Radon Gas Hazard

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Abstract

Radon (^{222}Rn) is a natural radioactive gas that occurs in rocks and soils and can only be detected with special equipment. Radon is a major cause of lung cancer. Therefore, early detection is essential. The British Geological Survey and Public Health England have produced a series of maps showing radon Affected Areas based on underlying geology and indoor radon measurements, which help to identify Radon Affected buildings. Many factors influence how much radon accumulates in buildings. Remedial work can be undertaken to reduce its passage into homes and workplaces and new buildings can be built with radon preventative measures.

Introduction

Radon is a natural radioactive gas that you cannot see, smell, or taste and that can only be detected with special equipment. It is produced by the radioactive decay of radium, which in turn is derived from the radioactive decay of uranium. Uranium is found in small quantities in all soils and rocks, although the amount varies from place to place. There are three naturally occurring radon (Rn) isotopes: ^{219}Rn (actinon), ^{220}Rn (thoron), and ^{222}Rn, which is commonly called radon. ^{222}Rn (radon) is the main radon isotope of concern to man. The production of radon by the radioactive decay of ^{238}U in rock, overburden, and soil is controlled primarily by the amount of uranium within the rock-forming minerals and their weathering products. The ^{238}U decay chain may be divided into two sections separated by ^{226}Ra (radium), which has a half-life of 1600 years. Earlier isotopes mostly have long half-lives, while the later isotopes, including radon (^{222}Rn), have relatively short half-lives (^{222}Rn half-life 3.82 days). ^{220}Rn (thoron) is produced in the ^{232}Th decay series and has a half life of 56 seconds. ^{220}Rn has been recorded in houses, and about 4% of the average total radiation dose for a member of the UK population is from this source. ^{219}Rn (actinon) has a very short half-life of about 4 seconds and this, together with its occurrence in the decay chain of ^{235}U, which is only present as 0.7% of natural uranium, restricts its abundance in gases from most geological sources.

There are a number of different ways to quantify radon. These include (1) the *radioactivity* of radon gas; (2) the *dose* to living tissue, e.g. to the lungs from solid decay products of radon gas; and (3) the *exposure* caused by the presence of radon gas. In the UK and most countries apart from the USA, radioactivity is measured using the SI unit becquerel (Bq). One becquerel represents one atomic disintegration per second and the level of radioactivity in the air due to radon is measured in becquerels per cubic meter (Bq m^{-3}) of air. The average radon concentration in houses in the United Kingdom is 20 Bq m^{-3}, which is 20 radon atoms disintegrating every second in every cubic meter of air. The population-weighted world average radon concentration is 40 Bq m^{-3} (UNSCEAR, 2009; HPA 2009).

The dose equivalent indicates the potential risk of harm to particular human tissues by different radiations, irrespective of their type or energy. It is measured in sieverts (Sv), where 1 Sv represents 1 joule of energy per kilogram, but normally expressed in mSv as the Sv is a large unit. The average person in the UK receives an annual effective radiation dose, which is the sum of doses to body tissues weighted for tissue sensitivity and radiation weighting factors, of 2.8 mSv, of which about 85% is from natural sources: cosmic rays, terrestrial gamma rays, the decay products of ^{220}Rn and ^{222}Rn, and the natural radionuclides in the body ingested through food and drink (Figure 1). Of this natural radiation, the major proportion is from geological sources. About 60% of the total natural radiation dose is from the decay products of radon isotopes (mostly due to alpha particle activity) while about 15% is thought to be due to gamma radiation from the U, Th, and K in rocks and soils and from building products produced from geological raw materials. Exposure to radon in buildings provides about half the total radiation dose to the average person in the UK (Watson et al., 2005). X-rays and radioactive materials used to diagnose and treat disease are the largest source of artificial exposure to people. The average dose due to anthropogenic isotopes (radioactive fallout, nuclear fuel cycle, etc.) is less than 1% of the total annual dose (Figure 1). The average annual dose to the UK population from radon is 1.2mSv with a range from 0.3 to more than 100 mSv depending on area. In the most radon-prone area in Great Britain, the average person receives a total annual radiation dose of 7.8mSv of which 81% is from radon. On an individual basis, the dose would be dependent largely upon where one lived in the UK, characteristics of the structure of one's home and one's lifestyle. Outdoors, radon normally disperses to low concentrations in the air, whereas in confined spaces such as buildings, mines, and caves (Talbot et al., 1997; Gillmore et al., 2002; Gillmore et al., 2000) it may accumulate. Radon in indoor air comes principally from soil gas derived from soils and rocks beneath a building with smaller amounts from the degassing of domestic water into the indoor air and from building materials. In very rare circumstances, radon may potentially be emitted from some anthropogenic sources, such as near-surface radioactive waste disposal sites (Appleton et al., 2011a). Building materials are the main source of thoron (^{220}Rn) in room air although a minor contribution comes from soil gas. Radon contributes by far the largest variation in the average dose from natural radiation sources.

Water in rivers and reservoirs usually contains very little radon, because radon decays almost completely in a few weeks, so homes that use surface water do not have a radon problem from their water. Water processing in large municipal systems aerates the water, which allows radon to escape and also delays the use of water until most of the remaining radon has decayed. Mains water supplies pass through treatments which tend to remove radon gas but small public water works and private domestic wells often have closed systems and short transit times that do not remove radon from the water or permit it to decay. In such situations, radon from the domestic water released during showering and other household activities could add radon to the indoor air. Areas most likely to have problems with radon from domestic water supplies include those with high levels of uranium in the underlying rocks.

In a study of private water supplies in south western England, a high proportion of water derived from granite areas exceeds the draft European Union action level of 1000BqL^{-1} (Talbot et al. 2000). It was also found that radon concentrations varied significantly over the course of a week and between samples taken several months apart. For water from groundwater sources, mean values (by source type) at the tap were generally lower than those at the source. This is consistent with loss of radon due to degassing as a result of water turbulence within the supply system and natural radioactive decay while the water is resident in the household supply system. All the water sources sampled showed large variability in radon concentration over the summer sampling period, whereas less pronounced variability was observed during the winter sampling. Maximum values were observed during the summer.

Building materials generally contribute only a small percentage of the indoor air radon concentrations, although this may be 20-50% of the radon in an average UK dwelling (Gunby et al., 1993). However, Groves-Kirkby et al. (2008) noted that in areas of generally low indoor radon concentrations, indoor radon may be mainly derived by emanation from building materials. The contribution of radon from the ground into homes varies over several orders of magnitude, in some cases giving substantial radiation doses to the occupants, while the contribution from building materials is much less variable. No cases have been identified in the UK where high indoor radon concentrations have been found to be caused by radon from conventional building materials alone although it is reported that some buildings in SW England made of mining waste have high radon concentrations.

Radon levels in outdoor air, indoor air, soil air, and groundwater can be very different. Radon concentrations in outdoor air in the UK are generally low, on average 4 Bq m^{-3} 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}. Radon in soil air (the air that occupies the pores in soil) ranges from less than 1 to more than 2500 kBq m^{-3}.

Other natural sources of radiation

Gamma Rays from the Ground and Buildings (Terrestrial Gamma Rays)

Everyone is irradiated by gamma rays emitted by the radioactive materials in the Earth. Terrestrial gamma rays originate chiefly from the radioactive decay of natural K, U, and Th, which are widely distributed in terrestrial materials including rocks, soils, and building materials extracted from the Earth. The average annual gamma radiation dose from all these sources to the population in Great Britain is about 350 µSv (Watson et al., 2005) with a range of 120–1200 µSv.

Within a masonry building, most of the gamma radiation is received from the building materials, whereas in wooden buildings a larger part of the dose is contributed from gamma radiation from the ground. The average person in the UK spends only 8% of their time outdoors so the contribution to total radiation dose from the ground is relatively small. The bulk of the radiation above the ground surface is derived from only the top 30 cm or so of soil or rock. Soils developed upon radioactive rocks generally have a much lower gamma radioactivity than the rock substrate. Whereas one can predict or identify areas of high geological gamma radioactivity, the resultant dose to the population depends on additional factors such as soil type, house construction, and lifestyle.

Radioactive materials also occur in food. ^{40}K, in particular, is a major source of internal irradiation; natural radioactivity in the human diet gives an average annual dose for adults of around 250 µSv each year of which 165 µSv is from ^{40}K (Watson et al., 2005). The range for all internal radiation sources in Great Britain is 100–1000 µSv per annum. Shellfish concentrate radioactive materials so that, even when there is no man-made radioactivity, people who consume large quantities of mussels, cockles, or winkles can receive a dose from natural radioactivity in food that is about 50% higher than average. Apart from restricting intake of shellfish, there is very little possibility of reducing the small exposure to natural radioactivity from food.

Cosmic Rays

Little can be done about cosmic radiation because it readily penetrates ordinary buildings and aircraft. The average annual dose from cosmic rays in Great Britain is 330μSv, with a range of 200–400μSv at ground level (Watson et al., 2005), which equates to about 10% of the average annual radiation dose (Figure 1). Aircrews, and frequent air travellers receive higher doses because the dose increases with altitude.

Health effects of radiation and radon

Most of the radon that is inhaled is exhaled again before it has time to decay and irradiate tissues in the respiratory tract. Radon (^{222}Rn), however, decays to form very small solid radioactive particles, including ^{218}Po, that become attached to natural aerosol and dust particles, typically within minutes of formation. The attached and unattached decay products may remain suspended in the air or settle onto surfaces. When the decay products are inhaled, a large proportion of them are deposited in the respiratory tract and irradiate the lining of the bronchi in the lung with alpha particles (Figure 2) increasing the risk of developing cancers of the respiratory tract, especially of the lungs. Only smoking causes more lung cancer deaths (Figure 3).

A study of lung cancer deaths from indoor radon gas, carried out for the Health Protection Agency (HPA, 2009), estimated that in the UK in 2006:

1. 1100 lung cancer deaths were caused by radon, representing 3.3% of total lung cancer deaths (34,000)
2. The dose-response relationship appears linear, in that the greater the concentration of indoor radon, the greater the risk of developing lung cancer. Also, there is no evidence of any threshold below which there is no risk.
3. Of the 3.3% of lung cancer deaths attributable to radon exposure, only 0.5% were due to radon acting alone; the remaining 2.8% were caused by a combination of radon and smoking, with nearly half the deaths likely to occur in people who had already given up smoking.

The Radon and Public Health report (HPA, 2009) also highlighted that the vast majority of radon-induced lung cancer deaths in the UK occur in areas that are not currently designated as ‘Radon Affected Areas’ (areas in which over 1% of homes are estimated to exceed 200 Bq m^{-3}, the UK radon Action Level). The overwhelming majority of the population live outside such areas, and around 95% of radon-attributable deaths are estimated to occur with residential concentrations below 200 Bq m^{-3}, and 70% at concentrations of less than 50 Bq m^{-3}.

Apart from lung cancer, there is no epidemiological proof of radon causing any other type of cancer (HPA, 2009) and no consistent association has been observed between radon exposure and other types of cancer. No clear link between radon and childhood cancer (especially leukaemia) emerged from a number of ecological studies, and a review of ecological, miner, and cohort studies did not find an association between radon and leukaemia (Laurier et al., 2001; Kendall et al., 2011). Radon ingested in drinking water may lead in some circumstances to organs of the gastrointestinal tract receiving the largest dose. Ingested radon is absorbed by the blood but most of the radon is lost quickly from the bloodstream through the lungs. However, the dose to the stomach from ingested radon can be significant and implies an increased risk of stomach cancer. Radon in soil under homes is the biggest source of radon in indoor air, and it presents a greater risk of cancer than radon in drinking water.

Estimation of the economic cost of radon-induced lung cancers is difficult. Using the Quality Adjusted Life Years approach (Gray et al., 2009), the total estimated cost of radon-induced lung cancers in the UK is £347 million per year.

Radon release and migration

Most of the radon atoms formed from the decay of radium remain in the mineral grains. In soils, normally 20–40% (in clays up to 70%) of the newly generated radon atoms are released to the pore space where they are mixed in with the gas (soil air) or water that fill the pores. From the pore space, radon can be transported by diffusion or by flow in carrier fluids such as soil-air or water. The rate of release of radon from rocks and soils is largely controlled by their uranium and radium concentrations, grain size, and by the types of minerals in which the uranium and radium occurs and their degree of alteration (Ball et al., 1991).

The most important factors controlling the migration of radon and its entry into buildings include:

1. the characteristics of the bedrock and soils that affect fluid transport, including porosity and permeability;
2. the nature of the carrier fluids, including carbon dioxide gas, surface water and groundwater;
3. the construction of the building and its use which includes the level of ventilation and heating;
4. environmental factors such as temperature (because increased heating in the buildings during the colder months causes a chimney effect which draws soil gasses including radon into the property), plus wind speed and direction which can increase the chimney effect.

The main mineralogical factors affecting the release of radon are the solubility, internal structure, and specific surface area of uranium-bearing minerals. Most of the uranium in rocks can be attributed to discrete uranium-bearing minerals, even when there is only a few mg kg^{-1} of uranium present. Because radon is a gas with a limited half-life, its chances of escaping from the parent mineral are much greater if it is generated from grain margins. Other important controls are the openness of and imperfections in the internal structure of the mineral and the specific surface area of the mineral grains.

The fraction of radon mainly produced by radium decay, that escapes from rock or soil (called the emanation coefficient) is dependent on the surface area of the source material. Emanation coefficients are greater for rocks than minerals, whereas soils usually have the highest values. When radium decays, the radon atom produced has a recoil energy which allows it to move a short distance through a rock grain, so it may escape into a pore, or may cross a pore space and become implanted into a neighbouring grain. If water is present in the pore space, however, the moving radon atom slows very quickly and is more likely to stay in the pore space. Differences in the uranium-bearing minerals, and especially in their solubility, control the amount of radon released. Uranium in the mineral uraninite (uranium oxide), commonly found in some granites, is easily weathered, especially near the surface. Uranium is more soluble in water so it is removed from the original mineral site, but the relatively insoluble radium, which is the immediate parent of radon gas, remains in a mixture of iron oxides and clay minerals. Uranium in other granites may occur in chemically resistant high-thorium uraninite, zircon, monazite, and apatite, all of which liberate less radon. The mineral associations typically found in sedimentary rocks differ significantly from those in granites.

In the Carboniferous limestone of northern England, for example, uranium is relatively uniformly distributed and associated with finely divided organic matter in the matrix of bioclastic limestones (usually <10 mg kg^{-1} U), although it may also be concentrated in stylolites, which typically contain 20–60 mg kg^{-1} U. Even though the overall concentration of U in the limestones is below 2 mg kg^{-1}, high radon emissions are probably derived from radium deposited on the surfaces of fractures and cavities. The high specific surface area of the radium permits efficient release of radon and high migration rates are promoted by the high permeability of the limestone. In addition, uranium and radium are concentrated in residual soil overlying limestone. In black shales in the UK, uranium is located mainly in the fine-grained mud matrix, where it may be present at levels up to 20 mg kg^{-1} U, and also in organic-rich bands at concentrations up to 40 mg kg^{-1} U. Uranium is rare in detrital phases and may also be remobilized and adsorbed on iron oxides. In sandstones, uranium is concentrated in primary detrital minerals, such as apatite and zircon, which can contain high concentrations of U (>100mgkg^{-1}). Uranium may also be adsorbed onto Fe oxides in the matrix of sandstone or its weathering products. Emission of radon from sandstones is restricted by the relatively low specific surface area of the uranium minerals and appears to be more dependent upon fracturing of the rock.

Once the radon is released from the parent mineral into the space between mineral grains (the intergranular region), its migration is controlled mainly by (a) the fluid transmission characteristics of the rock including permeability, porosity, pore size distribution, and the nature of any fractures and disaggregation features and (b) the degree of water retention (saturation) of the rocks. Faults and other fractures permit the efficient transmission of radon gas to the surface. The presence of faults with their enhanced fluid flow frequently results in high radon in soil gases (Ball et al., 1991; Varley and Flowers, 1993).

In highly permeable dry gravel, radon has decayed to 10% of its original concentration over a diffusion length of 5m (UNSCEAR, 2009). In more normal soils, which are generally moist, this distance would be substantially less. Diffusive ^{222}Rn in soil gas can be determined from the specific ^{226}Ra activity, specific density, effective porosity, and radon emanation coefficients of soils and rocks (Washington & Rose, 1992). In caves, radon concentrations of approximately 100 Bq m^{-3} would be expected if radon were generated by diffusion from solid limestone with 2.2mg kg^{-1} U. However, the enhanced concentration of radon in caves suggests that structurally controlled convective (i.e. pressure driven) transport of radon in fluids along faults, shear zones, caverns, or fractures is more significant than diffusive transport. Transportation of radon in this way may exceed 100m.

Following radon release, migration in carrier fluids, such as carbon dioxide gas or water, is considered to be the dominant means of gas transmission to the surface. Water flow below the water table is generally relatively slow as is ground-water transport in the soil aquifer (<1–10cm per day). Thus all hydraulically transported radon will have decayed over a distance of less than 1–2m in most soil aquifers.

Radon dissolved in groundwater can migrate over long distances along fractures and caverns depending on the velocity of fluid flow. Radon is soluble in water and may thus be transported for distances of up to 5 km in streams flowing underground in limestone. Radon remains in solution in the water until a gas phase is introduced (e.g., by turbulence or by pressure release). If emitted directly into the gas phase, as may happen above the water table, the presence of a carrier gas, such as carbon dioxide, would tend to induce migration of the radon. This appears to be the case in certain limestone formations, where underground caves and fissures enable the rapid transfer of the gas phase.

The principal climatic factors affecting radon concentrations in buildings are barometric pressure, rainfall, and wind velocity (Ball et al., 1991). Falling barometric pressure will draw soil gas out of the ground, increasing radon concentrations in the near-surface horizons, whilst increasing barometric pressure forces atmospheric air into the ground and dilutes radon concentrations in the near-surface soil horizon. For permeable soils, radon concentrations are only affected during precipitation when saturation of small pore spaces with moisture effectively prevents the rapid out-gassing of radon from the soil. This causes the build-up of radon below the moisture-saturated surface layer and increases of an order of magnitude are sometimes observed.

A similar build-up of radon can be produced when the ground freezes and is also often observed during the night when dew forms on the surface, which can result in a twofold increase in soil gas alpha activity. Dry conditions cause clay-rich soils to dry out and to fracture, allowing easier egress for the soil gases and hence an increase in radon activity at the soil surface. The radon concentration tends to be lower in the winter and higher in the summer, often varying by a factor of 3–10 (Rose et al., 1990). The variation is greater in the soil above 70cm depth than below this depth, presumably due to greater short-term fluctuations in soil moisture content. This suggests that radon in soil gas measurements should be taken at depths greater than 70cm in order to reduce the effects of temporal variations caused by rainfall and the effects of free exchange of soil gas and atmospheric air, especially in permeable soils.

The principal soil properties that influence the concentration of radon in soil gas, including the rate of release of radon and its transfer through soils, are soil permeability and soil moisture. Organically bound ^{226}Ra can be a principal source of ^{222}Rn in soil gas (Greeman et al., 1990; Greeman & Rose, 1996). In general, coarse gravelly soils will tend to have higher radon fluxes than impermeable clay soils. Soil permeability and rainfall (soil saturation) control radon concentrations in houses. Soil permeability generally closely reflects the permeability of the underlying rocks and superficial deposits such as glacial till, alluvium, or gravel. Water-saturated soils impede the diffusion of radon enough for it to decay to harmless levels before it has diffused more than 5–10cm. Consequently, radon from water-saturated soils is unlikely to enter buildings unless it is transported with other gases such as carbon dioxide or methane.

Radon migration may occur preferentially along natural planar discontinuities and openings including bedding planes, joints, shear zones, and faults although the precise location of such migration pathways is often difficult to establish, especially if the area is covered with soil or superficial deposits. In southwest England, high radon is associated with U-enriched shear zones in granites, which are characterized by high radon in soil gas and groundwater (Varley and Flowers, 1993). Radon and other gases are known to concentrate and migrate upward along faults and through caves and other solution cavities. However, natural cavities such as potholes and swallow holes in limestone would also be difficult to locate precisely due to their irregular and relatively unpredictable disposition. Whilst radon has been used to identify the location of faults and frequently reaches a maximum in the direct vicinity of faults (Barnet et al., 2008; Ielsch et al., 2010), in the UK a consistent decrease of indoor radon away from mapped faults is not observed (Appleton, 2004) and it is likely that elevated radon concentrations will be associated mainly with active faults.

Artificial pathways for radon migration underground include mine workings and disused tunnels and shafts. Radon concentrations in old uranium and other mine workings are commonly 10–60 kBq m^{-3} and can be as high as 7,100 kBq m^{-3} even when uranium is a very minor component of the metalliferous veins (Gillmore et al., 2001). High radon is known to be associated with gassy ground overlying coal-bearing rock strata. In addition, relatively randomly orientated and distributed blasting and subsidence fractures will affect areas underlain by mined strata. The sites and disposition of recent coal mine workings may be obtained from mine records. Other artificial pathways related to near-surface installations include electricity, gas, water, sewage, and telecommunications services, the location of which may be obtained from the local service agencies. Land drains provide another potential migration pathway. The detection and prediction of migration pathways is difficult and may be imprecise, although a detailed geological and historical assessment together with appropriate radon gas monitoring and a detailed site investigation should provide a reasonable assessment of the source and potential radon gas migration pathways. Information on the local geology may be obtained from maps, memoirs, boreholes, and site investigation records.

Factors Affecting Radon in Buildings

The design, construction, and ventilation of a building affect indoor radon levels as do both the season and the weather. Radon from soils and rocks is transported into buildings through cracks in solid floors and walls below construction level; through gaps in suspended concrete and timber floors and around service pipes; and through crawl spaces, cavities in walls, construction joints, and small cracks or pores in hollow-block walls (Figure 4). Radon concentrations are generally highest in basements and ground floor rooms that are in contact with the soil or bedrock. Air released by well water during showering and other household activities may also contribute to indoor radon levels, although this generally makes a relatively small contribution to the total radon level.

In a typical masonry building in which radon occurs at the UK national average level of 20 Bq m^{-3}, approximately 60% of radon comes from the ground on which the building stands, 25% from building materials, 12% from fresh air, 2% from the water supply, and 1% from the gas supply. These figures apply to the average house in the UK, but can vary substantially, and the proportion of radon entering a home from the ground will normally be much higher in homes with high radon levels (Appleton and Ball, 1995). The dominant mechanism of radon ingress is pressure-induced flow through cracks and holes in the floor, called the stack effect. Slightly negative pressure differences between indoor and outdoor atmospheres, caused by wind outside and heating inside the building, draw radon contaminated air into the building, especially through the floor. Energy-conserving measures such as double-glazing restrict the fresh supply of air and lessen the dilution of radon indoors. Conversely, such measures may also reduce the pressure difference between indoors and outdoors and thus reduce the influx of radon from the ground. Poor ventilation may increase radon concentrations, but it is not the fundamental cause of high indoor radon levels. Household energy efficiency improvements that decrease ventilation (e.g. better sealed windows and doors) could lead to an increase in exposure to radon.

Indoor radon concentrations are generally about 1000 times lower than radon in the soil underlying the house. Most houses draw less than one percent of their indoor air from the soil with the remainder from outdoors where, as noted earlier, the air is generally quite low in radon. In contrast, houses with low indoor air pressures, poorly sealed foundations, and several entry points for soil air may draw as much as 20% of their indoor air from the soil. Consequently, radon levels inside the house may be very high even in situations where the soil air has only moderate amounts of radon.

Geological associations

Geology is usually one of the most important factors controlling the distribution and level of indoor radon and the radon hazard. Mapped bedrock geology explains on average 25% of the variation of indoor radon in England and Wales, whilst mapped superficial geology explains, on average, an additional 2% (Appleton and Miles, 2010). The proportion of the total variation controlled by geology is higher (up to 37%) in areas where there is a strong contrast between the radon potential of sedimentary geological units and lower (14%) where the influence of confounding geological controls, such as uranium mineralisation, cut across mapped geological boundaries.

In the UK, relatively high concentrations of radon are associated with particular types of bedrock and unconsolidated deposits, for example some granites, uranium-enriched phosphatic rocks and black shales, limestones, sedimentary ironstones, permeable sandstones and uraniferous metamorphic rocks. Permeable superficial deposits, especially those derived from uranium-bearing rock, may also be radon prone. Geological units associated with the highest levels of naturally occurring radon (Figures 5-10) are: (i) granites in SW England, the Grampian and Helmsdale districts of Scotland and the Mourne Mountains in Northern Ireland, (ii) Carboniferous limestones throughout the UK and some Carboniferous shales in Northern England and Wales, (iii) sedimentary ironstone formations in the English Midlands, (iv) some Ordovician and Silurian mudstones, siltstones and greywackes in Wales, Northern Ireland and the southern uplands of Scotland, (v) Middle Old Red Sandstone of NE Scotland and (vi) Neoproterozoic psammites, semipelites and meta-limestones in the western sector of Northern Ireland (Appleton and Ball, 1995; Appleton and Miles, 2005; Scheib et al., 2009; Appleton et al., 2011b; Scheib et al., 2013).

Granites

In SW England (Ball and Miles, 1993; Scheib et al., 2013), the Grampian and Helmsdale areas of Scotland (Scheib et al., 2009) and the Late Caledonian and Palaeogene acid intrusive rocks of the Mourne Mountains in the SE sector of Northern Ireland (County Down and County Armagh; Appleton et al., 2015) there is a correlation between areas where it is estimated that more than 20% of the house radon levels are above 200 Bq m^{-3} and the major granite intrusions. Granites in south western England are characterized by high uranium concentrations, a deep weathering profile, and uranium in a mineral phase that is easily weathered. Although the uranium may be removed through weathering, radium generally remains *in situ* (Ball & Miles, 1993). Radon is easily emanated from the host rock and high values of radon have been measured in groundwaters and surface waters (110–740 BqL^{-1}) and also in soil gas (frequently >400 kBq m^{-3}). The highest radon potential values in Scotland are associated with Siluro-Devonian (late Caledonian) granite intrusions, notably those clustered within a zone to the west of Aberdeen and at Helmsdale (Scheib et al., 2009).

Black shales

The depositional and diagenetic environment of many black shales leads to enrichment of uranium. For example, some Lower Carboniferous shales in northern England and NE Wales contain 5–60 $mgkg^{-1}$ uranium, and weathering and secondary enrichment can substantially enhance U levels in soils derived from these shales. 15–20% of houses (rising to more than 65% in some areas) sited on uraniferous black shales with >60 $mgkg^{-1}$ and high soil gas radon (32 kBq m^{-3}; Ball et al., 1992) are above the UK radon Action Level.

Phosphatic rocks and ironstones

Uranium-enriched phosphatic horizons occur in the Carboniferous Limestone, the Jurassic oolitic limestones, and in the basal Cretaceous Chalk in the UK and these sometimes give rise to high radon in soil gas and houses.

Many iron deposits are both phosphatic and slightly uraniferous and a large proportion (>20%) of houses underlain by the ironstones of the Northampton Sand Formation (NSF) and the Marlstone Rock Formation in England are affected by high levels of radon. Phosphatic pebbles from the Upper Jurassic, and Lower and Upper Cretaceous phosphorite horizons in England contain 30–119 $mgkg^{-1}$ U. Radon in dwellings is a significant problem in areas where these phosphatic rocks occur close to the surface, especially if the host rocks are relatively permeable. The NSF consists of ferruginous sandstones and oolitic ironstone with a basal layer up to 30cm thick containing phosphatic pebbles. The ferruginous sandstones and ironstones mainly contain low concentrations of U (<3 $mgkg^{-1}$), whilst the phosphatic pebbles contain up to 55 $mgkg^{-1}$. However, it is probable that the mass of the NSF, which in many cases contains disseminated radium, may contribute more to the overall level of radon emissions than the thin U-enriched phosphate horizons. Laboratory investigations of Jurassic ironstones have demonstrated that the tightly cemented nature of the Marlstone Rock Formation ironstone impedes radon emanation due to low permeability, whilst the NSF has a fine grained, more permeable and often more altered matrix. Near surface weathering is likely to be very important in enhancing radon potential since weathered mineral phases emanate radon more efficiently. Bedrock fracturing and working of the ironstones both also have an important impact and increase the radon risk (Scheib et al., 2013). Worked ground on the Northampton Sand Formation exhibits increased radon potential relative to areas where the ironstone bedrock has not been extracted, possibly reflecting the phosphatic nature of the remaining basal beds, which were not worked.

Limestones and associated shales and cherts

High levels of radon occur in both soil gas and houses underlain by Carboniferous and Jurassic limestone in the UK as well as in caves and mines in these bedrocks. There are 10% to more than 30% of houses built on the limestones in England with radon concentrations greater than the UK Action Level (Appleton et al., 2000a; Appleton et al., 2011c; Scheib et al., 2013). High radon in houses is associated with all areas underlain by Lower Carboniferous limestones throughout Wales and also with Visean shales, sandstones and cherts in NE Wales. Moderate to high radon levels occur in houses built on Namurian Pentre Chert Formation and Westphalian (‘Coal Measures’) strata in Flintshire and Wrexham (Appleton and Miles, 2005). In the western sector of Northern Ireland, especially in County Fermanagh, Carboniferous limestone has >3% of dwellings above the Action Level (Appleton et al., 2011b). In Scotland, elevated radon potential of limestones ranging in age from Dalradian to Carboniferous is likely to relate to the high specific surface area and permeability of the uranium minerals present that permit efficient release of radon and also to the high joint and fracture permeability of the limestone. Some of the radon is thought to emanate from uranium- and radium-enriched residual soils that overlie the highly permeable limestones. In S. Wales, high radon is also associated with the Triassic basal Mercia Mudstone Group Marginal Facies and the limestone-mudstone sequences of the Jurassic Blue Lias Formation, a feature also seen in Somerset.

The radon emanation characteristics of chalk are different from the Carboniferous and

Jurassic limestones. Chalk still retains its primary porosity, although most of the water and gas flow is through fissures. The proportion of dwellings on chalk with radon above the Action Level is much lower than over the Carboniferous Limestone.

Sands and sandstones

Thick, permeable Cretaceous sand formations in south western England, including the glauconitic Lower and Upper Greensand and the Upper Lias Midford Sands, all emanate high levels of soil gas radon and are characterized by a high proportion of houses above the action level (13 and 22% for the Upper Greensand and Midford Sands, respectively). In Scotland, the geometric mean indoor radon for the Middle Old Red Sandstone bedrock of the Orcadian Basin is only slightly above average but there are high values probably related to U-mineralisation. Indeed, the locations of known U mineralisation, in the Caithness area and on the Orkney Islands, show evidence of elevated radon potential. In Pembrokeshire, south-west Wales, high radon potential characterises the arenaceous rocks of the Cosheston Group (Devonian) and in south-west England, the Devonian mudstones and sandstones in Devon and Cornwall.

Ordovician-Silurian greywackes and associated rocks

In Wales, the radon potential of the Cambrian is high in NW Wales and parts of Pembrokeshire whilst moderate to high radon levels occur in many areas underlain by Ordovician and Silurian mudstones, siltstones and greywackes throughout Wales. In Scotland, Ordovician greywackes of the Southern Uplands Terrain have a moderate radon potential but this decreases progressively from the NE to SW, suggesting a lateral variation in composition. The Silurian Riccarton Group greywackes derived from an evolved granitic sediment source also appear from limited data to have a moderate radon potential. In the south-east of Northern Ireland, the Silurian Hawick Group greywackes also display a moderate radon potential (5.7% > AL; Appleton et al., 2011b). Moderate radon levels are associated with some areas underlain by Ordovician and Silurian acid volcanic rocks in the Gwynedd, Conwy, Powys and Pembrokeshire districts of Wales.

Miscellaneous bedrock units

Other bedrock types that exhibit elevated radon potential include: Late Jurassic mudstones, siltstones and sandstones along the north east Scottish coast near Helmsdale, although it is likely that this is locally influenced by high U from the adjacent U-mineralised Helmsdale Granite; Devonian mafic lavas and tuffs, surrounding the Cheviot Granite on the England-Scotland border; and Dalradian metasediments on the Shetland Islands. In the western sector of Northern Ireland, the Neoproterozoic Argyll and Southern Highland Group psammites, semipelites and meta-limestones also have moderate radon potential 2-4% >AL(Appleton et al., 2011b).

Superficial deposits

The source, composition and permeability of superficial deposits determine their radon potential. In areas of relatively U-rich bedrock, for example south west England and Scottish Grampian granites or the Carboniferous limestone in Derbyshire, transported material such as alluvium often exhibits a similar radon potential to the local bedrock. Relatively high radon potential characterises Clay-with-Flints deposits which overlie parts of the Upper Greensand and the White Chalk Group in southern England. Clay-with-Flints is a heterogeneous, unbedded residual deposit formed partly by weathering and solifluction of the original Palaeogene cover and earlier Quaternary deposits, and partly by dissolution of the underlying chalk. Soils developed over the Clay-with-Flints are characterized by enhanced Zr and U concentrations which may explain the slightly enhanced radon potential. Killip (2004) suggested that the moderate radon potential was caused by phosphate-rich components with high uranium contents derived from the chalky source.

In Scotland, increased radon potential of permeable glaciofluvial deposits relative to bedrock and more impermeable superficial deposits is observed on the biotite granite plutons of the Grampian Region and the Hawick Group greywackes of the Southern Uplands. U-rich material influencing radon potential is evident on superficial deposits overlying the Argyll Group psammites, pelites and semipelites where large ranges of radon potential are exhibited, with the highest values found adjacent to the U-rich evolved biotite granite plutons of the Grampian Region. In Wales, where bedrock is overlain by unconsolidated deposits, such as glacial till or alluvium, the proportion of houses with high radon is usually reduced with respect to the underlying bedrock. In NE Wales, for example, approximately 30% of dwellings situated directly on the Lower Carboniferous limestone exceed the Action Level, whereas the proportion is reduced to about 2% where the limestone is covered with glacial till. Whilst most other superficial deposits reduce radon potential relative to the underlying bedrock since they reduce permeability, the variation is often complex and locally controlled.

Measurement of Radon

Radon Testing in the Home

The most common procedures for measuring radon make use of the fact that it is the only natural gas that emits alpha particles, so if a gas is separated from associated solid and liquid phases any measurements of its radioactive properties relate to radon or its daughter products.

Common short-term test devices are charcoal canisters, alpha track detectors, liquid scintillation detectors, electret ion chambers, and continuous monitors. A short-term testing device remains in the home for 2–30 days, depending on the type of device. Because radon levels tend to vary from day-to-day and season-to-season, a long-term test is more likely than a short-term test to provide an accurate estimate of the home's year-round average radon level. If results are needed quickly, however, a short-term test followed by a second short-term test may be used to determine the approximate severity of the radon hazard. Long-term test devices, comparable in cost to devices for short-term testing, remain in the home for three months or more. A long-term test is more likely to indicate the home's year-round average radon level than a short-term test. Alpha track detectors and electret ion detectors are the most common long-term test devices. Ambiguous short-term measurements should be followed up by a long-term measurement.

The alpha (etched) track detectors recommended for radon testing in the UK consist of a container holding a small sheet of plastic. Radon can enter the container, and the alpha particles emitted by radon and its decay products damage the plastic as they strike it. The damaged areas can be removed by etching in a laboratory, leaving tracks in the surface where alpha particles have struck. The tracks are counted to determine the exposure of the detector to radon. Etched track detectors are relatively cheap and suitable for long-term measurement and two detectors, placed in the living room and an occupied bedroom, are usually deployed for a period of three months.

Electret ion detectors contain an electrostatically charged PTFE disk. Radiation emitted by decay of radon and its decay products ionise the air inside the detector and reduce the surface voltage of the disk. By measuring the voltage reduction, the radon concentration can be calculated. Allowance must be made for ionization caused by natural background gamma radiation. Different types of electret are available for measurements over periods of a few days to a few months. The detectors must be handled carefully for accurate results.

Continuous monitors are active devices that need power to function. They require operation by trained testers and work by continuously measuring and recording the amount of radon in the home. These devices sample the air continuously and measure either radon or its decay products (NRPB, 2000).

Charcoal detectors absorb radon from the air, and must be returned to the issuing laboratory quickly for assessment before the radon has decayed. They are not suitable for measurements longer than about four days. The standard procedure for deployment of such detectors is intended to give a 'worst case' result. If a high radon concentration is found, a follow-up measurement using long-term detectors can be carried out, but if the result is low then it is unlikely that a longer measurement would find a high concentration. The standard procedure requires that doors and windows must be closed 12 hours prior to testing and throughout the testing period. The test should not be conducted during unusually severe storms or periods of unusually high winds. The test kit is normally placed in the lowest lived-in level of the home, at least 50 cm above the floor, in a room that is used regularly, but not in the kitchen or bathroom where high humidity or the operation of an exhaust fan could affect the validity of the test. At the end of the test period, the kit is mailed to a laboratory for analysis; results are mailed back in a few weeks. If the result of the short-term test exceeds 100 Bqm^{-3} then a long-term test is normally recommended.

Remediation of the home is recommended if the radon concentration determined by a 3 month test exceeds 200 Bqm^{-3}. Radon levels are generally highest in winter so seasonal corrections are usually applied to estimate the average annual radon level (Miles, 1998; Miles et al, 2011; Miles et al, 2012).

Bungalows and detached houses tend to have higher indoor radon than terraced houses or flats in the same area of the UK. Building material, double-glazing, draught-proofing, date of building, and ownership also have a significant impact on indoor radon concentrations.

In workplaces, consideration needs to be taken of work practices and the building design and use. For small premises at least one measurement should made in the two most frequently occupied ground floor rooms. In larger buildings at least one measurement is required for every 100m^2 floor area.

Measurement of radon in soil gas and solid materials

Measurement of radon in soil gas using pumped monitors is recommended as the most effective method for assessing the radon potential of underlying rocks, overburden, and soil. Instruments for the determination of soil gas radon are generally based upon either an extraction method, using a "pump monitor" device for transferring a sample of the soil gas to a detector, or simply emplacing the detector in the ground (passive methods). In the former method, a thin rigid tapered hollow tube is usually hammered into the ground to an appropriate depth (generally 70 – 100 cm), which causes minimum disturbance to the soil profile. Detection of radon is usually based upon the zinc sulphide scintillation method or the ionization chamber. Alpha particles produce pulses of light when they interact with zinc sulphide coated on the inside of a plastic or metal cup or a glass flask (Lucas cell). These may be counted using a photomultiplier and suitable counting circuitry. Because the radon isotopes are the only alpha-emitting gases, their concentration may be determined accurately using relatively simple equipment. The concentration of radon in soil gases is usually sufficient that the level may be determined relatively quickly; a few minutes is generally enough. Determination of radon potential from soil gas radon concentrations generally produces better results when soil permeability is also measured (Barnet et al., 2008; Kemski et al., 2001).

Radon release from disaggregated samples (soils, stream sediments, and unconsolidated aquifer sands) may be determined by agitating a slurry of the material with distilled water in a sealed glass container, allowing a period of about 20–30 days for the generation of radon from radium, and then measuring the radon in the aqueous phase using a liquid scintillation counter. Emanation of radon from solid rock samples can be determined using a similar method. Alternatively a degassing kit can be used and the radon gas measured with similar equipment to that described for soil gas measurement.

Radon hazard mapping and site investigation

Radon hazard mapping based on geology and indoor radon measurements

Requirements for mapping radon-prone areas using indoor radon data include (1) accurate radon measurements made using a reliable and consistent protocol, (2) centralized data holdings, (3) sufficient data evenly spread, and (4) automatic conversion of addresses to geographical coordinates. It appears that the UK is the only country that currently meets all of these requirements for large areas (Miles and Appleton, 2005)

Radon potential mapping is sometimes based on indoor radon data that have been normalized to a mix of houses typical of the housing stock as this removes possible distortion caused by construction characteristics. Maps based on results corrected for seasonal variations or temperature at the time of measurement but not normalized to a standard house mix reflect such factors as the greater prevalence of detached dwellings in rural areas, and hence the higher risk of high radon levels in rural areas compared with cities where flats are usually more prevalent. Radon potential estimates based on radon levels in the actual housing stock are more appropriate for the identification of existing dwellings with high radon.

In the UK, digital geological data compiled by the British Geological Survey (BGS) and indoor radon measurements by Public Health England (PHE, formerly the Health Protection Agency, HPA) are used to produce radon potential maps which indicate the spatial variation in radon hazard (Miles and Appleton, 2005; Miles et al., 2007, 2011; Scheib et al., 2009, 2013). The current radon potential maps indicate the probability that new or existing houses will exceed a radon reference level, which in the UK is termed the UK Action Level (of 200 Bq m^{-3}).

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.

Approximately 25% of the total variation of indoor radon concentrations in England and

Wales can be explained by the mapped bedrock and superficial geology. The proportion of the variation that can be attributed to mapped geological units increases with the level of detail of the digital geological data (Appleton and Miles, 2010). As a consequence, the most accurate and detailed radon potential maps are generally those based on house radon data and geological boundaries provided that the indoor radon data can be grouped by sufficiently accurate geological boundaries.

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 UK national grid, the cumulative percentage of the variation between and within mapped geological units is shown to be 34–40% (Appleton and Miles, 2010). This confirms the importance of radon maps that show the variation of indoor radon concentrations both between and within mapped geological boundaries. 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).

Each geological unit within a map sheet or smaller area, such as a 1-km grid square, has a characteristic geological radon potential that is frequently very different from the average radon potential for the geological unit. The results of the integrated mapping method allowed significant variations in radon potential within bedrock geological units to be identified, such as in the radon prone Jurassic Northampton Sand Formation (NSF). Moderate radon potential (<4%>AL) occurs within and to the northwest of the urban centre of Northampton with much higher potential (>12%>AL) to the north (Figure 11). The NSF comprises a lower ironstone, often with a uraniferous and phosphatic nodular horizon at the base (Sutherland 1991), overlain by a massive yellow or brown calcareous sandstone (locally called the "Variable Beds", Hains and Horton 1969). Variable Beds sandstones at Harlestone Quarry (HQ, Figure 11) contain on average 11% Fe_2O_3T, 0.37% P_2O_5 and 1.1 mg kg^{-1} uranium (Hodgkinson et al., 2005) in an area with a radon potential of about 3%>AL whereas at Pitsford Quarry (PQ, Figure 11), the ironstones contain 29% Fe_2O_3T, 1.0% P_2O_5 and 2.4 mg kg^{-1} uranium in an area with radon potentials in the range 8 – 21%>AL. Radon in soil gas correlates positively with the radon potential of the NSF (Figure 12), and there is also a close correlation (r=0.86, p 0.0005) between radon emanation and uranium in rock samples (Hodgkinson et al., 2005). Track etch alpha autoradiography studies indicate that uranium is associated predominantly with the goethite-rich clay matrix of the ironstones, and is also concentrated in occasional phosphatic nodules (Hodgkinson et al 2005).

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. It is, however, reassuring that even when the measurement density is as low as 0.2–0.4 per km^2, geological radon potential mapping discriminates between geological units in a logical way. These relationships can be explained on the basis of the petrology, chemistry, and permeability of the rock units and are confirmed in adjoining areas with higher measurement densities (Miles & Appleton, 2000). Other uncertainties in the mapping process relate to house-specific factors, proximity to geological boundaries and measurement error impact on the radon mapping process (Hunter et al., 2009, 2011).

Geological radon potential maps of the UK have been produced at 1:625,000 (Appleton and Ball, 1995), 1:250,000, and most recently at 1:50,000 (Figures 6, 8, 10) for the purpose of defining radon Affected Areas in the UK.

Radon hazard mapping based on geology, gamma spectrometry and soil gas radon data

In the absence of an adequate number of high quality indoor radon measurements, proxy indicators such as information on U content or soil gas radon data may be used to assess geological radon potential. The reliability of maps based on proxy data increases with the number of classes as well as the quantity and quality of available data. Uranium and radium concentrations in surface rocks and soils are useful indicators of the potential for radon emissions from the ground. Uranium can be estimated by gamma spectrometry either in the laboratory or by ground, vehicle, or airborne surveys (IAEA, 2003).

The close correlation between airborne radiometric measurements and indoor radon concentrations has been demonstrated in parts of the UK (Appleton & Ball, 2001; Appleton et al., 2008, 2011b Scheib et al., 2006). Areas with high permeability tend to have significantly higher indoor radon levels than would be otherwise expected from the equivalent ^{226}Ra concentrations, reflecting an enhanced radon flux from permeable ground. In Northern Ireland linear regression analysis of airborne and soil geochemical parameters revealed that the most significant independent variables were eU (equivalent uranium), a parameter derived from gamma spectrometry measurements of radon decay products in the top layer of soil and exposed bedrock, and the permeability of the ground. The radon potential map generated from airborne gamma spectrometry data agrees in many respects with the map based on indoor radon data and geology but there are several areas where radon potential predicted from the airborne radiometric and permeability data is substantially lower than that found from radon measurements (Appleton et al., 2011b). This under-prediction could be caused by the radon concentration being lower in the top 30 cm of the soil than at greater depth, because of the loss of radon from the surface rocks and soils to air.

It has been demonstrated in a number of countries, including the UK, Germany and the Czech Republic that soil gas radon measurements combined with an assessment of ground permeability can be used to map geological radon potential in the absence of sufficient indoor radon measurements. After uranium and radium concentration, the permeability and moisture content of rocks and soils are probably the next most significant factors influencing the concentration of radon in soil gas and buildings. Radon diffuses farther in air than in water, so in unsaturated rocks and overburden with high fluid permeability, higher radon values are likely to result from a given concentration of uranium and radium than in less permeable or water-saturated materials. Weathering processes can also affect permeability. Enhanced radon in soil gas is also associated with high-permeability features such as fractures, faults, and joints. The fracturing of clays, resulting in enhanced permeability, combined with their relatively high radium content and their emanation efficiency may also result in higher radon concentrations in dwellings. The permeability of glacial deposits exerts a particularly strong influence on the radon potential of underlying bedrock. Significant correlations between average indoor and soil gas radon concentrations, grouped according to geological unit, have been recorded in the UK (Appleton et al., 2000) as well as in Czech Republic (Barnet et al., 2008), Germany (Kemski et al., 2009) and the United States (Gunderson et al., 1992).

Other radon hazard mapping methods are discussed in Appleton and Ball (2001) and Appleton (2013).

Radon Site Investigation Methods

Radon migrates into buildings as a trace component of soil gas. Therefore the concentration of radon in soil gas should provide a good indication of the potential risk of radon entering a building if its construction characteristics permit the entry of soil gas. There is a growing body of evidence that supports the hypothesis that soil gas radon is a relatively reliable indirect indicator of indoor radon levels at the local as well as the national scale (Ball et al., 1992; Barnet et al., 2008; Kemski et al., 2009). However, in some cases, soil gas radon data may be difficult to interpret due to the effects of large diurnal and seasonal variations in soil gas radon close to the ground surface as well as variations in soil gas radon on a scale of a few meters. The former problem may be overcome by sampling at a depth greater than 70cm or by the use of passive detectors with relatively long integrating times, although this may not be a practical option if site investigation results are required rapidly. Small-scale variability in soil gas radon may be overcome by taking 10–15 soil gas radon measurements on a 5- to 10-m grid to characterize a site. Radon in soil gas varies with climatic changes including soil moisture, temperature, and atmospheric pressure so weather conditions should be as stable as possible during the course of a soil gas radon survey.

A range of methods such as controlled gas extraction, air injection procedures, or water percolation tests can be used to estimate gas permeability at a specific site. In the absence of permeability measurements, more qualitative estimates of permeability can be based on visual examination of soil characteristics, published soil survey information, or on the relative ease with which a soil gas sample is extracted.

In some areas and under some climatic conditions, site investigations using soil gas radon cannot be carried out reliably, for example, when soil gas cannot be obtained from waterlogged soils or when soil gas radon concentrations are abnormally enhanced due to the sealing effect of soil moisture. If soil gas radon concentrations cannot be determined because of climatic factors, measurement of radon emanation in the laboratory or gamma spectrometric measurement of eU can be used as radon potential indicators in some geological environments. However, few data are available and the methods have not been fully tested.

Radon may also be a problem underground, such as in tunnels. Radon emanation from borehole core samples can be determined to derive values of radon emanation per unit of surface area, which is an effective and simple way of assessing radon hazard in tunnels at the site investigation stage although the effects of larger scale features such as fractures may not be accounted for (Talbot et al., 1997).

9. Strategies for management: avoidance, prevention and mitigation

Introduction

Accurate mapping of radon-prone areas helps to ensure that the health of occupants of new and existing dwellings and workplaces is adequately protected. Radon potential maps have important applications, particularly in the control of radon through planning, building control, and environmental health legislation. The overall aim of most countries that have identified a radon problem is to map radon-prone areas and then identify houses and workplaces with radon concentrations that exceed the radon reference level. An Action Level (AL) for radon in homes of 200 Bq m^{-3} has been established in the UK. Public Health England (PHE) has recommended that parts of the UK with 1% probability or more of homes being at or above the Action Level should be designated as radon Affected Areas. In 2010, PHE guidance on radon gas concentrations introduced a new ‘target level’ of 100 Bq m^{-3} above which remediation work should be seriously considered especially by high risk groups such as smokers and ex smokers.

In the UK, testing for radon is recommended by government in radon Affected Areas where more than 1% of dwellings exceed the Action Level of 200 Bq m^{-3}. Householders are encouraged to have radon measured in existing and new dwellings in Affected Areas and local authority environmental health departments are generally responsible for ensuring that radon in workplaces is monitored in such areas.

PHE and the BGS have produced a series of radon maps showing Radon Affected Areas, based on the underlying geology and indoor radon measurements. The maps are used (i) to assess whether radon protective (preventive) measures may be required in new buildings; (ii) for the cost-effective targeting of radon monitoring in existing dwellings and workplaces to detect those buildings with radon above reference levels which need to be remediated; (iii) to allow measurement campaigns and public awareness to be targeted on areas at greatest risk and (iv) to provide radon risk assessments for home buyers and sellers. In the UK, this is achieved by the online reports services developed by BGS and PHE: (i) for existing homes with a valid postcode, a Radon Risk Report can be ordered online from the UK Radon website (http://www.ukradon.org/); (ii) for existing large homes and other large buildings and plots of land, a GeoReport can be obtained from BGS (http://shop.bgs.ac.uk/georeports/). The radon map data helps local authorities to communicate quickly and effectively with existing home owners or developers planning to build new homes in high radon areas.

It is important, however, to realize that 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. Whereas a radon potential map can indicate the relative radon risk for a building in a particular locality, it cannot predict the radon risk for an individual building. Once identified as being in a high risk area, homes and workplaces can have the radon levels measured and if found to be high, remedial work undertaken.

Environmental Health Regulations

There are environmental or safety thresholds of radioactivity such as *dose limit, Action Level,* and *reference level,* which are used in legislation and advice. Governments set occupational *dose limits* in order to ensure that individuals are not exposed to an unacceptable degree of risk from artificial radiation. Historically, occupational exposure to radon decay products has been expressed in working level (WL) units. A WL is any combination of short-lived radon decay products (^{218}Po, ^{214}Pb, ^{214}Bi, and ^{214}Po) in one litre of air that will result in the emission of 1.3×10^5 MeV of potential alpha energy. Exposures may be measured in working level months (WLM). A WLM is the cumulative exposure equivalent to 1WL for a working month (170 hours). In SI units, a WLM is defined as 3.54 mJhm^{-3} (ICRP, 1993). One WL is approximately equal to a radon exposure of 7500 Bq m^{-3} and 1 WLM to an average radon exposure of about 144 Bq m^{-3} y (on the assumption that people spend most of their time indoors) (NRPB, 2000).

The International Commission for Radiological Protection (ICRP) has recommended that all radiation exposures should be kept as low as reasonably achievable taking into account economic and social factors. In the UK, statutory regulations apply to any work carried out in an atmosphere containing ^{222}Rn gas at a concentration in air, averaged over any 24-hour period, exceeding 400 Bq m^{-3} except where the concentration of the short-lived daughters of ^{222}Rn in air averaged over any 8-hour working period does not exceed $6.24.10^7$ Jm^{-3}. The limit on effective dose for any employee of 18 years of age or above is 20mSv in any calendar year. This dose limit may be compared with the dose to the average person in the UK of 2.5mSv, the dose of 7.5mSv to the average person living in the high radon area of Cornwall, UK, and 0.4mSv to the average nuclear worker in the UK (Watson et al., 2005).

A number of occupations have the potential for high exposure to ^{222}Rn progeny: mine workers, including uranium, hard rock, and vanadium; workers remediating radioactive contaminated sites, including uranium mill sites and mill tailings; workers at underground nuclear waste repositories; radon mitigation contractors and testers; employees and recreational visitors of natural caves (Gillmore et al., 2002; Gillmore et al., 2000); phosphate fertilizer plant workers; oil refinery workers; utility tunnel workers; subway tunnel workers; construction excavators; power plant workers, including geothermal power and coal; employees of radon ‘health mines’; employees of radon balneotherapy spas (waterborne ^{222}Rn source); workers and visitors to hot spring hotels; water plant operators (waterborne ^{222}Rn source); fish hatchery attendants (waterborne ^{222}Rn source); employees who come in contact with technologically enhanced sources of naturally occurring radioactive materials; and incidental exposure in almost any occupation from local geologic ^{222}Rn sources. Recreational and other visitors to abandoned metalliferous mines may also be exposed to high radon concentrations (Gillmore et al., 2001).

Environmental health responses include provision of guidance for radon limitation including recommendations for dose limits and action levels, establishment of environmental health standards for houses and workplaces, and enforcement of Ionizing Radiations Regulations to control exposure to radon in workplaces (Appleton et al., 2000b; WHO, 2009). National authorities are recommended to set a reference level for radon that represents the maximum accepted radon concentration in a residential dwelling. Remedial actions may be recommended or required for homes in which radon exceeds the reference level. Various factors such as the distribution of radon concentrations, the number of existing homes with high radon concentrations, the arithmetic mean indoor radon level and the prevalence of smoking are usually considered when setting a national radon reference level. WHO (2009) proposed a reference level of 100 Bq m^{-3} to minimize health hazards due to indoor radon exposure although if this concentration cannot be reached, the reference level should not exceed 300 Bq m^{-3}. This represents approximately 10 mSv per year according to recent calculations and recommendations by the International Commission on Radiation Protection (ICRP, 2007, 2009) which also recommends 1000 Bq m^{-3} as the entry point for applying occupational radiological protection requirements. There are substantial variations in action levels (or their equivalents) in countries that recognise a radon problem. International and national recommendations for radon limitation in existing and future homes, given as the annual average of the gas concentration in Bq m^{-3}, range from 150 to 1000 for existing dwellings and from 150 to 250 for new dwellings (Åkerblom, 1999). The majority of countries have adopted 400 and 200 Bq m^{-3}, respectively, for the two reference levels (HPA, 2009).

The reasons for these different reference levels appear largely historical but are also due to a combination of environmental differences, different construction techniques, and varying levels of political and environmental concern. There would be advantages in harmonizing standards because the existence of different levels may lead to confusion among the public.

In addition to variations in house radon standards between countries, there also appears to be some variation in standards applied within the field of radiological protection. However, international and national radiological protection authorities are united in acknowledging the need for a distinction in the ways radiation is approached in different situations, such as dwellings and nuclear installations.

The European Commission Recommendation (2001/928/EURATOM) on the protection of the public against exposure to radon in drinking water supplies recommends 1000 Bq/L as an action level for public and commercial water supplies above which remedial action is always justified on radiological protection grounds. Water supplies that support more than 50 people or distribute more than 10 m^3 per day, as well as all water that is used for food processing or commercial purposes, except mineral water, are covered by the European Commission Recommendation. The 1000 Bq/L action level also applies to drinking water distributed in hospitals, residential homes, and schools and should be used for consideration of remedial action in private water supplies.

Radon and the Building Regulations: protecting new buildings

Provisions have been made in the building regulations to ensure that new dwellings are protected against radon where a significant risk of high radon concentrations in homes has been identified on the basis of house radon surveys.

The UK has regulations and guidelines for radon prevention in the planning stages of new development (e.g., where construction permits are applied for dwellings, offices, and factories). Cost-effectiveness analysis in the UK suggest that radon protective (preventive) measures, such as a sealed membrane under the ground floor in new homes would be justified in all areas (HPA, 2009).

Provision has been made in Requirement C1 (2) of Schedule 1 of the Building Regulations 2000 for the protection of buildings against the ingress of radon. The Approved Document C (ODPM, 2004) refers to BRE Report, BR211 Radon: guidance on protective measures for new buildings (Scivyer, 2007), for detailed guidance on where such protection is necessary and practical construction details. The guidance in the Approved Document C (ODPM, 2004) applies to all new buildings including dwellings, extensions, conversions and refurbishment whether they be for domestic or non-domestic use. BRE provides technical guidance on protective and remedial measures. Local Authority building control officers and Approved Inspectors enforce regulations and guidance for dealing with radon in new development through the Building Regulations.

In England and Wales, radon protective measures currently need to be installed in new dwellings, extensions to dwellings and buildings where there is a change of use to a residential or sleeping use where it is estimated that the radon concentration exceeds the Action Level in 3% or more of homes. In Scotland and Northern Ireland, radon protective measures have to be installed in all new dwellings where greater than 1% of dwellings are estimated to exceed to Action Level. Guidance is provided in BRE report BR376, *Radon: guidance on protective measures for new dwellings in Scotland*. Guidance for Northern Ireland is provided in BR413 *Radon guidance on protective measures for new dwellings*. Supplementary guidance is contained in BRE Good Building Guide GBG 73, (Scivyer, 2008) *Radon protection for new domestic extensions and conservatories with solid concrete ground floors*, BRE Good Building Guide GG 74, *Radon protection for new dwellings avoiding problems and getting it right!* and BRE Good Building Guide GG 75, *Radon protection for new large buildings* (Scivyer, 2015).

Radon and work places

Under the Health and Safety at Work etc. Act 1974 (HSW Act), employers must ensure the health and safety of employees and others who have access to that working environment. Protection from exposure to radon at work is specified in the Ionising Radiations Regulations 1999 (IRR, 1999) made under the HSW Act. The concentration at which measures to protect employees should be taken in work places is 400 Bq m^{-3} averaged over a 24 hour period, as specified in the HSE (Health and Safety Executive) Approved Code of Practice and guidance for IRR (1999) (*Working with ionising radiation*, L121).

Persons responsible for a workplace are required to assess the risks from radon in Affected Areas, and this usually requires a radon measurement. Enforcement of regulations is done through the Health and Safety Executive (HSE) and Local Authority Environmental Health Departments. Further Guidance is contained in Scivyer (2011).

As radon in Affected Areas contributes a higher dose to staff than work with ionizing radiations, it is important that all work place affected rooms are located and remediated (Denman et al 2002).

Radon and the planning system

Appleton et al. (2000b) recommended that the planning system should address the problem of radon in new development and that information on radon should be contained in development plans and in decision letters for individual planning applications. In 2004, ODPM issued Planning Policy Statement PPS23: Planning and Pollution Control, which complements the new pollution control framework under the Pollution Prevention and Control Act 1999 and the PPC Regulations 2000. Radon is mentioned in Annex 2 to PPS23 (Development on Land Affected by Contamination) on the basis that since radon may pose a risk to human health its presence is a material planning consideration. PPS23 indicates that Local Planning Authorities should include appropriate information on radon in the land condition and quality section of their Local Development Documents as well as in the determination of planning applications in relation to development on radon affected land. This guidance applies only in England and no equivalent planning policy statement or technical guidance has yet been published for Northern Ireland, Scotland or Wales.

Remedial measures

Before considering how to reduce the radon level in a home, a reliable radon measurement must be taken. This will usually comprise a whole house average reading based upon a pair of detectors placed in the main living room and main bedroom. For most homes this average reading will be adequate for helping to select appropriate remedial measures. Larger houses, houses of unusual layout or construction, and work places may need additional measurements to help target remedial measures. If the annual average radon level exceeds 200 Bq m^{-3} in a home, householders or owners are advised to take action to reduce it. These measures should be designed to reduce the annual average as low as reasonably practicable, not just to get below the Action Level. Effective remedial measures to reduce domestic exposure to radon can be carried out to a typical house for around £1,000.

In the case of high radon levels in workplaces, the law requires employers to avoid exposing their employees to excessive radiation doses, either by reducing radon levels or by other means. In the UK, owners of workplaces may be forced to carry out remedial measures whereas householders in dwellings with radon above the action level are generally only advised to take action to reduce the radon level. Guidance is provided in a number of BRE publications (BRE, 1996b; Pye 1993, Scivyer 1993; Scivyer and Jaggs, 1998; Scivyer, 1993, 2007, 2011, 2012, 2013 a-b).

Guidance on reducing radon levels in dwellings is provided on the PHE Ukradon web site (http://www.ukradon.org/) , but the cost of installing remedial measures in a dwelling is normally the householder's responsibility. Grant aid may be available.

The principal ways of reducing the amount of radon entering a dwelling include (i) active under-floor ventilation, i.e., drawing the air away from underneath the floor so that any air containing radon gas is dispersed outside the house; (ii) subfloor depressurization (radon sump); (iii) positive pressurization (i.e., pressurize the building in order to prevent the ingress of radon); (iv) ventilation (i.e., avoid drawing air through the floor by changing the way the dwelling is ventilated)

Radon gas may be easily removed from high-radon groundwaters by aeration and filter beds will remove daughter products. Various aeration technologies are available including static tank, cascade, or forced aeration in a packed tower. Packed tower aeration is simple and cheap and is recommended for large drinking water supplies.

Monitoring and remediation in existing homes are not cost-effective at present in the UK but might become so in areas with mean indoor radon concentrations of 60 Bq m^{-3} or above if the UK Action Level was reduced from 200 to 100 Bq m^{-3} (HPA, 2009).

Scenarios for future events

Very high indoor radon concentrations (5000 to 17,000 Bq m^{-3}) have been measured in UK homes but it is possible higher concentrations may be found in the future. Household energy efficiency drives that decrease ventilation (e.g. better sealed windows and doors) could lead to an increase in exposure to radon. Climate change and greater weather variability may influence annual indoor radon concentrations and also seasonal correction factors.

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FIGURES

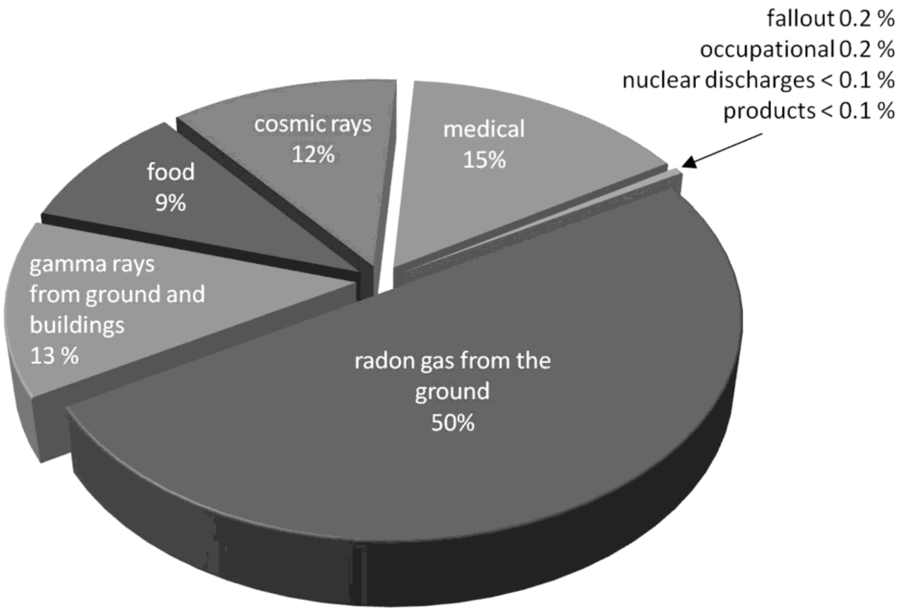

Fig. 1 Average annual radiation dose to the UK population (data from Watson et al. 2005)

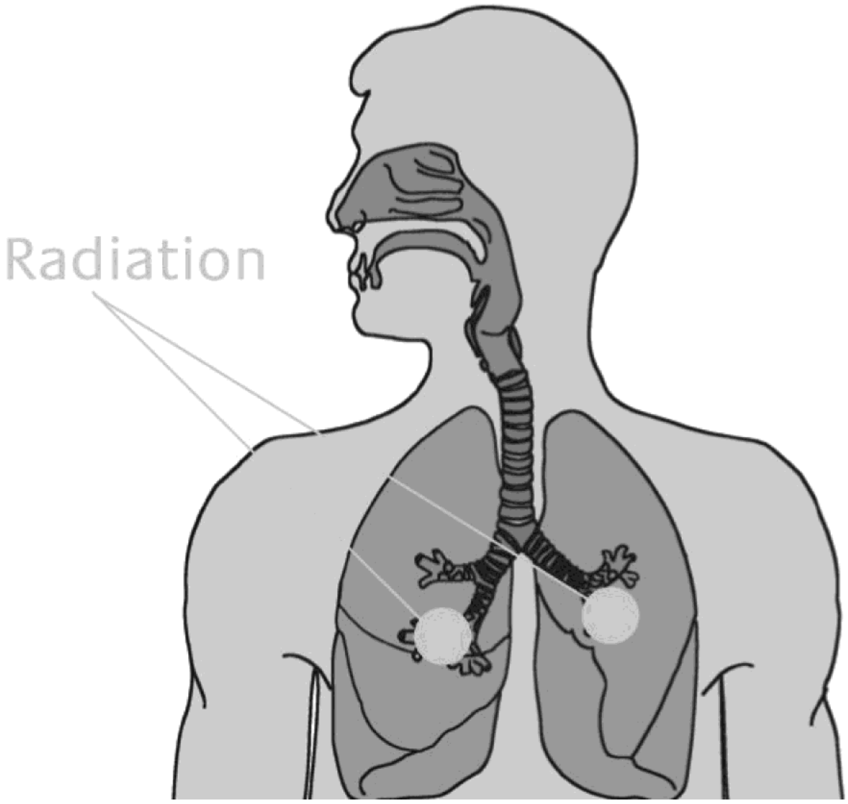

Fig. 2: Solid radioactive decay particles from radon (^{222}Rn), including polonium-218, attached to natural aerosol and dust particles are inhaled and irradiate the lining of the bronchi in the lung with alpha particles.(Image © Public Health England).

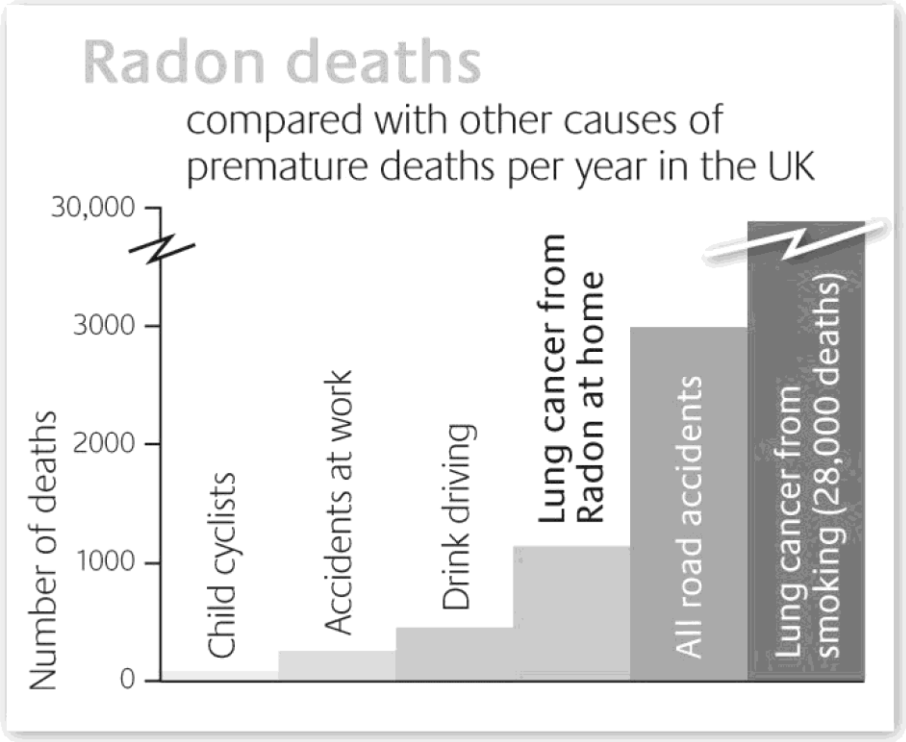

Fig. 3. Radon deaths compared to other causes of premature deaths per year in the UK . (Image © Public Health England).

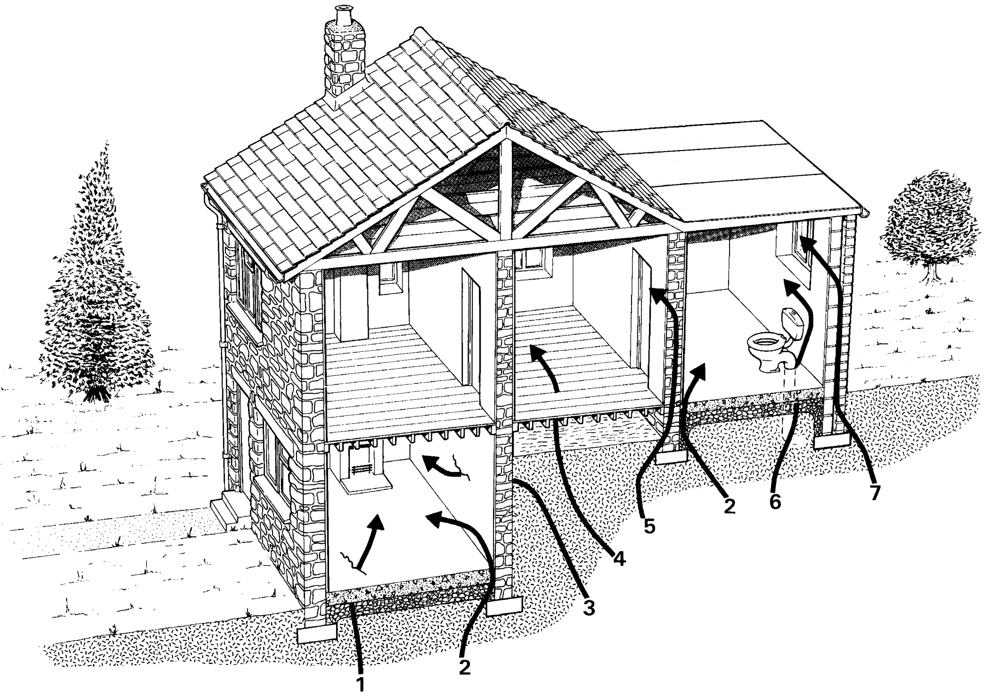

Fig. 4. Routes by which radon enters a dwelling. (Reproduced from BR211, Scivyer 2007; Ingress routes: 1- cracks in solid floors; 2 - construction joints; 3 - cracks in walls below ground; 4 - gaps in suspended floors; 5 - cracks in walls; 6 - gaps around service pipes; 7- cavities in walls)

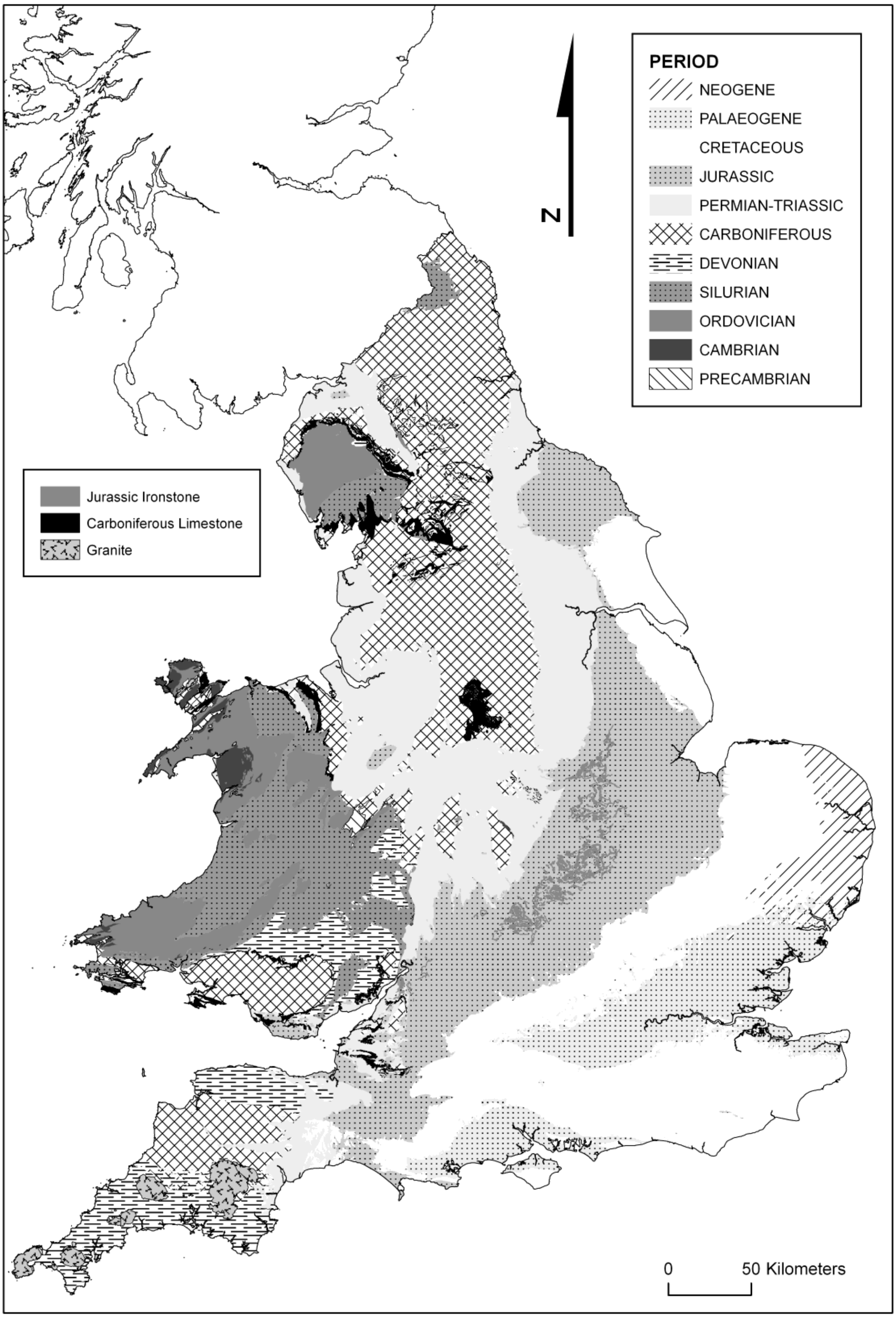

Fig. 5 Simplified geological map of England and Wales

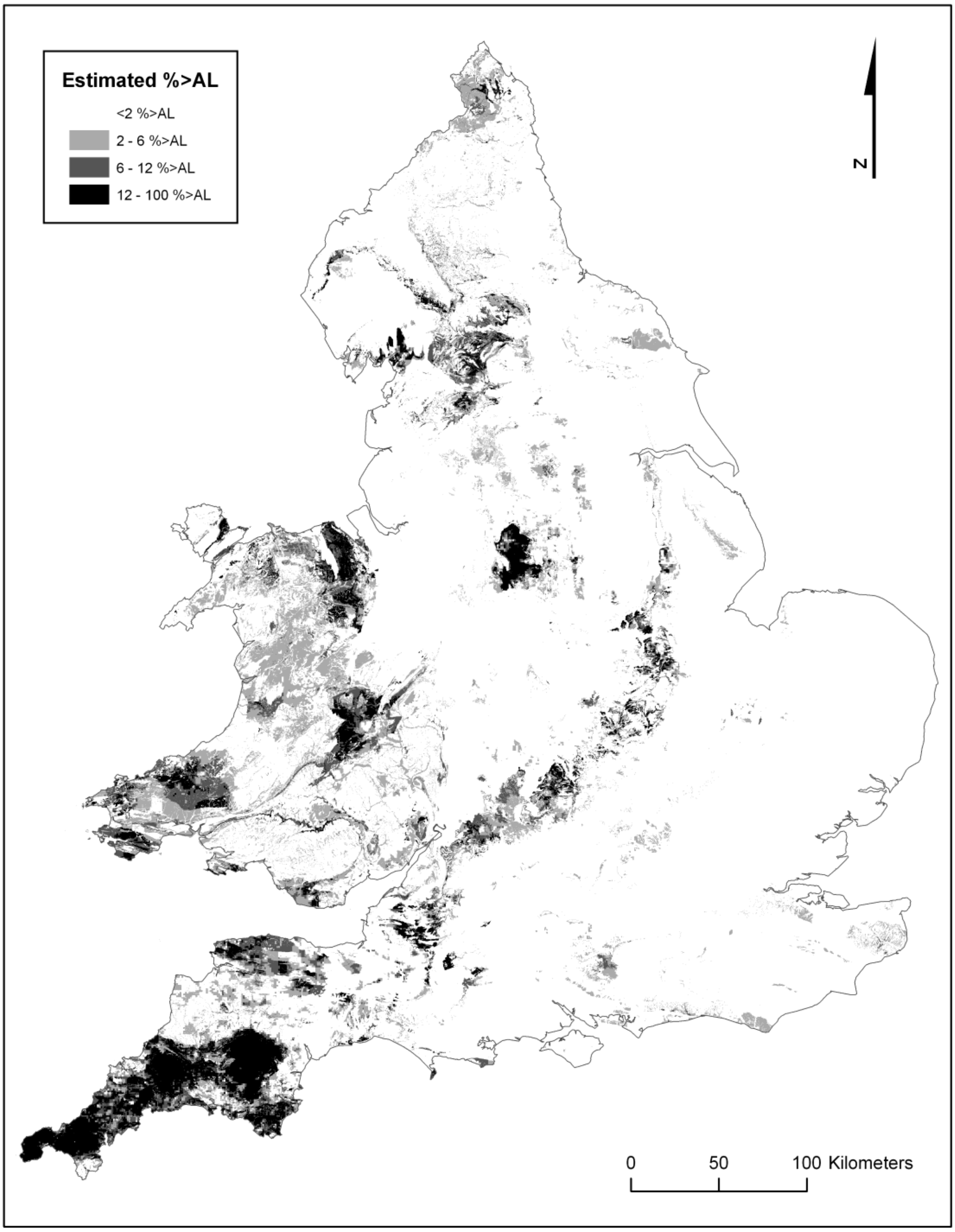

Fig. 6 Radon potential map of England and Wales

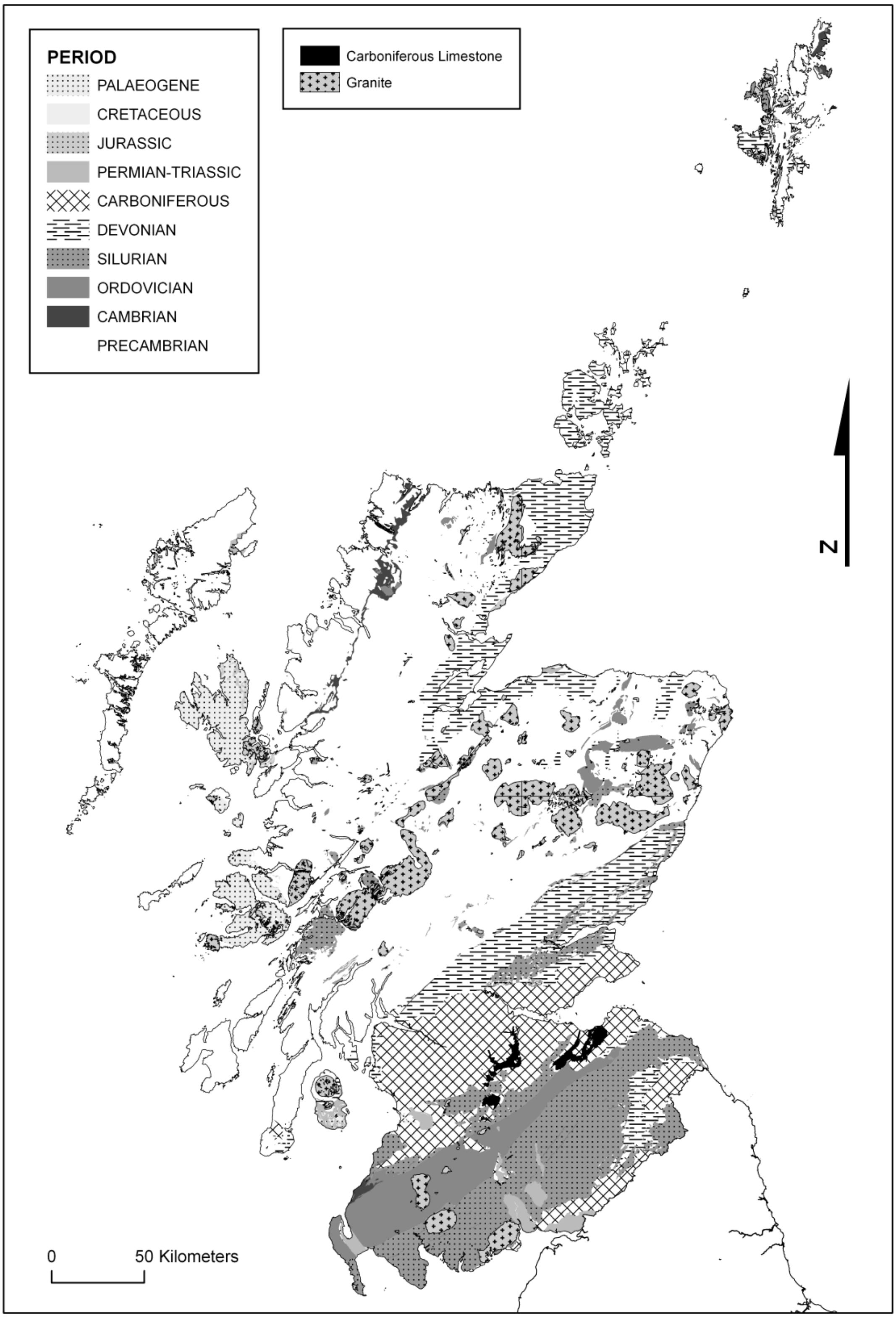

Fig. 7 Simplified geological map of Scotland

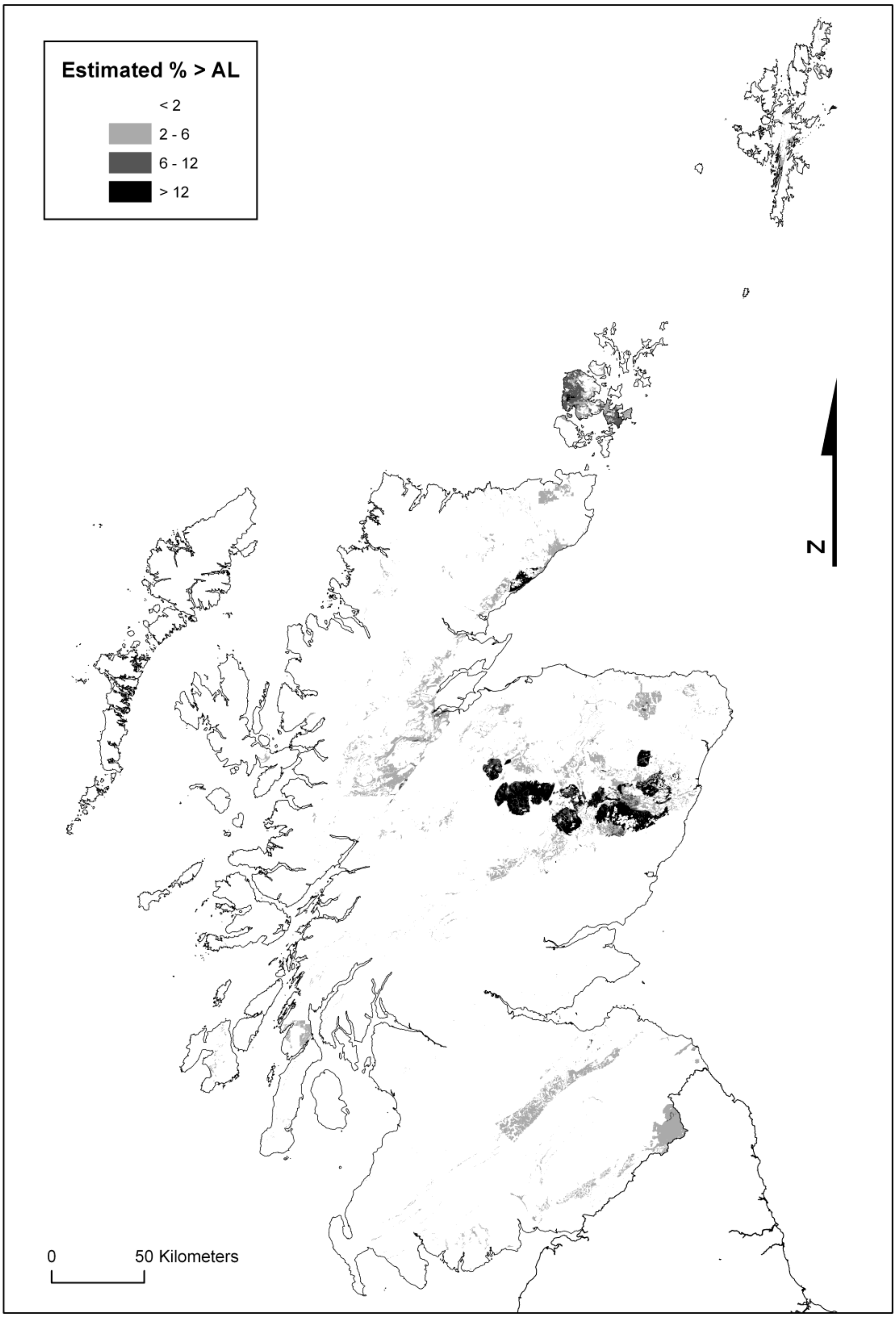

Fig. 8 Radon potential map of Scotland

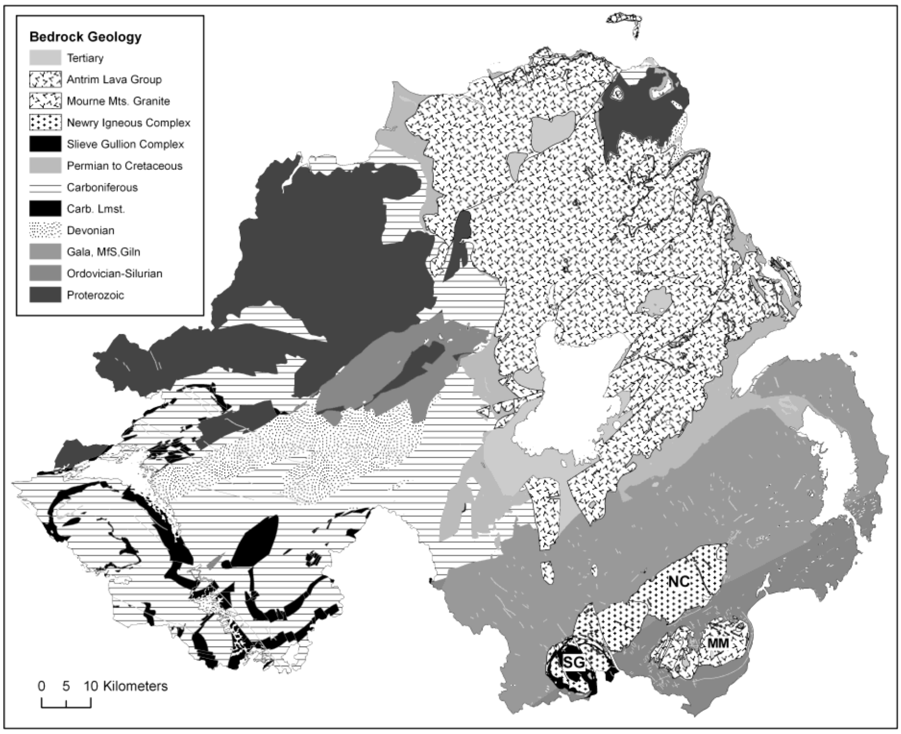

Fig. 9. Simplified bedrock geology of Northern Ireland. MM – Mourne Mountains Granite; SG – Slieve Gullion Complex; NC – Newry Igneous Complex

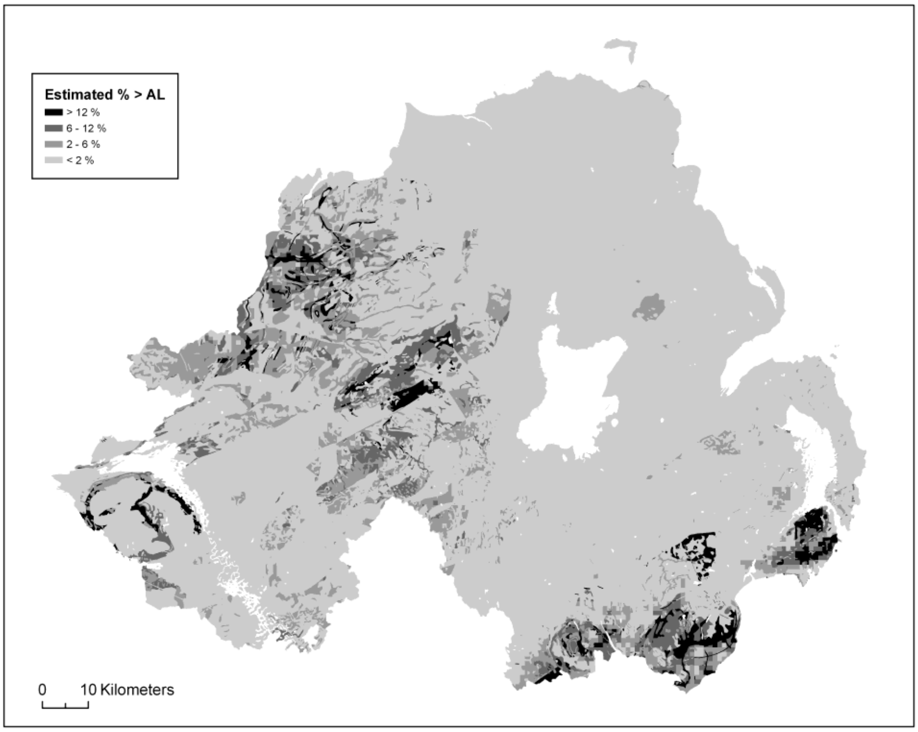

Fig. 10 Radon potential map of Northern Ireland

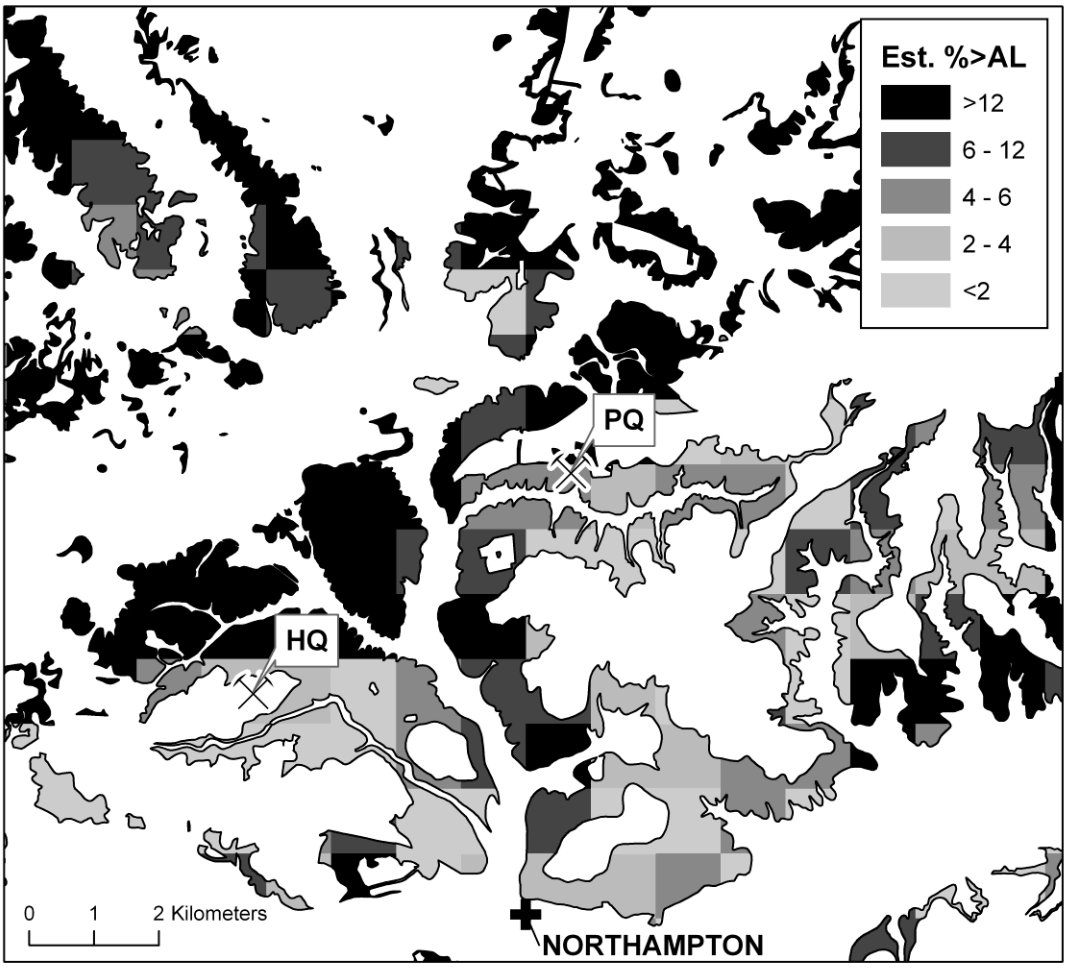

Fig. 11 Radon potential of ground underlain by the Northampton Sand Formation (but not covered by superficial deposits) in the Northampton area (HQ = Harlestone Quarry; PQ = Pitsford Quarry).

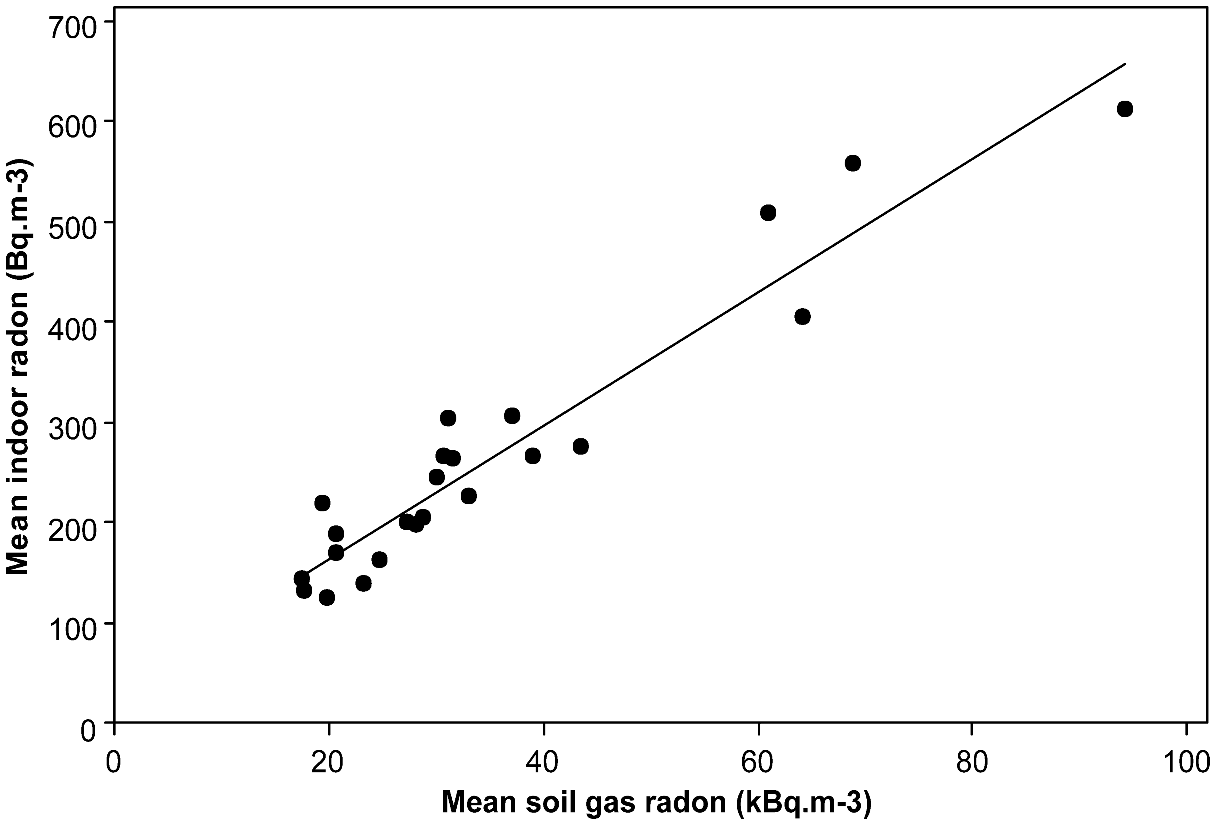

Fig. 12 Relationship between average soil gas radon concentration (kBq m^{-3}) and the geological radon potential (estimated proportion of dwellings exceeding the UK radon Action Level (200 Bq m^{-3})) for the Northampton Sand Formation. Data grouped by 5 km grid square.