RADON IN WALES

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Introduction

Radon is a natural radioactive gas that you can't see, smell or taste and 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. Radon provides about 50% of the total radiation dose to the average person in Wales. The other principal geological source of radiation is terrestrial gamma radiation, which originates chiefly from the radioactive decay of natural potassium, uranium and thorium. These elements are widely distributed in terrestrial materials including rocks, soils and building materials manufactured from raw materials extracted from the earth. Most exposure to radon and terrestrial gamma rays results from living indoors because the average person in the UK spends only 8% of their time out-of-doors. Gamma-radiation is mainly received from building materials whereas most radon comes from the ground underneath a building. Building materials generally contribute only a very small percentage of the indoor air radon concentrations.

Radon decays to form radioactive particles that can enter the body by inhalation. Inhalation of the short-lived decay products of radon has been linked to an increase in the risk of developing cancers of the respiratory tract, especially of the lungs. Breathing radon in the indoor air of homes is the second largest cause of lung cancer deaths after smoking (National Radiological Protection Board (NRPB) 2000).

Factors controlling radon in air and water

Geology is the most important factor controlling the source and distribution of radon. Relatively high levels of radon emissions are associated with particular types of bedrock and unconsolidated deposits, for example some, but not all, granites, limestones, phosphatic rocks, and shales rich in organic materials. The release of radon from rocks and soils is controlled largely by the types of minerals in which uranium and radium occur. Where thick residual soil has developed, radon comes almost entirely from the soil. Once radon gas is released from minerals, its migration to the surface is controlled by the transmission characteristics of the bedrock and soil; the nature of the carrier fluids, including carbon dioxide gas and groundwater; meteorological factors such as barometric pressure, wind, relative humidity and rainfall; as well as soil permeability, drainage and moisture content (Ball et al. 1991; Appleton and Ball, 1995; Appleton and Ball, 2001; Appleton, 2005).

Radon levels in outdoor air, indoor air, soil air, and ground water can be very different. Radon released from rocks and soils is quickly diluted in the atmosphere. Concentrations in the open air are normally very low and probably do not present a hazard. Radon that enters poorly ventilated buildings, caves (e.g. Friend and Gooding, 2002), mines, and tunnels can reach high concentrations in some circumstances. The construction method and the degree of ventilation influence radon levels in buildings. A person’s exposure to radon will also vary according to how particular buildings and spaces are used. Homes and workplaces can easily be tested for radon, usually over a 3-month period so as to average out the strong variations with time.

Radon dissolved in groundwater can migrate over relatively long distances along fractures and cave systems depending on the velocity of fluid flow. 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 particularly the case in certain limestone formations, where underground caves and fissures enable the rapid transfer of gas. Radon in water supplies can result in radiation exposure of people in two ways: by ingestion of the water or by release of radon into the air during showering, washing clothes or dishes, allowing radon and its decay products to be inhaled. It is generally accepted that 100 Bq L^{-1} (becquerels per litre) of radon in the domestic water supply contributes about 10 Bq m^{-3} to the indoor air of a home. Areas most likely to have problems with radon from domestic water supplies include those with high levels of uranium in the underlying rocks, such as uraniferous granites. This association has been observed in private water supplies in SW England where a high proportion derived from granite areas exceed the draft European Union action level of 1000 Bq L^{-1} (Talbot et al., 2000).

A study of radon levels in Welsh private water supplies was carried out to define guidance for local authorities on the future targeting of private water supply monitoring to meet Section 77 of the Water Industry Act. 1991. The maximum level determined in tap and source water samples in Anglesey, Denbighshire and Ceredigion was 151 Bq L^{-1} which is well below UK and European Action Levels (1000 Bq L^{-1}) (Assinder and Russell, 2003). Radon in soil under homes is usually the biggest source of radon in indoor air, and presents a greater risk than radon in drinking water (Kendall, 2004).

Radon Affected Areas

Since 1995, the National Radiological Protection Board (NRPB) has worked with the Welsh Office/Welsh Assembly Government to identify areas of Wales with elevated indoor radon levels and individual dwellings that are affected. The NRPB has found that the average level of radon in dwellings in Wales is about 20 Bq m^{-3}. Based on the estimated risks of lung cancer from prolonged exposure, the NRPB has recommended, and the Government has accepted, an Action Level (AL) for radon in homes of 200 Bq m^{-3}.

The NRPB has recommended that parts of Britain with 1% probability or more of homes being above the Action Level should be designated as Radon Affected Areas. The concept was introduced in 1990 to provide guidance to householders and the relevant authorities on the need to test a dwelling for high radon levels. Radon Affected Areas are currently designated by the NRPB by mapping levels of radon in existing homes. Radon Affected Areas maps for Wales were published in 1996 (Miles et al.), 1998 (Miles et al.; Lomas et al.) and 2002 (Green et al.). Some additional areas with moderate to high radon potential that have been identified by new joint BGS-NRPB radon potential mapping (see below) have not yet been designated as Radon Affected Areas.

Radon mapping

The cost-effective identification of (a) existing buildings with high radon and (b) those areas where protective measures need to be installed in new buildings depends on the existence of accurate radon potential maps. The principal objective of radon potential mapping in the UK is to map the variation in probability that new or existing buildings will exceed a radon reference level, which is termed the Action Level (200 Bq m-3). The method normally used to map radon potential in the UK has been to group the house radon results by area, and to use the data to estimate mean radon levels in houses or the proportion of them exceeding the UK radon Action Level in each area by log-normal modelling. The NRPB has mapped radon by grouping house radon data by square blocks of a convenient size, such as 5 or 1 km. This has the disadvantage that a square may cover two or more geological units with different radon potential (the probability of this happening being lower for smaller squares). However, it has the advantages that all areas are treated equally, and if data are missing it is simple to interpolate from surrounding squares. The NRPB has designated radon Affected Areas in Wales on the basis of house radon data grouped by 5 km grid squares (Miles et al, 1998; Green et al., 2002).

A second way of grouping the house radon data is by geological unit (Miles and Ball, 1996, Appleton, Miles and Talbot, 2000, Miles and Appleton, 2000). Whereas a wide variety of factors affect the concentration of radon in buildings, regional variations are related principally to the geological characteristics of the ground. This is the most logical way of grouping data, as radon potential clearly differs between geological units. Whereas use of geological boundaries generally helps to delineate differences in radon potential with greater spatial accuracy than other types of boundary, there are significant lateral variations in radon potential within bedrock-superficial geology combinations that are not identified when data are grouped solely by geology (Miles and Appleton, 2000; Appleton and Miles, 2002). Indoor radon surveys in Great Britain have confirmed the association of high levels of radon in dwellings with uraniferous granites, uraniferous sedimentary rocks, permeable limestones and phosphatic ironstones, as well as fault and shear zones (Appleton & Ball 1995, Miles & Ball 1996, Appleton, Miles and Talbot, 2000, Miles and Appleton, 2000, Appleton and Ball 2002). Miles and Ball (1996) showed that UK geological maps at 1:50,000 scale were detailed enough to distinguish rock types with different radon potentials. In other countries, geological radon potential maps predict the average indoor radon (Appleton and Ball, 2002) or give a more qualitative indication of radon risk (Mikšová and Barnet, 2002). However, since the purpose of radon potential maps is to indicate radon levels in buildings, maps based on actual measurements of radon in buildings are generally preferable to those based on radiometric, geochemical or pedological data. It is also relatively inexpensive to map by this method as passive radon detectors can be distributed by post (Miles 1994). 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. Radon potential mapping is sometimes based on indoor radon data that have been normalised 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 temporal variations in temperature (Miles, 2001) but not normalised 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.

The BGS and the HPA are collaborating on the production of more detailed radon potential information, based on a combination of 1:50,000 scale geological and 1-km grid square mapping techniques. Combining the grid square and geological mapping methods gives more accurate maps than either method can provide separately.

For the integrated mapping method, the land area is first divided up using a combination of geological characteristics derived from the BGS 1:50,000 scale digital bedrock and superficial geological map data, or 1:250,000 and 1:625,000 data for the areas where 1:50,000 data is not currently available. HPA has a database of about 15,000 houses in which long-term measurements of radon concentration have been made in Wales and the Welsh Borders, and whose locations are accurately known. Each of these measurements is allocated to the appropriate geological combination underlying it.

Taking each bedrock-superficial geological combination in turn, the spatial variation of radon potential is mapped, treating the combination as if it was continuous over the land area. Log-normal modelling (Miles, 1998) is used to estimate the geological radon potential for each geological (bedrock-superficial) combination in each 1-km grid square when the combination has 100 or more indoor radon measurements. The calculated geometric mean (GM) and calculated geometric standard deviation (GSD) were used when 30 or more measurements are available for a geological combination in a 1-km grid square. When less than 30 measurements are available, the GM was estimated from the nearest 30 measurements and a Bayesian statistical procedure was used to determine the GSD (Miles and Appleton, 2005).

The measured GSD for any group of 3-month house radon measurements is higher than the GSD that would be observed if the measurements were made over several years in each house. The difference is caused by uncertainties in estimates of long-term average radon concentrations and from year-to-year variations in radon levels (Miles and Appleton, 2005). It is possible to correct measured GSDs for this effect and these corrections always reduce GSDs and percentages above the AL, if the GM is below the AL. Correction of GSD was not applied in earlier mapping exercises in the UK and was not applied for the maps and data presented in this paper.

The method of mapping the variation within a combination is very similar to that used earlier to map variations in radon potential between grid squares. In cases where there are too few house radon results attributed to a geological combination to allow the spatial variation to be mapped, the average radon potential for all the houses on the combination is estimated and applied to the whole combination in each 100 km grid square of the British National Grid. Some combinations have too few results to allow radon potential to be calculated directly, and in these cases the data for similar combinations are grouped together, or radon potential is assigned by analogy with similar combinations. All of the radon potential data for different geological combinations are then combined to produce a map of variation in radon potential over the whole land surface (Figure 2).

Radon potential and geology

In the following analysis of the relationship of geology and radon potential, Low, Moderate and High radon potential are used to describe geological units characterised by <2%, 2-8% and >8% 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 Wales (Figure 1). Sub-areas are sometimes defined on the basis of 100 km squares of the British National Grid (SH to ST)

Neoproterozoic

Neoproterozoic strata crop out on Anglesey and in Pembrokeshire. In Anglesey, schists of the Gwna and New Harbour Groups have low radon potential (approx 1%>AL, max. 89 Bq m^{-3}), whereas volcanic rocks including the felsic ash-flow tuffs and rhyolite lavas of the Padarn Tuff Formation (Arfon Group) and pelitic lavas of the New Harbour Group have moderate radon potential (4%>AL, max. 308 Bq m^{-3}). In Pembrokeshire, rhyolites of the Benton Volcanic Group and trachytic and andesitic tuffs, with locally conglomeratic tuffaceous sediments, of the Pebidian

Supergroup have high radon potential (18%>AL, max. 453 Bq m^{-3}) of which the Benton Volcanic Group rhyolites has a particularly high radon potential (35%>AL). Both quartz-feldspar porphyry intrusive rocks and basaltic rocks of the Johnson Intrusive Complex in Pembrokeshire have high radon potential (12%, max. 398 Bq m^{-3} and 22%, max. 1978 Bq m^{-3}, respectively). Relatively high radon may also be associated with the St David's Granophyre (max. 192 Bq m^{-3}, n=2).

Cambrian

The Early to Mid Cambrian include the Arfon and Harlech Grits Groups in NW Wales. The Arfon Group comprises welded, felsic ash-flow tuff, volcanogenic conglomeratic sandstone, fine interlaminated tuffite and tuffaceous sediment that crops out in Anglesey and Gwynedd. The Harlech Grits Group comprises sandstones, mudstones and turbiditic siltstones, conglomerates and manganese ore beds and is exposed principally in the central area of the Harlech Dome. There are very few radon measurements in dwellings located on Early to Mid Cambrian strata in NW Wales but available data (principally from the Harlech Dome area) indicate low to moderate radon potential for sandstones of the Rhinog Formation and Bronllwyd Grit Formation (Harlech Grits Group; 2.4%>AL, max. 140 Bq m^{-3}). In Pembrokeshire, the Comley Series includes the Caerfai Group (green, fine-grained micaceous sandstone, purple-red mudstone, purple-red micaceous sandstone and reddish, basal conglomerate) and the Solva Group (greenish grey sandstones and interbedded mudstones), which, on the basis of only 5 measurements, appears to have a high radon potential (22%>AL, max. 319 Bq m^{-3}).

In north-west Wales, dark grey to black mudstone, siltstone and sandstone of the Middle Cambrian to Tremadoc Mawddach Group, cropping out in the Harlech Dome and southern Snowdonia, have low potential (1.4%>AL, max. 122 Bq m^{-3}) and include units such as the Ffestiniog Flags (<1%, max 108 Bq m^{-3}). Discrete zones of higher radon potential may, however, exist because bedrock uranium concentrations up to 14 mg kg^{-1} have been recorded from the Dolgellau and the Clogau Formations at the south and eastern edge of the Harlech Dome. The

St. David's Series mudstone, siltstone, sandstone sequence in NW Wales has low potential (2%>AL, max. 157 Bq m^{-3}) whereas in Pembrokeshire it has high potential (10%>AL, max. 621 Bq m^{-3}) and includes units such as the Lingula Flags (Mid–late Cambrian interbedded siliceous siltstones and micaceous mudstones; 8.5%>AL, max. 333 Bq m^{-3}) and the dark grey laminated shaley mudstones of the Menevian Group (13%>AL, max. 349 Bq m^{-3}).

Ordovician

The Ordovician is dominated by argillaceous and volcanic rocks with a high average radon potential (9.7%, n = 1944). Ordovician strata crop out in Anglesey, Gwynedd and in the Clwyd-Powys border area in the northern part of Wales, as well as in a large part of Dyfed, with a tongue stretching into mid Powys (Figure 1). For data analysis, the Ordovician has been grouped into the Lower – Middle Ordovician (Tremadoc-Arenig-Llanvirn-Caradoc; OTACL) and the younger Upper Ordovician Ashgill strata (OASH).

Predominantly argillaceous bedrocks of the Lower-Middle Ordovician have a high average potential (9.4%>AL based on all 685 measurements), being approximately the same in N. Wales and Central – S. Wales (9%>AL, max.1784 Bq m^{-3} and 10%>AL, max. 625 Bq m^{-3} respectively for the SH-SJ and SM-ST 100km grid squares). In NE Wales (SJ) high radon is associated with the mudstones with intercalated tuffs, tuffites, lavas and limestones of the Llangynog Formation (10%>AL, max. 1784 Bq m^{-3}), whilst in N.W. Wales, the black, pyritous, graptolitic mudstone of the Nod Glas Formation has high potential (34%>AL, max 1570 Bq m^{-3}). Bedrock uranium concentrations of up to 20 mg kg^{-1} have been recorded from the Caradocian Nod Glas and Ceiswyn Formations and the Ashgillian Broad Vein Mudstone Formation in an area 7-10 km to the S and E of Cadair Idris. In NW Wales (SH), high radon is also associated with felsic tuffs of the Snowdon Volcanic Group, Middle Crafnant Volcanic Formation (13%>AL, max. 259 Bq m^{-3}) whereas in SW Wales (SM-SN), acid lavas and tuffs have moderate radon potential (5%>AL, max. 480 Bq m^{-3}). Relatively high bedrock uranium (up to 8 mg kg^{-1}) characterises the rhyolitic tuffs of the Snowdon Volcanic Group.

The majority of Lower to Middle Ordovician radon measurements are from the Fishguard area of Pembrokeshire, which is underlain by Didymograptus bifidus Beds and Didymograptus Murchisoni Beds. The former comprise grey, silty graptolitic mudstones with thin tuffaceous horizons and are characterised by high radon potential (>10%>AL). Further east, approximately midway between Fishguard and Carmarthen, high uranium (10-12 mg kg^{-1}) has been recorded in some bedrock samples from the Hendre Shales and Mydrim Shales Formations even though the area apparently has low radon potential. This discrepancy may reflect the paucity of indoor radon measurements in this area. Lower to Middle Ordovician arenaceous strata appear to be characterised by moderate radon potential (3% in N. Wales and 7% in S. Wales) although these estimates are based on a small number of radon measurements.

The average radon potential based on all measurements on the Ashgillian argillaceous strata, is high (10%). Ashgillian strata in N. Wales have only moderate potential with high potential characterising SW Wales (7%>AL, max. 387 Bq m^{-3} for SH-SJ and 11% >AL, max. 1267 Bq m^{-3} for SM-ST). The major Ashgillian argillaceous bedrock units with a substantial number of indoor radon measurements include the Nantmel Mudstones Formation (4%>AL, max. 391 Bq m^{-3}) and the Portfield Formation (4%>AL, max 228 Bq m^{-3}) in SW Wales (SM-SN). The Conwy Mudstones Formation in NW Wales and the siltstones and mudstones of the Dolhir Formation in N-NE Wales (SJ) both have moderate potential (3-4%>AL, max. 387 Bq m^{-3}). The majority of measurements on Ashgillian rocks are in SW, S. and Central Wales where the highest radon potentials are also recorded. For example, in the SN grid square, the majority (839 of a total of 1012) of measurements relate to Llanvirn to Ashgillian argillaceous strata with 12%>AL (max. 1267 Bq m^{-3}).

High radon concentrations are associated with Ordovician granite (max.225 Bq m^{-3}, n=5) and porphyritic microtonalite (max. 667 Bq m^{-3}, n=2) in Pembrokeshire and felsite intrusions in N. Wales (max. 546 Bq m^{-3}, n=2), although the number of measurements on individual units is too small to make a reliable estimate of the radon potential. Bedrock uranium concentrations range up to 9 mg kg^{-1}.

Silurian

Silurian strata crop out principally in Clwyd, Dyfed, Powys and Gwent (Figure 1) and have been grouped on age into Llandovery (SLLA), Wenlock (SWEN), Ludlow (SLUD) and Pridoli (SPRD) with each of these subdivided on the basis of lithology into principally argillaceous (MDMIX) and arenaceous (SDMIX) groups (Table 1). In addition, volcanics occur in the Llandovery and limestones in the Wenlock. Overall the Silurian has a high potential (9.3%, n=2836, max. 2536 Bq m^{-3}).

Llandovery argillaceous rocks (SLLAMDMIX) have a moderate average potential (4.1%>AL) being approximately the same in N. Wales and Central – S. Wales (Table 1). This group includes the thinly interbedded green and grey turbidite mudstones, hemipelagites and thin turbidite sandstones of the Rhayader Mudstones Formation in Central Wales (6%>AL, max 549 Bq m^{-3} in SN). The Devil's Bridge Formation in the Aberystwyth area has a radon potential of 6.4%>AL (max 779 Bq m^{-3}). In contrast, low radon potential characterises Llandovery arenaceous rocks (SLLASDMIX, Table 1), which crop out principally in N. Wales.

Wenlock argillaceous rocks (SWENMDMIX) have moderate radon potentials in both N. and Central - S. Wales (7-8%>AL, Table 1). The Nantglyn Flags Formation in NE Wales (SJ) comprising mudstone and laminated muddy siltstone with subordinate thin lenticular bands of calcareous siltstones and graptolitic mudstones has a high radon potential (11%>AL, max 294 Bq m^{-3}) as do the argillaceous Wenlock rocks in the SO 100km square (11%>AL) where the majority (157 out of 199) radon measurements were made in Central - S. Wales. Wenlock arenaceous rocks of the Denbigh Grits Formation in SH have a lower radon potential (4%>AL).

High radon potential (16%>AL) characterises Ludlow argillaceous rocks (SLUDMDMIX) with similar radon potentials and maximum values in N. and Central – S. Wales (Table 1). The majority of radon measurements are associated with siltstones and mudstones in SO. In SJ, the Elwy Formation, comprising silty mudstones and subordinate sandstones, has very high radon potential (23%>AL, max. 2536 Bq m^{-3}, n=89). Bedrock uranium concentrations range up to 7 mg kg^{-1}. Arenaceous strata of Ludlow age (SLUDSDMIX) crop out principally in Central – S. Wales and have a moderate to high radon potential (Table 1). The majority of radon measurements are sited on sandstones and siltstones of the Bailey Hill Formation in SO (8%>AL; n= 207).

Moderate radon potential characterises argillaceous rocks of Pridoli age (SPRDMDMIX), which crop out principally in Central – S. Wales (Table 1). In Pembrokeshire (SM), high potential (16%>AL, max. 779 Bq m^{-3}, n=150) is associated with the argillites and sandstones of the Milford Haven Group (Figure 3) whereas the Raglan Mudstone Formation has low potential (1%>AL, max. 409 Bq m^{-3}, n=111). This contrasts with the argillaceous rocks and sandstones of Raglan Mudstone Formation in the eastern part of Powys (BGS Map Sheet 180), which has high potential (10%>AL, max. 1925 Bq m^{-3}, n=178).

Few of the other Silurian geological units have many radon measurements available although there are indications of high radon potential being associated with Llandovery volcanic rocks (18%>AL, max. 256 Bq m^{-3}, n=8) in Central – S. Wales and with Wenlock limestones (max. 253 Bq m^{-3}, n=2).

Devonian

Apart from a small area underlain by Devonian arenaceous rocks in N Wales (5%>AL, max. 206 Bq m^{-3}, n=9) most Devonian strata occur in SW and SE Wales (Figure 1). The principal Devonian arenaceous units of the Lower Old Red Sandstone Group (LORS) are the Cosheston Subgroup (23%>AL, max 1314 Bq m^{-3}, n=244) in the Pembrokeshire-Milford Haven area, which comprises breccias and conglomerates of igneous and other fragments in a quartzitic matrix, interbedded with red or green marls and green sandstones. Dominantly argillaceous Lower Devonian rocks (comprising argillites, with sandstones and conglomerates) in SE Wales have a slightly lower potential (16%>AL, max. 561 Bq m^{-3}).

The St Maughans Formation (LORS) in SE Wales comprises interbedded purple, brown and green sandstones and red mudstones with intraformational conglomerates, characterised by low radon potential (1%>AL). The red-brown and purple fluvial sandstones with red mudstone interbeds of the Brownstones Formation (LORS) in SE Wales also has low radon potential (0.7%>AL). Both the arenaceous Senni Formation (LORS, in BGS map sheet 214) and the Tintern Sandstone Formation (Upper Old Red Sandstone Group; buff-yellow sandstone with subordinate marls and pebble beds in BGS map sheet 233) have moderate radon potentials (3%>AL).

Carboniferous

Dinantian Predominantly limestone sequences of the Carboniferous Limestone Supergroup (Tournasian-Visean) have high potential (22%>AL) with very high potential in NW and NE Wales (28-29%>AL) and lower potentials in S. Wales (15%>AL). The radon potential is substantially reduced when limestone is covered with glacial till in N. Wales and only marginally in S. Wales (Table 2)

In NE Wales (SJ), Visean limestone-mudstone bedrocks such as the Cefn Mawr Limestone Formation, comprising thinly interbedded dark grey argillaceous limestones and mudstones with intercalated thick-bedded to massive, pale shelly limestones and lenticular crinoidal limestone bodies, have a very high radon potential (43%>AL) as do the interbedded limestones and calcareous sandstones of the Minera Formation (25%>AL), principally because of the highly permeable limestone component in these units.

Sandstones and conglomerates of the Minera Formation in NW and NE Wales have very high radon potential (32%>AL, n=31, max 890 Bq m^{-3}; 23%>AL, n=26, max. 620 Bq m^{-3}, respectively). Low potential (0.3%>AL, n=16, max. 95 Bq m^{-3}) characterises the fine- to coarse-grained quartzitic sandstone with subordinate mudstones and sparse thin limestones of the Cromhall Sandstone Formation in S. Wales, although this estimate should be treated with caution due to the relatively small number of radon measurements.

In South Wales, such as along the northern crop of the South Wales Coalfield (Figure 4), the Pembroke Limestone Group, comprises skeletal and ooidal limestones with subordinate calcareous and dolomitic mudstones, sandstones and mudstones, and a few coals and cherts. The rocks are extensively dolomitised on the eastern crop of the South Wales Coalfield. Stacked cyclic sequences of dark grey limestones with locally sandy and cherty layers, seat earths and thin coals characterise the Dowlais Limestone Formation and it has been suggested that the thin black shales and mudstones in the Dowlais Limestone Formation may have higher concentrations of uranium (Friend and Gooding, 2002). Uranium in limestones is normally associated with interstitial organic material (Ball, Davies and Ford, 1996) and this is the likely source of the radon in buildings constructed on limestone bedrock as well as the very high radon (2000-3000 Bq m^{-3}) reported in limestone caves, such as the Ogof Ffynnon Ddu system (Friend and Gooding, 2002). High radon potential (12%>AL, n=132, max. 1189 Bq m^{-3}) characterises the Carboniferous Limestone around the margins of the South Wales Coalfield although this appears to vary from 11%>AL (n=11, max. 618 Bq m^{-3}) along the northern edge, 21%>AL (n=28, max. 1189 Bq m^{-3}) on the Gower peninsula and only 8%>AL (n=81, max. 744 Bq m^{-3}) in the Vale of Glamorgan.

Namurian Both the mudstones of the Bowland Shale Formation (former Holywell Shales), which have a high potential (15%>AL, n=13, max. 545 Bq m^{-3}) and the fine- to medium-grained quartzose sandstones, with subordinate conglomerates, chert, siliceous mudstones, siltstone, mudstone, and coal seams of the Cefn-y-Fedw Sandstone Formation (25%>AL, n=95, max. 2569 Bq m^{-3}) are found only in NE Wales. Consistently high radon appears to be associated with chert units in the Cefn-y-Fedw Sandstone Formation (67%>AL, n=7, max 522 Bq m^{-3}). Also in NE Wales, the banded glassy cherts and cherty mudstones with subordinate thin siltstone and silicified crinoidal limestone beds of the Pentre Chert Formation have very high radon potential (27%>AL, n=15, max.1316 Bq m^{-3}) whereas the mixed sandstones and argillites of the Gwespyr Sandstone appear to have only moderate potential (5%>AL, n=11, max. 163 Bq m-3). In Pembrokeshire, Namurian mudstones, sandstones and siltstones of the Marros Group (former Millstone Grit) have high potential (10%>AL, n=39, max. 298 Bq m^{-3}). In S Wales, radon potential is dramatically reduced when Namurian bedrocks are overlain by glacial till, whereas the reduction is less over the cherts of NE Wales and radon potential increases slightly over argillaceous units in NE Wales, possibly because the till has a higher permeability that the bedrock (Table 3).

Westphalian The system used for grouping indoor radon data associated with Westphalian strata in Wales is summarised in Table 4. The Pennine Lower Coal Measures Formation (WESLAMDMIX) in NE Wales appears, on the basis of relatively few measurements, to have low to moderate potential (2.4%>AL, max. 131 Bq m^{-3}, n=15). The potential is much higher when bedrock is overlain by head (9%>AL), or sand and gravel (15%>AL) superficial deposits but only slightly enhanced when overlain by glacial till (4%>AL). Sandstones in the Pennine Lower Coal Measures of NE Wales appear to have high potential (14%>AL, n=14, max. 641 Bq m^{-3}).

No radon measurements are available for homes on the Pennine Middle Coal Measures Formation (WESDUMDMIX) bedrock in NE Wales but high potential occurs where bedrock is overlain by glacial sand and gravel (17%>AL, n=65, max. 713 Bq m^{-3}) and low to moderate potential when overlain by glacial till (2.3%>AL, n=57, max. 372 Bq m^{-3}).

Similarly, very few measurements are available for the Etruria Formation (former Ruabon Marl Formation) in NE Wales (4.4%>AL, n=12, max. 199 Bq m^{-3}) because bedrock is generally covered by glacial till (4.2%>AL, n=431, max. 2117 Bq m^{-3}) or glacial sand and gravel (15%>AL, n=288, max. 986 Bq m^{-3}). Duckmantian to Bolsovian (WESBOSD) sandstones comprising the Cefn Rock (massive, quartzose sandstone with subordinate mudstone and coal) and Hollin Rock Members (fine to coarse or pebbly, commonly feldspathic, laminated and bedded sandstone) of the Pennine Coal Measures Group, have moderate radon potential (6.6%>AL, n=17, max. 933 Bq m^{-3}) although the potential is reduced when bedrock is covered with glacial till (0.3%>AL, n=17, max. 87 Bq m^{-3}) but largely unchanged when overlain by sand and gravel (5.5%>AL, n=14, max. 360 Bq m^{-3}). Westphalian D argillaceous rocks (WESDMDMIX) of the Salop Formation (former Erbistock Formation) comprising red to red-brown mudstone and sandstone with subordinate pebbly sandstone, conglomerate, and thin limestone beds, and the Halesowen Formation (former Coed-yr-Allt Formation; grey-green, micaceous sandstone and mudstone, with thin coals and limestone beds, and intraformational conglomerate) are largely covered by glacial till (1.5%>AL n=127, max. 272 Bq m^{-3}) or glacial sand and gravel (5.6%>AL, n=190, max. 360 Bq m^{-3}).

Only the Lower and Middle Coal Measures Formations of the South Wales Coal Measures Group crop out in Pembrokeshire whereas a full Westphalian sequence occurs further east in South Wales (Table 4). Moderate potential characterises the Lower Coal Measures in SM (4%>AL, n=41, max. 169 Bq m^{-3}) and SN (3.3%>AL, n=38, max. 148 Bq m^{-3}) whereas the Middle Coal Measures occurs only in SN and appears to have low radon potential (<0.1%>AL, n=17, max. 57 Bq m^{-3}). In Pembrokeshire and S. Wales, the average radon potential for the Lower Coal Measures is reduced from moderate (4.2%>AL, n= 87, max. 300 Bq m^{-3}) to only 1.1%>AL when overlain by glacial till. In South Wales, both the Middle Coal Measures (WESDUMDMIX; 0.9%>AL, n= 27, max 68 Bq m^{-3}) and Upper Coal Measures (1.5%, n=18, max. 640 Bq m^{-3}) have low potential whereas the permeable Pennant Sandstone Formation has moderate potential (3.5%>AL, n=51, max. 303 Bq m^{-3}). When Pennant Sandstone is overlain by glacial till or glacial sand and gravel, its radon potential is reduced to low (<1%>AL). The Grovesend Formation in S. Wales (WESDMDMIX) has low potential (1.5%>AL, n=17, max. 136 Bq m^{-3}) whilst the more permeable upper Westphalian sandstones (WESDSD) have moderate potential (6.8%>AL, n=118, max. 1099 Bq m^{-3}), although this is reduced to 0.4%>AL when sandstone bedrock is overlain by glacial till.

Triassic

Mudstones with subordinate siltstones and sandstones of the Mercia Mudstone Group have low potential (0.8%>AL, max. 180 Bq m^{-3}, n=55), as do the sandstones with subordinate mudstone and siltstone of the Sherwood Sandstone (1.9%, max. 157 Bq m^{-3}, n=7).

Moderate radon potential is associated with the basal Mercia Mudstone Group Marginal Facies which comprise conglomerate and/or breccia with clasts derived frequently from the underlying Carboniferous Limestone. The rock matrix usually consists of finer grained rock fragments or, less commonly, siltstone, sandstone or micritic limestone. Where these deposits overlie Carboniferous limestones, both the matrix and limestone clasts are commonly dolomitised and the bedrock called "Dolomitic Conglomerate". Fenestral and algal carbonates interdigitate with conglomerates and breccias in exposures to the south of Cardiff. The average radon potential for the Mercia Mudstone Group Marginal facies is 6%>AL (n=74) being highest in the Porthcawl area (BGS map sheet 261, 11%>AL, n=37, max. 350 Bq m^{-3}).

Rhaetian-Jurassic

Jurassic strata occur principally in the Vale of Glamorgan between Bridgend and Barry. Two sub-groups were established for estimating radon potential: (a) the limestones and subsidiary mudstones of the Blue Lias Formation (including the Porthkerry and St Mary's Well Bay Members) and the Marginal Facies of the Blue Lias Formation (LLILMST) and (b) the mudstones (LLI) with subsidiary limestones of the Blue Lias Formation and Penarth Group. This latter group comprises grey to black mudstones with subordinate limestones and sandstones, predominantly of marine origin, and including sandstones of the Penarth Group Marginal Facies. The Penarth Group (Rhaetian) is grouped with the Blue Lias in S. Wales because of the overlap in time range and similarity in lithologies. On average, both the limestone dominated and mudstone dominated sub-groups have the same moderate to high radon potentials (9.4% and 8.5% respectively for LLILMST and LLI). Within the LLILMST group, the Marginal Facies of the Blue Lias appears to have higher potential (13-21%>AL) than the Porthkerry (5-11%>AL) and St Mary's Well (1%>AL) Members. Within the LLI, the sandstones of the Penarth Formation Marginal Facies have high potential (15%>AL) whilst the Lavernock Shales Member of the Blue Lias has moderate potential (3%>AL) and the Penarth Group mudstones have low potential (<1%>AL). In all cases, these are preliminary estimates due to the relatively small number of radon measurements for individual bedrock formations. Estimates for radon data grouped by bedrock and 1-km grid square indicate strong lateral variation in radon potential within these units (0.4 to 34%>AL for LLILMST and 0.4 to 15%>AL for LLI).

Uranium in bedrock, stream sediment and soil

Because radon is derived from the radioactive decay of uranium in rocks and soil, a positive relationship between these geochemical indicators and radon potential might be expected, although it should be remembered that the permeability of soil, superficial deposits and bedrock may also have a major influence on radon potential. Geometric mean uranium in bedrocks is compared with radon potential in Table 5. Data are included only where there are more than 10 rock samples and 10 indoor radon measurements available for a geological group. No relationship between bedrock uranium and radon potential can be detected when data are grouped by general geology and there are insufficient numbers of rock uranium analyses for more detailed grouping by 1:50,000 scale geological unit and geological map sheet, for example. It must therefore be concluded that the available BGS rock geochemical data are inadequate for studies of the relationship between bedrock geology and radon potential in Wales.

Soil uranium data are available for very restricted parts of Wales (BGS, 2000) and show no obvious relationship with radon potential. Background uranium concentrations are generally low in Wales and, in general, there is not a positive correlation between the distribution of uranium in stream sediments (BGS, 2000) and radon potential (Figure 2).

Airborne radiometric data

Airborne gamma spectrometric data are available for a small sector of NE Wales and, as in the East Midlands (Appleton et al., 2000), patterns on the eU-eTh-K ternary image correlate reasonably closely with radon potential, especially where eU (^{226}Ra) is relatively high compared with eTh and K. The ternary image is not reproduced here because its significance can be appreciated only as a three-colour (RGB) image (see Map R5 in BGS, 2004).

Radon testing in Wales

Testing of radon in homes is carried out to (a) identify the most affected areas, and (b) identify individual homes in which radon exceeds the Action Level. Out of the approximately 5600 homes tested in Wales as part of a national survey, about 220 were above the Action Level (Lomas et al., 1998; Miles et al., 1998). The NRPB manages a government programme of free testing and advice to all householders within 5 km grid squares where there is a high probability (greater than 10 per cent) of dwellings exceeding the action level of 200 Bq m^{-3}. Where radon levels above the action level are detected, the householder is offered advice on remedial measures to reduce the risk. A focussed survey of radon in dwellings in the forty four 5x5 km grid squares with an estimated 10% of dwellings exceeding the Action level identified by the national survey, detected 850 houses above the AL from the 5610 measured, out of a total of 27,428 houses in the target grid squares.

In 2004-2005 the Welsh Assembly Government funded a pilot programme in conjunction with local authorities, BRE and NRPB in order to encourage householders in the high-risk areas of Wrexham and Flintshire to have radon levels measured and to take remedial action where recommended. Part of the Vale of Glamorgan was also in this radon testing programme. In Flintshire, free measurements are being offered to 7400 dwellings in four 5x5km grid squares with >10%>AL. It is expected that more than 900 dwellings in the four grid squares will exceed the AL. The outcomes of this pilot study will inform development of further programmes with other local authorities. The NRPB estimates that approximately 10,000 dwellings out of the 1,250,000 dwellings in Wales exceed the Action Level.

Radon limitation policies

The Fire, Construction and Domestic Energy Unit of the Housing Directorate of the Welsh Assembly Government has the overall responsibility for radon advice, policy and programmes related to radon in dwellings in Wales. The ODPM Building Regulations Division is responsible for Regulations and guidance relating to radon protection in new buildings in both England and Wales.

The Welsh Assembly Government's current strategy is aimed at raising awareness of the risk of radon in the most affected areas that involves the provision of a proactive testing programme together with a range of promotional literature and more proactive support by working with the local authority and other organisations involved in the housing field.

Assuming that the current policy of the Housing Directorate is totally successful and all houses above the Action Level are identified and remedial work carried out it is estimated that there would be a reduction of about 15% in radon related deaths a year (HSS, 2002). The remainder of radon related deaths would affect residents in the much greater number of houses that are below the Action Level because the collective risk in this much more numerous group of dwellings is considerably greater than in the relatively small number of homes above the Action Level. A much greater proportional reduction in lung cancer would be achieved by cessation of smoking as NRPB estimate that about two thirds of radon related deaths are associated with smoking; the risk to radon exposed smokers being approximately ten times that of radon exposed non-smokers.

Radon and the Building Regulations

Provision has been made in Requirement C1(2) of Schedule 1 of the Building Regulations 1991 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 dwellings* (BRE, 1999), 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 and any change of use to a residential or sleeping 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.

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 England and Wales, these areas are currently estimated by a dual data system based on a combination of NRPB grid square and BGS geological radon potential maps. A geological assessment may need to be carried out where the development site is located within a shaded square on the BGS map in Annex B of BR211 (1999). Digital geological radon potential map data is used by the BGS to provide reports that fulfil the requirements of the Stage 2 Geological Assessment outlined in the BR211 (1999). The reports are essential for builders and developers (to ensure compliance with Building Regulations) and invaluable for planners, architects and surveyors, who need to know what level of protection is needed in new buildings.

No guidance on protection from radon in non-domestic buildings is currently available, but the guidance in BR211 (BRE,1999) and BR293 (Scivyer and Gregory, 1995) may be used where appropriate. Interim guidance on extensions is available in BRE GBG25: *Buildings and Radon* (BRE, 1996a).

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 made under the HSW Act. The concentration at which measures should be taken in work places, based on the Ionising Radiations Regulations 1999 and the associated Approved Code of Practice - Part 3 Exposure to radon, is 400 Bq m^{-3}. Persons responsible for a workplace are required to measure radon levels when directed to do so. Enforcement of regulations is done through the Health and Safety Executive (HSE) and Local Authority Environmental Health Departments.

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. (2000) 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 by the Welsh Assembly Government.

Radon remediation

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. Guidance is provided in a number of BRE publications (BRE, 1996b; Pye 1993, Scivyer 1993; Scivyer and Gregory, 1995; Scivyer and Jaggs, 1998; Scivyer et al., 1998; Stephen, 1995).

Conclusions

The radon potential of the Cambrian in NW Wales is generally low whereas it is high in Pembrokeshire. Throughout Wales, moderate to high radon levels occur in many areas underlain by Ordovician and Silurian mudstones, siltstones and greywackes. Moderate radon levels are associated with some areas underlain by Ordovician and Silurian acid volcanic rocks in Gwynedd, Conwy, Powys and Pembrokeshire. In Pembrokeshire, high radon potential characterises the arenaceous rocks of the Cosheston Group (Devonian). High radon is associated with all areas underlain by Dinantian and Visean 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.

Where bedrock is overlain by unconsolidated deposits, such as glacial till or alluvium, the proportion of houses with high radon is usually reduced. In NE Wales, for example, it is estimated that approximately 30% of dwellings situated directly on the Visean limestone exceed the Action Level, whereas the proportion is reduced to about 2% where the limestone is covered with glacial till. 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. Uncertainty in radon potential estimates are higher with small numbers of radon measurements so a targeted programme of additional measurements would help to ascertain the true radon potential of those geological combinations for which few data are currently available.

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 new joint NRPB-BGS radon maps (similar to Figures 2, 3 and 4, but with different break points) will eventually replace the current maps, published by NRPB, and will be used to provide advice to builders and developers as well as to householders and their legal advisers when a radon enquiry is made in England and Wales as part of property searches (CON29 (2002): Standard Enquiries of Local Authority).

It is important to remember 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 of a building. 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. This can only be established by having the building tested.

Results from a large new study of the risk from radon, based on data on radon and lung cancer from nine European countries confirms that domestic exposure to radon carries a risk of lung cancer and demonstrates an increased risk of lung cancer at radon concentrations below the present UK Action Level of 200 Bq m^{-3} set in 1990 (Darby et al., 2005). NRPB are considering the implications of this study and will issue advice on any changes that should be made to the UK scheme for controlling radon exposures, including the Action Level and thresholds for the installation of radon protective measures in new buildings.

Acknowledgements

This chapter is published by permission of the Executive Director, British Geological Survey and the Director, National Radiological Protection Board. The authors acknowledge with thanks the assistance and advice provided by Keith Ball, David Jones, Barry Smith, Colin Waters, David

Wilson (BGS), Gerry Kendall (NRPB) and Havard Prosser (Environmental Science Adviser, Welsh Assembly).

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TABLES

Table 1: Summary statistics for principal Silurian bedrock groups.

	All Wales			N. Wales (SH-SJ)			Central & S. Wales (SM-ST)		
Geological group*	%>AL	Max Rn (Bq m^{-3})	n	%>AL	Max Rn (Bq m^{-3})	n	%>AL	Max Rn (Bq m^{-3})	n
SPRDMDMIX	7.7	1925	642	nd	nd	nd	8	1925	642
SLUDSDMIX	8.5	640	298	nd	nd	nd	8	640	298
SLUDMDMIX	15.7	2536	768	18	2536	137	15	2054	631
SWENMDMIX	7.8	610	349	7	338	150	8	610	199
SLLASDMIX	3.1	293	124	2	227	118	nd	293	6
SLLAMDMIX	5.8	779	596	4	282	63	6	779	533

nd = no data or not determined due to inadequate no. of radon measurements
* see text for explanation of bedrock group codes

Table 2. Summary statistics for Carboniferous Limestone Supergroup limestones (LM) and bedrock overlain by glacial till.

	Isle of Anglesey (SH)		NE Wales (SJ)		S. Wales (SM, SN, SO, SR, SS, ST)	
	LM	LM/glacial till	LM	LM/glacial till	LM	LM/glacial till
no.	212	230	150	62	396	133
GM Bq m^{-3}	124	58	112	78	68	54
max. Bq m^{-3}	1211	1460	1051	449	1512	443
%>AL	29	15	28	17	15	13

Table 3. Summary statistics for Namurian chert (CHRT), argillaceous (MDMIX) and arenaceous (SD) units and bedrock overlain by glacial till.

	NE Wales (SJ)				S Wales (SM, SN, SO, SR, SS, ST)			
	CHRT	CHRT/ till	MDMIX	MDMIX/ till	MDMIX	MDMIX/ till	SD	SD/ till
no.	15	16	11	80	51	12	14	5
GM Bq m^{-3}	116	80	49	47	57	17	39	12
max. Bq m^{-3}	1314	263	163	650	852*	76	108	73
%>AL	27	15	5.5	7.7	10.9	0.15	3.0	0.03

*max. value in SS 100 km square

Table 4. Bedrock geological grouping system for radon potential assessment.

<table>
<tr><th>Bedrock Code</th><th>Groups</th><th>N Wales</th><th>Pembrokeshire</th><th>S Wales</th></tr>
<tr><td>WESD</td><td rowspan="2">Warwickshire Group</td><td>Halesowen Fm. & Salop Fm.</td><td></td><td>Grovesend Fm. & Pennant Sandstone Fm.</td></tr>
<tr><td>WESE
WESBO</td><td>Etruria Fm.</td><td></td><td>Pennant Sandstone Fm. (in west); Deri Fm. (in east)</td></tr>
<tr><td rowspan="2">WESDU</td><td rowspan="3">Pennine Coal Measures Group (N. Wales); South Wales Coal Measures Group</td><td rowspan="2">Pennine Middle Coal Measures Fm.</td><td rowspan="2">S Wales Middle Coal Measures Fm.</td><td>South Wales Upper Coal Measures Fm.</td></tr>
<tr><td>South Wales Middle Coal Measures Fm</td></tr>
<tr><td>WESLA</td><td>Pennine Lower Coal Measures Fm.</td><td>South Wales Lower Coal Measures Fm.</td><td>South Wales Lower Coal Measures Fm.</td></tr>
</table>

Table 5. Comparison of uranium in rock samples, indoor radon and radon potential for data grouped by bedrock geology

Bedrock Group	Bedrock Group Code	No. rock samples	GM rock U mg kg^{-1}	Max rock U mg kg^{-1}	No. indoor Rn	GM indoor Rn Bq m^{-3}	Max. indoor Rn Bq m^{-3}	Est. % houses >AL
Silurian (Wenlock) argillaceous rocks	SWENMDMIX	13	2.0	4	349	51	610	7.8
Silurian, Ludlow, argillaceous rocks	SLUDMDMIX	53	3.5	7	768	75	2536	15.7
Silurian (Llandovery) argillaceous rocks	SLLAMDMIX	15	3.4	7	596	46	779	5.8
Ordovician (Ashgill) argillaceous rocks	OASHMDMIX	45	2.5	12	1012	57	1267	10.8
Ordovician, (Tremadoc-Arenig-Llanvirn-Caradoc), argillaceous rocks	OTACLMDMIX	287	2.1	20	685	55	1784	9.4
Ordovician, (Tremadoc-Arenig-Llanvirn-Caradoc), arenaceous rocks	OTACLSDMIX	46	2.5	6	46	37	342	4.6
Ordovician, (Tremadoc-Arenig-Llanvirn-Caradoc), volcanic rocks	OTACLVOLC	567	1.8	8	128	52	480	7.2
Ordovician Granite	OUNDGRAN	34	3.2	8	19	66	225	10.6
Ordovician Intrusive rocks	OUNDINTR	203	1.2	8	22	44	667	8.3
Cambrian (St David's Group) arenaceous rocks	CSTDSDMIX	21	1.2	4	27	60	621	10.9
Cambrian (L-Middle) argillaceous rocks	CMERMDMIX	12	2.6	14	18	40	122	1.4
Neoproterozoic intrusive	NEOPINTR	21	1.4	4	42	77	1978	16.7
Neoproterozoic volcanic	NEOPVOLC	32	1.6	5	55	60	453	14.8

FIGURES

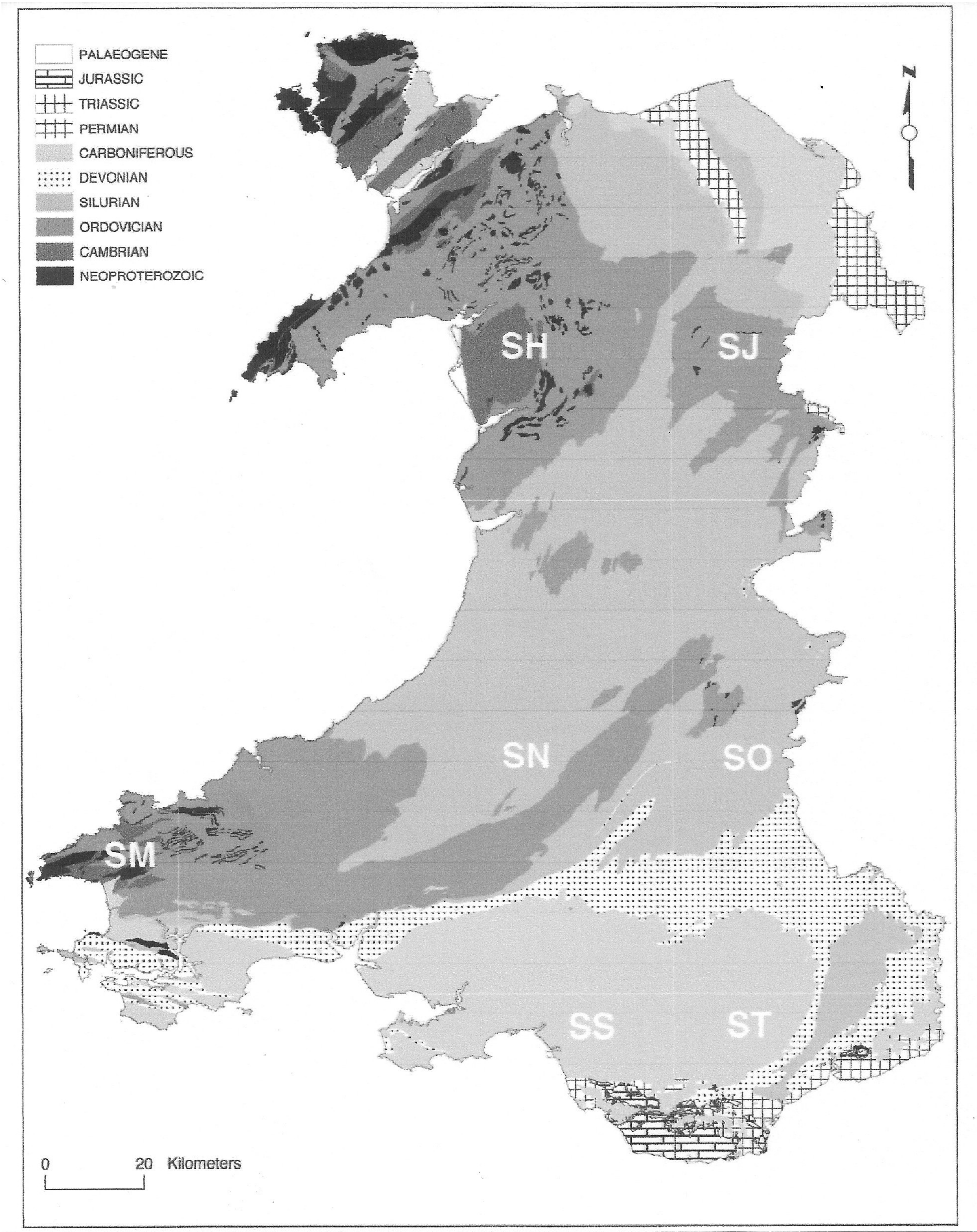

Figure 1. General bedrock geological map of Wales, derived from BGS 1:250,000 scale digital map data; SH etc. = 100 km squares of National Grid.

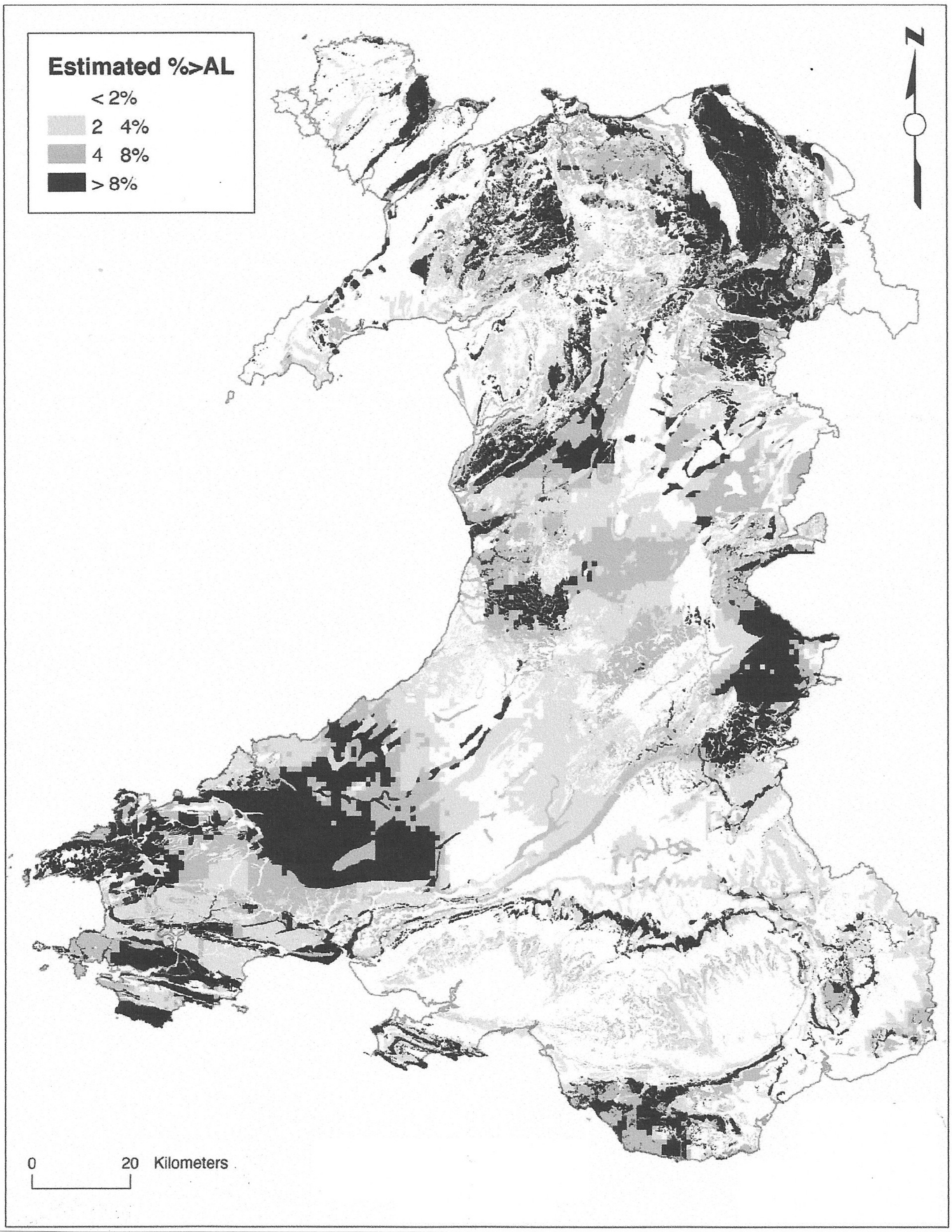

Figure 2. Provisional radon potential map of Wales

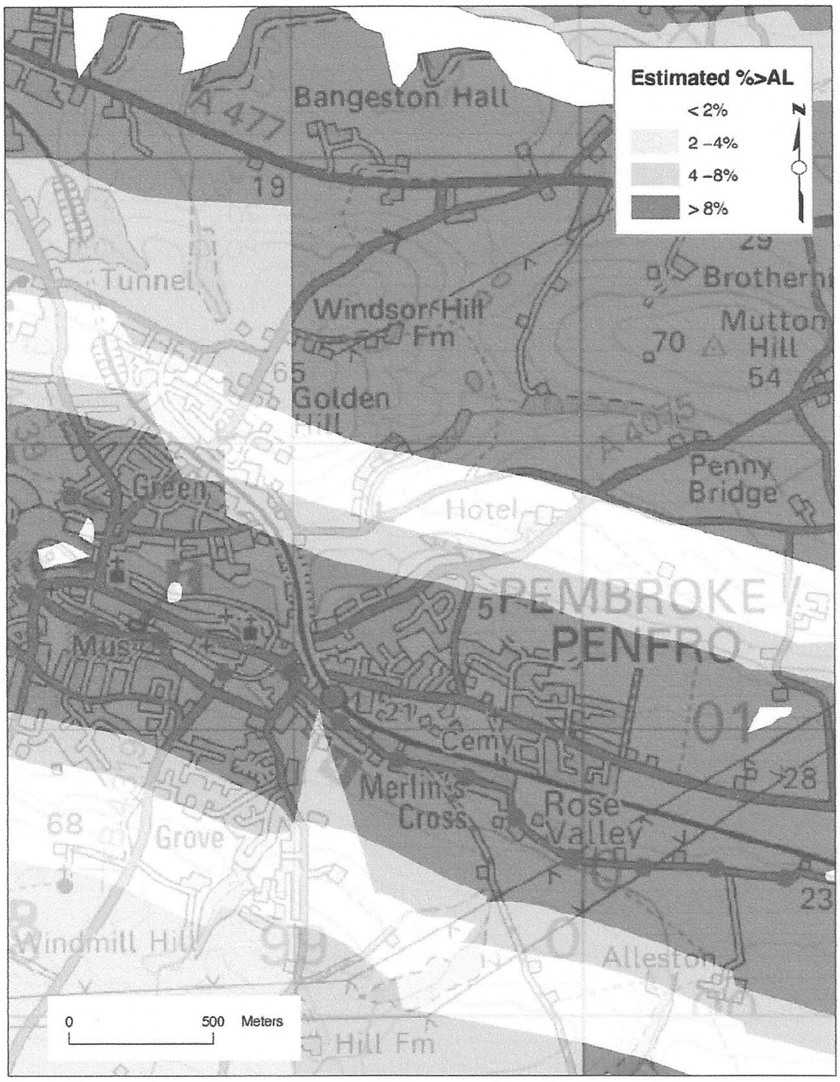

Figure 3. Radon potential map of the Pembroke area (*High potential (10-30%>AL) is associated with Carboniferous limestone in the Merlin Cross –Rose Valley area. Devonian bedrock has low potential (<1%>AL) to the north (Hotel) and south (Grove) of the limestone, Further north, in the vicinity of Windsor Hill Farm and Penny Bridge, high potential (8-20%>AL) is associated with Silurian argillaceous rocks of the Milford Haven Formation and also with Carboniferous limestone (20%>AL) in the Bangerston Hall area*. Topography © Crown Copyright, all rights reserved.

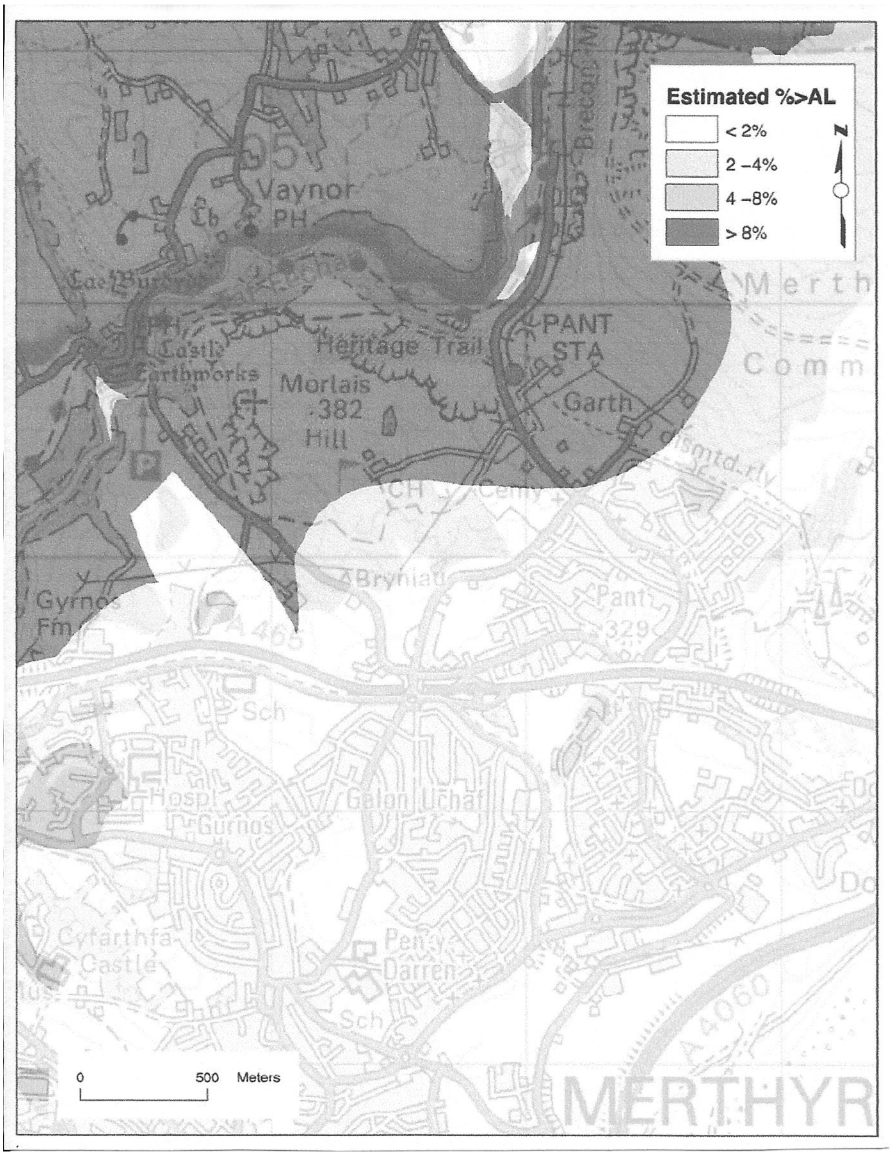

Figure 4. Radon potential map of the NW sector of Methyr Tydfil (*The high radon potential of Visean limestones (15%>AL or >10%>AL when covered with till) in the Vaynor area contrast with the low radon potential that characterises most of the NW sector of Merthyr which is underlain by Westphalian bedrocks with <1%>AL. Small areas underlain by Millstone Grit mudstone and siltstone have moderate radon potential (4-8%)*). Topography © Crown Copyright, all rights reserved.