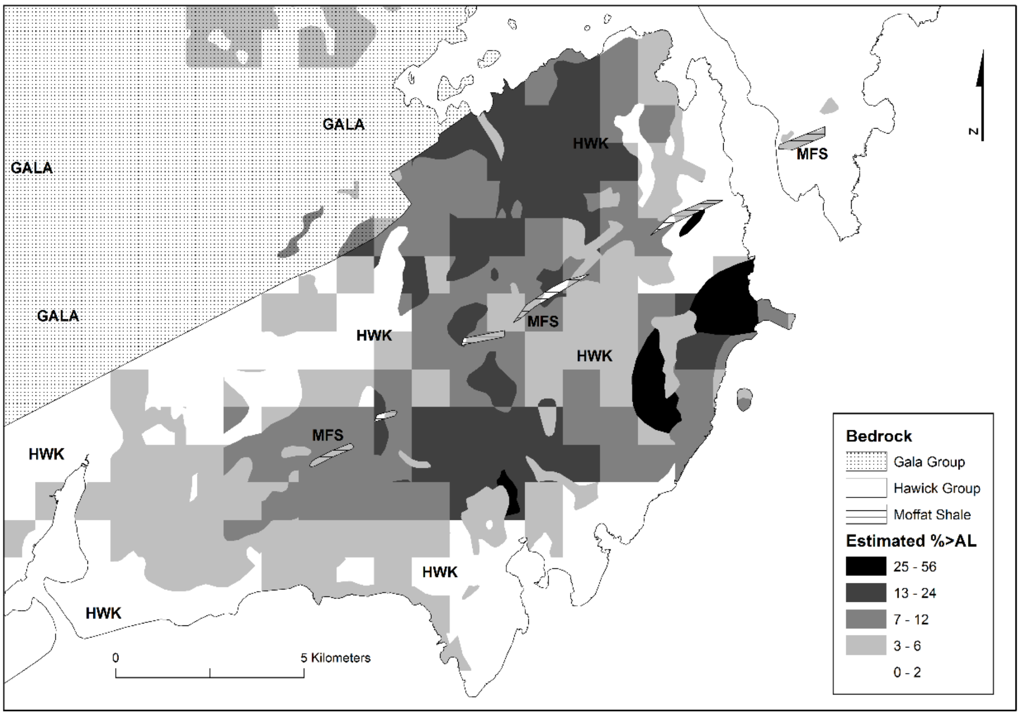

Figure 11 Radon potential map of the Lecale peninsula (Bedrock: GALA = Gala Group; HWK = Hawick group; MFS = Moffat Shale Formation) (BGS © NERC 2014. Radon data BGS © NERC 2014/PHE © Crown copyright 2014. Based on LPS data © Crown Copyright & Database Right 2014, DMOU 205)

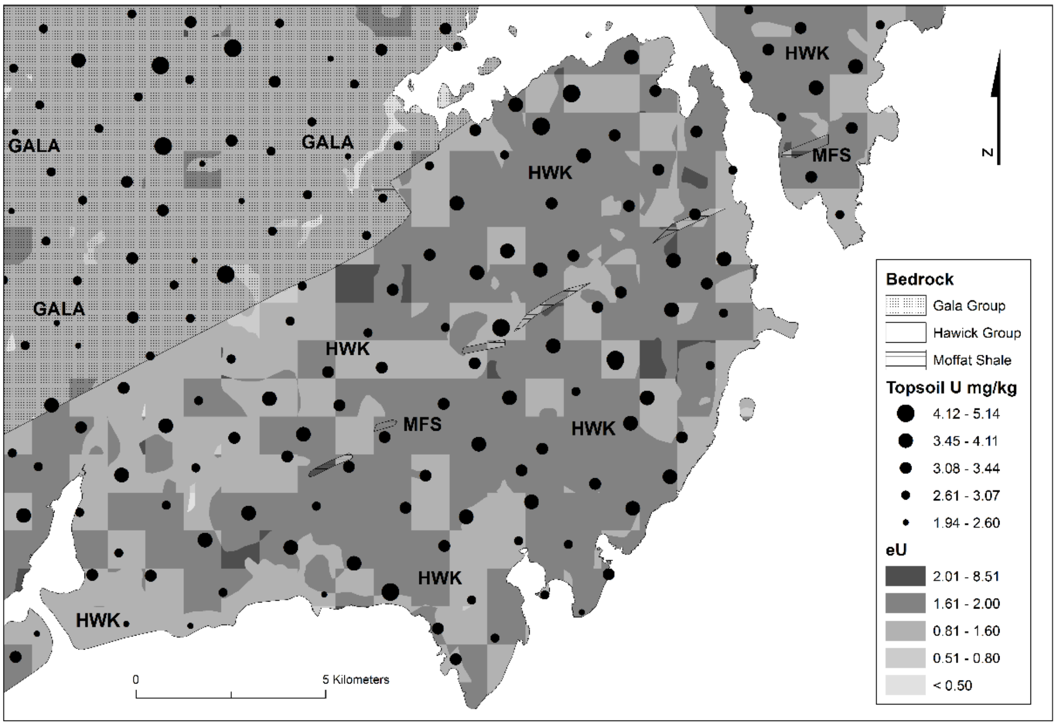

Figure 12 Gamma-ray spectrometry eU for the Lecale peninsula interpolated by geology and 1-km grid square overlain by proportional symbol U (mg kg^{-1}) in surface soil samples. (BGS © NERC 2014. Tellus and Geological data, GSNI © Crown Copyright 2014. Based on LPS data © Crown Copyright & Database Right 2014, DMOU 205)

3.5 Late Palaeozoic (Caledonian)

During the late Silurian early Devonian, granite rocks of the Newry Igneous Complex comprising three granodiorite plutons (NEGD-GD) and a small ultramafic-intermediate complex (NEGD-DI) at the northeast margin, were intruded into the Silurian greywackes and mudstones of the Hawick and Gala Groups. Radon measurements for the three granodiorite plutons were not differentiated due to the small number of radon measurements. The radon potential of the bedrock ranges from 0.1 to 21% (average 6%), <0.01 – 30% (average 2.4%) where till-moraine overlies bedrock, 0.01 – 9.5% (average 4%) where bedrock is overlain by alluvium, and only 0.1% where bedrock is overlain by peat (Table 9).

Table 9 Summary radon statistics for Newry Igneous Complex bedrock\superficial geology combinations with 5 or more radon measurements

Bedrock\superficial geology	No. Rn measurements	GM Rn Bq m^{-3}	Max. Rn Bq m^{-3}	Ave. %>AL	Min. %>AL	Max. %>AL
Newry Igneous Complex\alluvium	95	42	398	4.01	0.01	9.51
Newry Igneous Complex\peat	10	22	148	0.12		
Newry Igneous Complex\bedrock	200	54	455	5.94	0.10	20.90
Newry Igneous Complex\till-moraine	2479	48	1922	2.37	0.00	29.81

3.6 Devonian

The Devonian of the Fintona Group crops out extensively in the Omagh-Fintona area with minor occurrences of the Cross Slieve Group in the Cushendum-Cushendall area of northeast County Antrim. The Early Devonian (EDEV), comprising sandstone, siltstone, mudstone of the Shanmullagh Formation and the subsidiary Tedd Formation is characterised by low radon potential apart from when bedrock is overlain by high permeability glaciofluvial-lacustrine (GFL) deposits when the RP estimate based on only four measurements is 3% (Table 10). In the northeast, the supposed Early Devonian Cushendall Formation (Cross Slieve Group) includes conglomerate and sandstone, but the exact age is uncertain (Mitchell, 2004).

The Shanmaghery Sandstone is the main formation of the Middle Devonian (MDEV) in the Fintona area and this is characterised by low RP (<1%) apart from when bedrock is covered with GFL (RP 6%).

In contrast, the combined Middle-Late Devonian (MLDEV), comprising the Gortfinbar Conglomerate Formation and subsidiary Late Devonian Raveagh Sandstone Formation, has moderate RP (6%), although the RP is reduced to low (0.7%) where bedrock is covered with till-moraine (TIM) and enhanced to 12% when covered with high permeability glaciofluvial-lacustrine deposits (GFL) (Table 10).

The higher RP of the Mid-Late Devonian Gortfinbar Conglomerate (MLDEV-COMIX) compared with the sandstones, siltstones and mudstones of the Early and Middle Devonian (EDEV-SDMIX and MDV-SDMIX) may reflect higher permeability of soils developed over the conglomerates as the soil U and eU data are similar for the EDEV, MDEV and MLDEV (Table 6).

Andesitic volcanic rocks occur in the early Devonian of the Fintona area but there are no indoor radon data for this bedrock. The Middle-Late Devonian Barrack Hill Andesite in the Fintona area and the Cushendall volcaniclastics and dacite porphyry in NE Antrim all have low RP (0.5%) although all but two of the 25 radon measurements are for dwellings where till-moraine (TIM) overlies bedrock.

Table 10 Summary radon statistics for Devonian bedrock\superficial geology combinations with 3 or more radon measurements (EDEV = Early, MDEV = Middle, MLDEV = Middle-Late Devonian)

Bedrock\superficial geology code	No.	GM Rn. Bq m^{-3}	Max. Rn Bq m^{-3}	Ave. %>AL	Min. %>AL	Max. %>AL
MLDEV-COMIX\GFL	39	88	658	11.94	1.54	31.71
MLDEV-COMIX	66	52	303	6.03	0.52	16.68
MLDEV-COMIX\TIM	106	36	192	0.70	0.01	3.51
MLDEV-VOLC\TIM	23	26	94	0.45		
MDEV-SDMIX\GFL	17	45	431	5.57		
MDEV-SDMIX	3	28	74	0.54		
MDEV-SDMIX\TIM	20	26	67	0.20		
EDEV-SDMIX\ALV	4	32	57	0.84		
EDEV-SDMIX\GFL	4	45	128	2.82		
EDEV-SDMIX\PEA	11	35	90	0.23		
EDEV-SDMIX	16	24	185	0.43		
EDEV-SDMIX\TIM	200	34	201	0.70	0.02	4.18

3.7 Carboniferous

For the purposes of radon mapping, the Lower Carboniferous (Dinantian) sedimentary rocks, mainly from the Tyrone and Armagh Groups, have been subdivided into:

(i) limestones (DIN-LMST),

(ii) units in which limestone is a major component (DIN-LMMIX),

(iii) sandstone or mixed sedimentary units in which sandstone is the major component (DIN-SDMIX),

(iv) mudstone (DIN-MDST), and

(v) mixed units in which mudstone is the major component (DIN-MDMIX).

In addition there are Lower Carboniferous mafic intrusions (DINMAIN), basic and intermediate lavas (DIN-LAVA) and felsic lavas (DIN-FLAV). The Namurian, consisting of most of the Leitrim Group and the 'Millstone Grit', is sub-divided into limestone (NAM-LMST), sandstone (NAM-SDST) and mixed sedimentary units in which sandstone is the dominant component (NAM-SDMIX). The Westphalian

(‘Coal Measures’ and Slievebane Group) is subdivided into mixed sedimentary units with either sandstone (WES-SDMIX) or mudstone (WES-MDMIX) as the major component. Experience in GB has demonstrated that this chrono-lithological classification is an effective method for sub-dividing the Carboniferous sedimentary strata for radon potential mapping (Appleton and Miles, 2005; Scheib et al., 2009; Scheib et al., 2013). In the simplified geological map (Figure 2), almost all the ground underlain by undivided ‘Carboniferous’ is DIN-MDMIX and DIN-SDMIX.

Table 11 Summary radon statistics for Carboniferous bedrock\superficial geology combinations with 4 or more radon measurements

Bedrock\superficial geology code[a]	No. Rn measurements	GM Rn. Bq m^{-3}	Max. Rn Bq m^{-3}	Ave. %>AL	Min. %>AL	Max. %>AL
DIN-SDMIX\ALV	27	25	113	0.23	0.00	1.20
DIN-SDMIX\GFL	307	41	602	1.68	0.02	6.94
DIN-SDMIX\LSC	10	67	298	7.64		
DIN-SDMIX\PEA	29	28	92	0.26	0.00	0.86
DIN-SDMIX	71	31	287	1.86	0.00	6.69
DIN-SDMIX\TIM	555	29	344	0.43	0.00	2.17
DIN-SDMIX\TSC	6	21	35	0.13		
DIN-MDMIX\ALV	6	36	55	1.37		
DIN-MDMIX\GFL	20	26	105	0.05		
DIN-MDMIX	10	38	84	0.24		
DIN-MDMIX\TIM	41	26	160	1.10	0.29	2.36
DIN-MDST\GFL	8	43	123	2.53		
DIN-MDST\PEA	4	44	59	2.60		
DIN-MDST	4	169	313	41.66		
DIN-MDST\TIM	30	47	543	3.22	0.05	7.46
DIN-LMMIX\ALV	14	33	85	0.36		
DIN-LMMIX\GFL	44	45	348	3.10	1.13	5.82
DIN-LMMIX\LSC	32	30	707	2.17	0.01	7.17
DIN-LMMIX\PEA	28	32	211	1.46	0.00	5.85
DIN-LMMIX	87	55	610	6.98	0.54	18.67
DIN-LMMIX\TIM	741	32	475	1.18	0.01	5.26
DIN-LMST\ALV	5	34	69	1.13		
DIN-LMST\BSD	8	49	230	3.72		
DIN-LMST\GFL	22	52	163	1.73		
DIN-LMST\LSC	9	23	185	1.15		
DIN-LMST\PEA	14	25	117	1.26		
DIN-LMST	65	53	657	6.85	1.06	32.37
DIN-LMST\TIM	296	33	3936	3.89	0.05	22.36

[a] Explanation of superficial and bedrock geology codes in Tables 1 and 6

The radon potential (RP) of Dinantian limestone and limestone dominant sedimentary units are both high (7%) ranging up to 19% for DIN-LMMIX and 32% for DIN-LMST. The RP is relatively low when these bedrock units are overlain by superficial deposits (0.4 – 3.9%>AL, Table 11). Glaciofluvial-lacustrine (sand-gravel, GFL) produces the highest average RP (3.1%) for a superficial deposit overlying DIN-LMMIX whereas only low RP (1.7%) results when glaciofluvial-lacustrine deposits (GFL) overlie Dinantian limestone (DINLMST).

Dinantian mudstone (DIN-MDST) bedrock is characterised by high GM radon (160 Bq m^{-3}) and very high RP (42%, n = 4) whilst the RP is moderate (3%) when the mudstone is overlain by ALV, GFL and TIM. Mudstone dominant Dinantian (DINMDMIX) has consistently low RP (0.1 – 1.4%>AL).

The radon potential of the sandstone dominant Dinantian (DINSDMIX) is low 0.1-1.9% apart from where bedrock is overlain by lacustrine silt-clay which has a surprisingly high RP (8%, n=10). The low number of measurements and correspondingly high uncertainty of the estimated RP may explain this 'anomalous' result because the low permeability of the LSC would be expected to produce a low RP.

Namurian sandstone-dominant strata (NAM-SDMIX) overlain by till-moraine (TIM) has a low RP (<0.1%, n=8) whilst high permeability glaciofluvial-lacustrine deposits (GFL) over NAM-SDMIX results in a moderate RP of 6% (n = 3). Indoor radon above Westphalian SDMIX and MDMIX is consistently low (GM 5 – 28 Bq m^{-3}; RP 0.1 – 0.3%).

In the sector of County Fermanagh where DINLMST has very high RP (Figures 13-14), there is a broad correlation between RP (Figure 14) and gamma ray spectrometry eU, soil U (Figure 15) although the spatial correlation is variable. For example, eU appears to be highest when associated with DIN-LMST (Ballyshannon Limestone Formation) immediately west of the south-east margin of Lower Lough Erne compared with limestone exposed at the surface in the central, western and north-western sectors of the peninsula underlain by the Daltry and Knockmore Limestones (Figures 13-14). The Ballyshannon Limestone is relatively coarse grained packstone and grainstone whilst the Daltry Limestone is fine grained and cherty and the Knockmore Limestone comprises poorly and unbedded mudmound facies limestones. Soil U is also higher over the Ballyshannon Limestone immediately to the west of the SE margin of Lower Lough Erne and also with the E-W trending interbedded limestones and argillites of the Ballyshannon Limestone Formation located between Ballyshannon town and Lower Lough Erne (Figures 13,15), where eU is also relatively high. Appleton et al., (2011) explain why eU tends to be lower than soil U. One other sector of high eU and soil U is associated with alluvium and lacustrine alluvium in the E-W valley draining into Lough Macnean Lower (Figures 13 to 15). Insufficient indoor radon and soil U data are available to make a detailed assessment of inter unit variation.

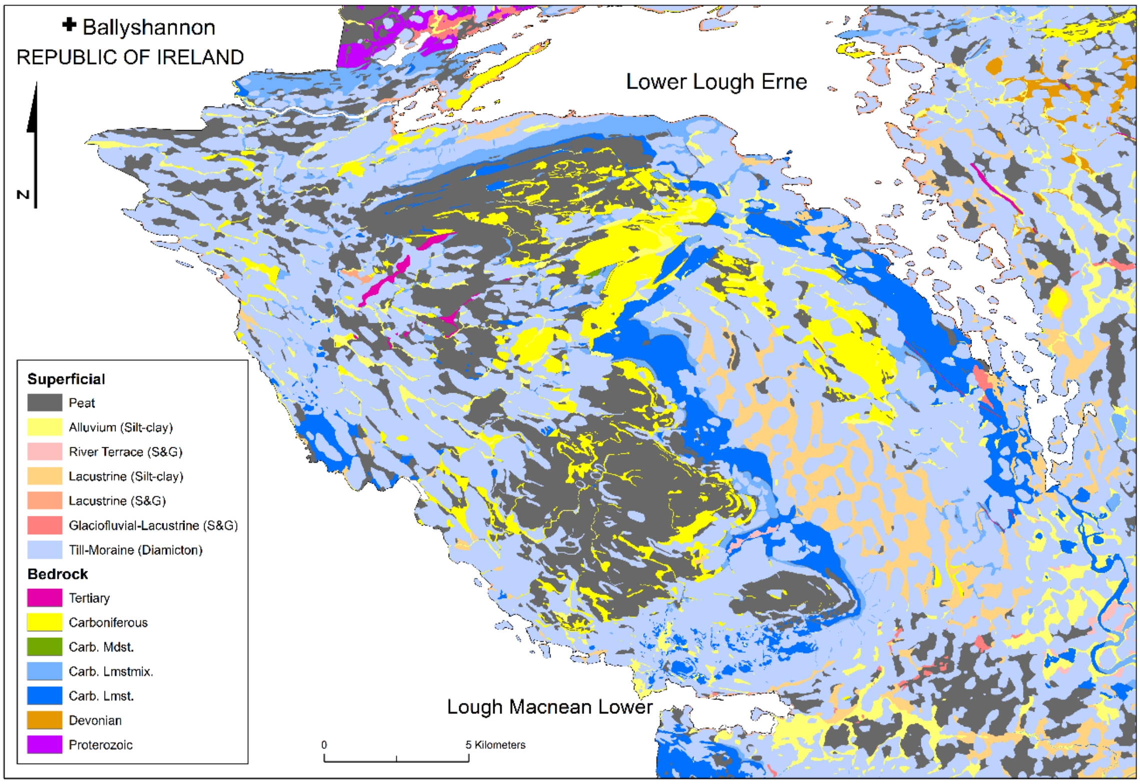

Figure 13 Surface geology map of part of County Fermanagh (BGS © NERC 2014. Geological data, GSNI © Crown copyright 2014. Based on LPS data © Crown Copyright & Database Right 2014, DMOU 205)

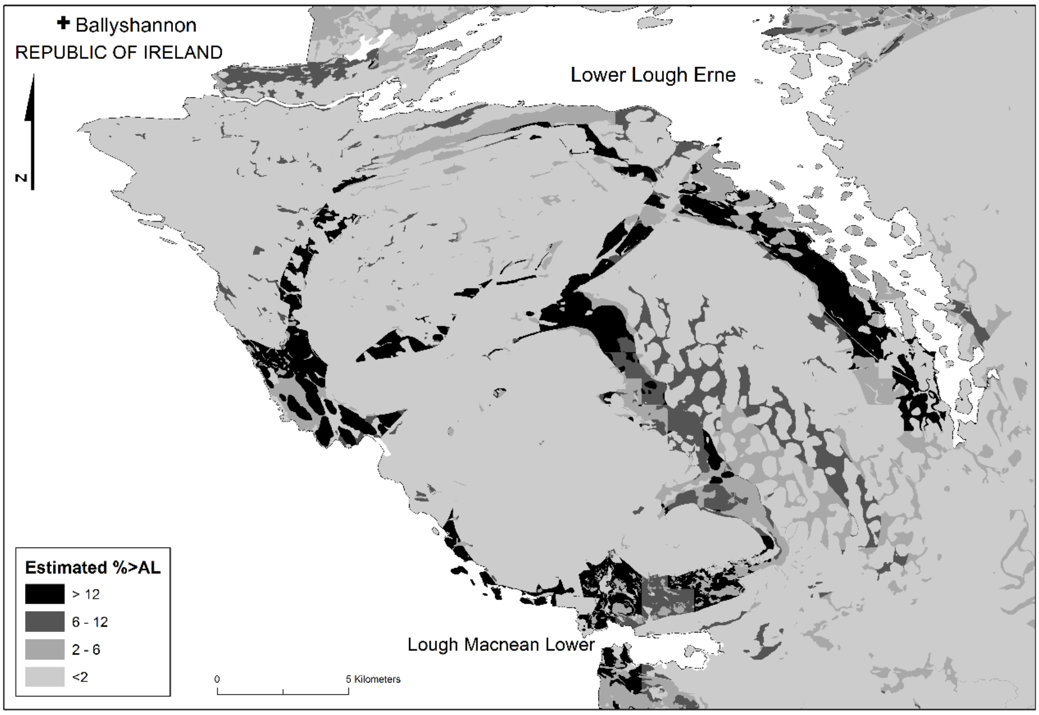

Figure 14 Radon potential (RP) map of part of County Fermanagh (extract of Figure 5). (BGS © NERC 2014. Radon data BGS © NERC 2014/PHE © Crown copyright 2014. Based on LPS data © Crown Copyright & Database Right 2014, DMOU 205)

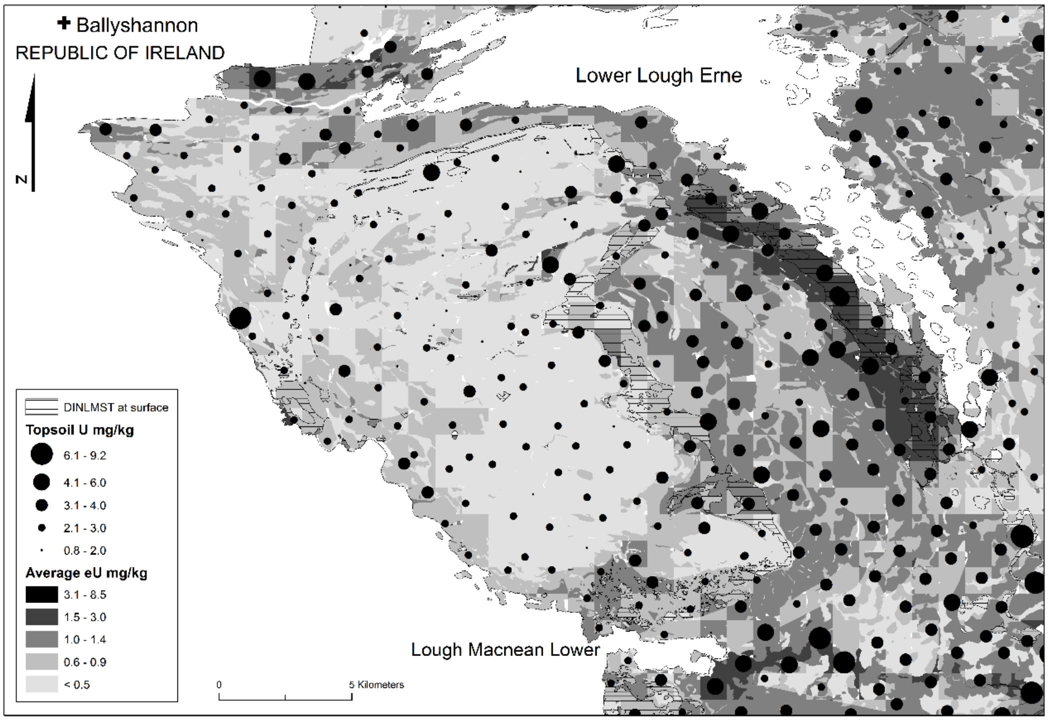

Figure 15 Gamma-ray spectrometry eU for part of County Fermanagh interpolated by geology and 1-km grid square overlain by proportional symbol U (mg kg^{-1}) in surface soil samples. (BGS © NERC 2014. Tellus and Geological data, GSNI © Crown Copyright 2014. Based on LPS data © Crown Copyright & Database Right 2014, DMOU 205)

3.8 Permian

The Permian succession consists of the coarse clastics (PER-SDMIX) of the Enler Group overlain by the 'Magnesian Limestone' and argillites and evaporites of the Belfast Group.

The Enler Group includes the Coolbeg Breccia Formation, Carnamuck sandstone, Dobbin Sandstone Formation, Drumarg Conglomerate Formation, and the Newforte Breccia Formation. The Belfast Group comprises the Magnesian Limestone Formation (PER-DOLO) and the argillites and marls (Connswater Marl) of the Belfast Group (PER-MDMIX). Although very few measurements are available, all Permian units appear to have low RP (<1%) both for bedrock and when overlain by all superficial geology units.

3.9 Triassic

Sherwood Sandstone Group (TRI-SDMIX) includes the Ballyloughan Formation (sandstone) and the Milltown Conglomerate Formation. This is overlain by Mercia Mudstone Group (TRI-MDST). Both have low RP (<1%). The Penarth group mudstone and limestone (PNG-MDMIX) has only 3 measurements, all of which are low (max. 29 Bq m^{-3}).

3.10 Jurassic

Jurassic sedimentary (JUR-SED) rocks have a very restricted occurrence at the surface at White Park Bay in the north of Co. Antrim and comprise of the Waterloo Mudstone Formation (calcareous mudstone with thin siltstone and nodular limestone bands). The Tircrevan Sandstone Member occurs elsewhere. Only 24 measurements exist for the Jurassic sedimentary sequence, and only one, in a dwelling sited on bedrock, is high (223 Bq m^{-3}). None of the others exceed 50 Bq m^{-3}. The average RP for bedrock with no superficial cover is 1.7% (Table 6).

3.11 Cretaceous

Cretaceous sedimentary (CRET-SED) strata occur along the coast on Co. Antrim and around the western and southern margin of the Palaeogene basalt lavas of the Antrim Lava Group. The Cretaceous comprises the Hibernian Greensands Formation (glauconitic sandstone, siltstone, and mudstone) and the limestone, white chalk with flints and basal glauconite-rich beds of the Upper White Limestone Group. RP is consistently low both where bedrock is exposed (2%, Table 6) and when covered with TIM (0.4%).

3.12 Palaeogene extrusive rocks

The Lower and Upper Basalt Formations of the Antrim Lava Group (ALG-BLAV) include lava, agglomerate, and ignimbrite tuff of basalt and subsidiary andesite composition. The only three radon measurements >200 Bq m^{-3} are from glaciofluvial-lacustrine deposits (GFL) overlying ALG-BLAV. The highest radon concentration (1474 Bq m^{-3}), is from a dwelling located close to the contact between Tertiary lava and Carboniferous limestone in an area totally covered by till-moraine with subsidiary glaciofluvial-lacustrine and alluvial deposits, so there may be some uncertainty about the bedrock at this location. The other two measurements >200 Bq m^{-3} are in dwellings where till-moraine (TIM) overlies the Antrim Lava Group, one in northeast Antrim and the other above an ALG-BLAV outlier surrounded by Hawick Group greywackes, immediately to the SW of Banbridge. The Tardree Rhyolite Complex includes rhyolites (PGU-FLAV) for which only one measurement (149 Bq m^{-3}) is available where bedrock is at the surface; the only other measurement, where glaciofluvial-lacustrine deposits overlie PGU-FLAV, is also high (356 Bq m^{-3}).

3.13 Palaeogene intrusive rocks

A succession of intrusions occurred during the Palaeogene starting with (1) the dyke swarms and sills of County Fermanagh, including felsic (PGU-FEIN) and microgabbro and dolerite mafic intrusives (PGU-MAIN), mafic (dolerite, basalt, trachybasalt; PGU-MADY) dykes and felsic (rhyolite; PGU-FEDY) dykes; (2) Palaeogene mafic igneous intrusions (PGU-MAIN), (3) the Portrush Sill, (4) Slieve Gullion Complex and finally the (5) Mourne Mountains Complex. Only one measurement (5 Bq m^{-3}) is available for PGU-FEIN and PGU-FEDY, 23 for PGU-MADY (max 310 Bq m^{-3} for a dyke cutting NEOP in the western domain) and 11 (max. 191 Bq m^{-3}) for PGU-MAIN. There is no indication that RP greatly exceeds 1% for PGU-FEIN, PGE-FEDY or PGU-MADY, which are mainly overlain by a range of superficial deposits, and in the case of the dykes are generally less than 10m wide.

The Slieve Gullion Complex represents the roots of a volcanic caldera which has been sub-divided for radon potential mapping into felsic intrusive (SGD-FEIN) which includes granophyre forming the core of the complex and granophyric microgranite in the southeast of the complex. This has a very high RP (13%) for bedrock and high when bedrock is overlain by till-moraine (TIM, average 9%, range 0.6-27%, Table 12). Mafic intrusive (SGD-MAIN: dolerite and gabbro) has an RP of 5% for bedrock and 10% for bedrock overlain by till-moraine, although the composition of the till-moraine may be enhanced by SGD-FEIN or even Mourne Mountains Complex (MNG-GRAN) bedrock fragments. SGD-AGGL (vent agglomerate) only has two measurements (GM 59, max. 80 Bq m^{-3}).

The Mourne Mountains Complex comprises five principal granite intrusions which have all been grouped together as MNG-GRAN because there are insufficient radon measurements for the radon potential of the individual granites to be evaluated separately. Only two measurements exist for bedrock (GM 108, Max 163 Bq m^{-3}). Very high RP characterises granite overlain by alluvium (ALV, 17%, n = 5), glaciofluvial-lacustrine sand and gravel (GFL, 39%, n = 7) and till-moraine (TIM, 28%, range 8 – 71%) (Figures 7 and 8; Table 12). The Mourne Mountains Granite has the highest average and maximum eU and soil U in Northern Ireland (Table 6). In general, there is a close relationship between airborne eU (Figure 9, radon potential (Figure 8) and bedrock geology (Figure 7) upon which is superimposed the impact of superficial geology, soil formation processes (McAlister et al., 1997), and uranium mineralisation (Moles et al., 1995, 1998). In some areas of the Mourne Mountains, low eU areas include many negative values that are associated with peat and surface water humic gley soils but in other areas peat does not appear to be associated with abnormally low eU, perhaps because U is absorbed onto soil organic matter in some circumstances. The effect of peat is very variable but as there are few dwellings located on peat this may not be a major problem with respect to radon hazard.

Table 12 Summary radon statistics for Slieve Gullion Complex and Mourne Mountains Granite bedrock\superficial geology combinations with 2 or more radon measurements

Bedrock\superficial geology code	No. Rn measurements	GM Rn Bq m^{-3}	Max. Rn Bq m^{-3}	Ave. %>AL	Min. %>AL	Max. %>AL
SGD-AGGL	2	59	80	1.70		
SGD-FEIN	15	73	1072	12.61		
SGD-FEIN\TIM	175	68	1791	8.65	0.57	27.43
SGD-MAIN	19	54	188	4.69		
SGD-MAIN\TIM	23	79	293	10.40		
MNG-GRAN\ALV	5	93	311	16.73		

MNG-GRAN\GFL	7	158	887	38.57		
MNG-GRAN	2	108	163	21.91		
MNG-GRAN\TIM	78	122	1273	27.79	7.51	71.07

3.14 Tertiary sedimentary

Only one measurement (45 Bq m^{-3}) exists for the Coagh Conglomerate Member of the Antrim Lava Group (OLIG-CONG) at a location where bedrock is overlain by till-moraine (TIM). The younger Lough Neagh Clays Group includes the Dunaghy Formation (clays, thin lignites and thin conglomerates) and the lignites and clays of the Ballymoney Formation (OLIG-MDMIX). The maximum radon value is 77 Bq m^{-3} and both bedrock and bedrock overlain by a range of superficial geology units have estimated RPs less than 0.5%.

4. Conclusions

This analysis of the geological controls on radon potential of the ground has demonstrated that a range of bedrock types contribute to the extent of radon prone areas of Northern Ireland. In Northern Ireland 12% of the total variation of indoor radon concentration can be explained by the mapped bedrock and superficial geology combination, although this is higher (14%) in the sector where the radon map is based on the more accurate 1: 10 000 scale digital data. Intra-geological unit variance ranges from 6 to 27%. Airborne gamma-ray spectrometry and uranium in topsoil data has helped to elucidate some of the controls on indoor radon.

Moderate and high radon potential in Northern Ireland is associated mainly with (i) the Neoproterozoic psammites, semipelites, meta-limestones, volcanics and mafic intrusives of Londonderry and Tyrone; (ii) Silurian Hawick Group greywackes and, to a much more limited extent Gala Group greywackes, in the southern sector of Counties Armagh and Down; (iii) Ordovician and Silurian acid intrusives and volcanics in eastern Counties Londonderry and Tyrone; (iv) Middle-Late Devonian conglomerates in County Tyrone; (v) Lower Carboniferous (Dinantian) limestone in the western sector of Northern Ireland, especially in County Fermanagh; (vi) Palaeogene and Late Caledonian acid intrusive rocks of the Mourne Mountains Granite, Slieve Gullion Complex and Newry Granodiorite Complex in County Down and County Armagh.

Moderate to high radon potential is sometimes associated with glacio-fluvial sand and gravel deposits where these overlie a range of bedrocks, some of which have relatively low radon potential. In this latter case the enhanced radon potential is probably caused by the high permeability of superficial deposits. Radon potential tends to be lower when bedrocks characterised by moderate or high radon potential are overlain by relatively impermeable silt-clay alluvium, glaciolacustrine, and lacustrine deposits; peat; and glacial till and moraine. The eU and soil U data suggest that very high radon potential associated with alluvium in the valleys to the south and south-east of the Mourne Mountains Granite may be related to enrichment of U bearing minerals in alluvial sediments derived from the uranium enriched granite. Dispersion and transport of U-rich granite debris by glacial processes may explain the high radon potential in till and moraine overlying Hawick Group greywackes immediately to the south of the Mourne Mountains granite.

The main objective for investigating the distribution and geological controls on radon by radon potential mapping is to help ensure that the health of occupants of new and existing dwellings and workplaces is adequately protected. Geological information, soil geochemistry, and gamma spectrometry data all help to improve knowledge of the distribution of indoor radon concentrations and may be particularly useful where there are few indoor radon measurements. The new detailed radon potential map described here should facilitate cost-effective radon measurement campaigns designed to identify dwellings and other buildings with radon above the Action Level. Uncertainty in radon potential estimates are higher for areas with a small numbers of radon measurements so a targeted programme of additional measurements would help to ascertain the true radon potential of those bedrock-superficial geology combinations for which few radon data are currently available. Radon levels often vary widely between adjacent buildings due to differences in the radon potential of the underlying ground as well as differences in construction style and use of a building. The radon map can indicate the relative radon risk for a building in a particular locality, but it cannot predict the radon risk for an individual building. This can only be established by having the building tested.

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