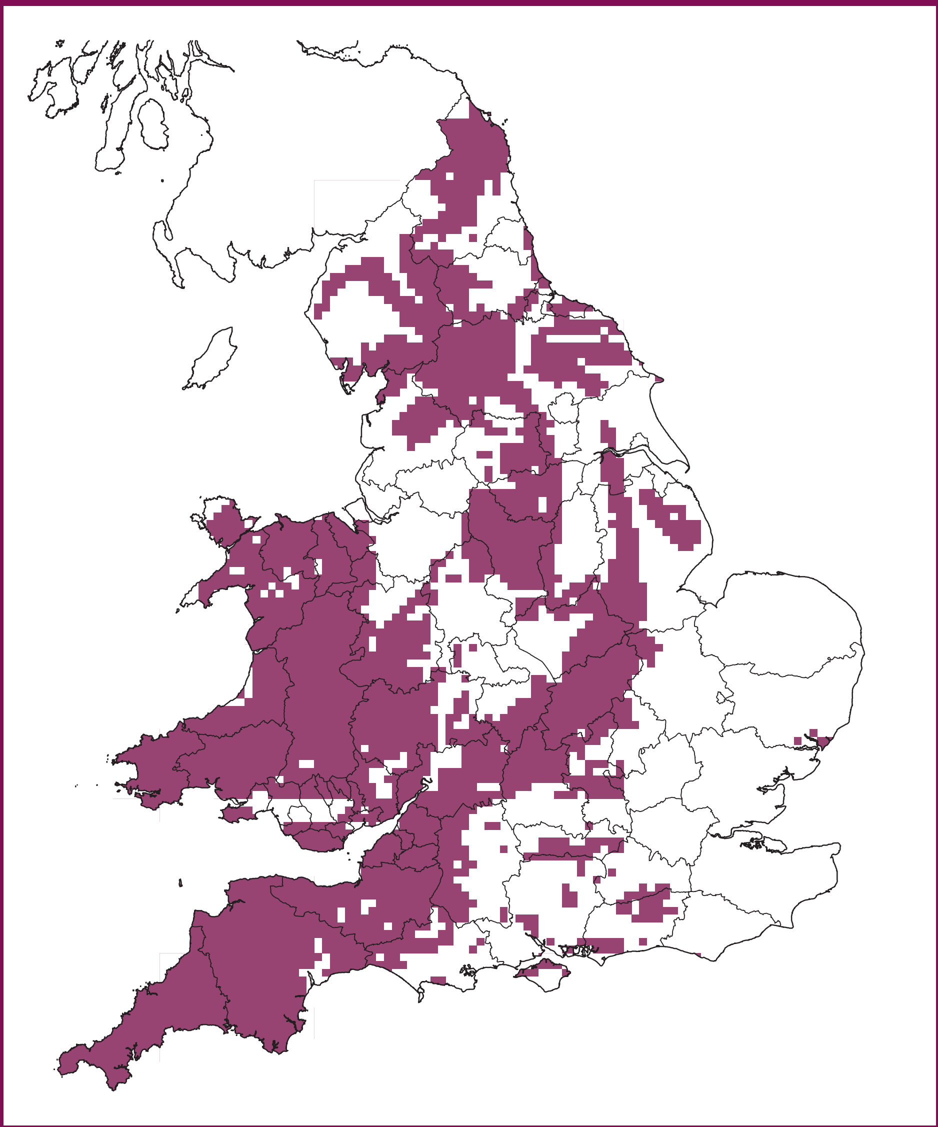
DETR
Environment
Transport
Regions

Dealing with radon emissions in respect of new development

Evaluation of mapping and site investigation methods for targeting areas where new development may require radon protective measures



British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

BRITISH GEOLOGICAL SURVEY

RESEARCH REPORT RR/00/12

Dealing with radon emissions in respect of new development

Evaluation of mapping and site investigation methods for targeting areas where new development may require radon protective measures.

Preparation of this report was funded by the Department of the Environment, Transport and the Regions

BRITISH GEOLOGICAL SURVEY
RESEARCH REPORT RR/00/12

Dealing with radon emissions in respect of new development

Evaluation of mapping and site investigation methods for targeting areas where new development may require radon protective measures.

J D Appleton
British Geological Survey

J C H Miles
National Radiological Protection Board

D K Talbot
British Geological Survey

This study was commissioned by the Department of the Environment, Transport and the Regions (Contract No. MP0621), but the views expressed in it are not necessarily those of the Department

Geographical Index
England and Wales

Subject Index
Radon, mapping, site investigation, land-use planning, development, building control, health and safety, environmental health

ISBN **0 85272 377 6**

Cover illustration
Recommended radon planning constraints map of England and Wales (derived from Maps 1 and 2, BR211 (1999)).

Bibliographic reference
APPLETON, J D, MILES, J C H, AND TALBOT, D K. 2000. Dealing with radon emissions in respect of new development: Evaluation of mapping and site investigation methods for targeting areas where new development may require radon protective measures. *British Geological Survey Research Report.* RR/00/12. 150pp.

Published for the Department of the Environment, Transport and the Regions under licence from the Controller of Her Majesty's Stationery Office

Keyworth, Nottingham British Geological Survey 2000

BRITISH GEOLOGICAL SURVEY

The full range of Survey publications is available from the BGS Sales Desk at the Survey headquarters, Keyworth, Nottingham. The more popular maps and books may be purchased from BGS-approved stockists and agents and over the counter at the Bookshop, Gallery 37, Natural History Museum (Earth Galleries), Cromwell Road, London. Sales desks are also located at the BGS London Information Office, and at Murchison House, Edinburgh. The London Information Office maintains a reference collection of BGS publications including maps for consultation. Some BGS books and reports may also be obtained from the Stationery Office Publications Centre or from the Stationery Office bookshops and agents.

The Survey publishes an annual catalogue of maps, which lists published material and contains index maps for several of the BGS series.

The British Geological Survey carries out the geological survey of Great Britain and Northern Ireland (the latter as an agency service for the government of Northern Ireland), and of the surrounding continental shelf, as well as its basic research projects. It also undertakes programmes of British technical aid in geology in developing countries as arranged by the Department for International Development and other agencies.

The British Geological Survey is a component body of the Natural Environment Research Council.

British Geological Survey Offices

Keyworth, Nottingham NG12 5GG
☎ 0115–936 3100 Fax 0115–936 3200
e-mail: sales @bgs.ac.uk
www.bgs.ac.uk
BGS Internet Shop: www.british-geological-survey.co.uk

Murchison House, West Mains Road, Edinburgh EH9 3LA
☎ 0131–667 1000 Fax 0131–668 2683

London Information Office at the Natural History Museum (Earth Galleries), Exhibition Road, South Kensington, London SW7 2DE
☎ 020–7589 4090 Fax 020–7584 8270
☎ 020–7942 5344/45

Forde House, Park Five Business Centre, Harrier Way, Sowton, Exeter, Devon EX2 7HU
☎ 01392–445271 Fax 01392–445371

Geological Survey of Northern Ireland, 20 College Gardens, Belfast BT9 6BS
☎ 028–9066 6595 Fax 028–9066 2835

Maclean Building, Crowmarsh Gifford, Wallingford, Oxfordshire OX10 8BB
☎ 01491–838800 Fax 01491–692345

Parent Body

Natural Environment Research Council
Polaris House, North Star Avenue, Swindon, Wiltshire SN2 1EU
☎ 01793–411500 Fax 01793–411501

ACKNOWLEDGEMENTS

The authors are grateful to Dr. David Brook (Chairman of the Steering Group), Dr Brian Marker, Ms Moira Johnson, Ms Melissa Thomas (Nominated Officers) and Mr Brian Freeland of the DETR, to all other members of the Steering Group (listed below), and to Local Planning Authorities personnel who assisted in the study as well as to colleagues at the British Geological Survey (David Jones, Tony Myers, John Stevenson, Niall Spencer), BRE (Chris Scivyer) and LUC (Philip Smith and Jon Grantham). Glenn Sharman kindly permitted BGS to use soil gas radon data from his Ph.D. thesis (Sharman, 1995) to inform an evaluation of historical radon site investigation data that is presented in Section 3 of this report.

DETR Steering Group

Mr F J Atkins (NHBC)
Dr A J Burke (BRD-DETR)
Mr T J Gregory (Cornwall County Council/Association of County Councils)
Mr J T Hague (Local Government Associations)
Mr G A Hudd (Somerset County Council)
Mr M Johnson (BRD-DETR)
Mr M Jones (Association of District Councils)
Dr A J Macpherson (RAS-DETR)
Dr H J Prosser (Welsh Assembly)
Mr B WT Spiers (Scottish Executive)
Prof. I Thornton (Centre for Environmental Technology, Imperial College of Science, Technology and Medicine)
Mr D W Tuffin (The Royal Institution of Chartered Surveyors)
Mr P Watson (County Planning Officer's Society)
Mr P Watts (The Royal Town Planning Institute)

The data in this report should not be used as the basis for a Stage 2 Geological Assessment that will be required in some areas to determine the level of radon protection needed in new dwellings (see BR211: guidance on protective measures for new dwellings, 1999 edition). This is because the information in this report dates back to 1996 and is not necessarily the same as the information currently used to generate site specific Radon Protective Measures (RPM) Site Reports. Please refer to the BGS web sites (www.bgs.ac.uk/radon and www.bgs.ac.uk/reference/radon) for further information.

Executive summary

Introduction

Radon gas comes from uranium that occurs naturally in the ground. The variation in radon levels between different parts of the country is mainly controlled by the underlying geology. 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, and is considered to cause approximately 5% of deaths from lung cancer in the UK. In order to limit the risk to individuals, the Government has adopted an Action Level for radon in dwellings of 200 becquerels per cubic metre (Bq m^{-3}). The Government advises householders that, where the radon level exceeds the Action Level, measures should be taken to reduce the concentration.

In the early 1990s, administrative and policy responses to radon problems in new development had limitations in that:

- new development was not adequately covered by existing responses in radon-prone areas which had not been designated as radon Affected Areas.
- the mapping procedures used to identify those areas where protective measures were required in new dwellings in some cases resulted in radon protection not being installed where required, and vice versa.
- they did not adequately cover material change of use or non-domestic development, including workplaces and certain residential institutions.
- procedures were not in place to ensure that developers were made aware of requirements for protective measures in new dwellings or of employers' responsibilities with regard to radon under the *Health and Safety at Work etc. Act 1974* and *Ionising Radiations Regulations 1985* at the planning or pre-planning stage.
- developers and future occupiers of buildings subject to material change of use (for example from agricultural or workplace to domestic use (e.g. barn conversions)) but not subject to Requirement C2 of Schedule 1 of Building Regulations 1991 were not necessarily made aware of the possible need for protective or remedial measures.

These limitations have been addressed by the Department of the Environment, Transport and the Regions (DETR) research programme 'Dealing with radon emissions in respect of new development' which aimed to identify the circumstances, if any, where new development may be adversely affected by radon emissions and the appropriate response to such problems. Fulfilment of these objectives will help to ensure that occupiers of new domestic and non-domestic developments will be adequately protected against the harmful affects of radon. The research programme, carried out by the British Geological Survey (BGS) working in collaboration with the Building Research Establishment Ltd. (BRE), Land Use Consultants (LUC) and the National Radiological Protection Board (NRPB).

The report *Dealing with radon emissions in new development: Summary report and recommended framework for planning guidance* (Appleton et al., 2000) explains the background to dealing with radon in new development. It highlights where improvements to the responses could be made and identifies the available options for dealing with radon in new development, including their relative advantages and disadvantages. The report also identifies the potential role of the planning system and presents conclusions and recommendations on which option(s) would be most appropriate and effective for ensuring that new development is protected against radon emissions.

This report summarises an evaluation of mapping and site investigation methods currently available for targeting areas where new development may require radon protection. The report also describes the system adopted in revised guidance (BR211, 1999) to determine the level of protection needed in new dwellings and discusses mapping and site investigation costs.

Mapping

Two main procedures have been used for mapping radon-prone areas in the UK. The first uses radon measurements in existing dwellings to map the variation of radon potential between administrative districts or grid squares. The 5 km grid square radon potential (GRIDRP) mapping procedure developed by the NRPB has, to date, provided the basis for identifying those areas where protective measures need to be installed in new homes and where monitoring of existing dwellings is recommended. The second procedure, geological radon potential mapping, is based on the interpretation of indoor radon within the framework of a geological map. Geological radon potential (GEORP) mapping requires greater development effort than GRIDRP mapping and it relies on the availability of digital geological maps at an appropriate scale. The BGS 1:50,000 scale digital geological data base for the UK will be completed in March 2001.

This research programme has demonstrated that there is scope for using indoor radon results, classified in terms of the underlying geology, in order to delineate radon-prone areas more clearly. In areas where many indoor radon measurements are available, it has been possible to demonstrate that each geological unit within a map sheet or smaller area, such as a 5 km grid square, has a characteristic geological radon potential (GEORP) which is frequently very different from the average radon potential for the grid square. Using geological criteria, extrapolations can be made to other areas with similar rocks, and areas of potentially high or low radon levels, can therefore be predicted. However, this alone is insufficient for accurately determining radon potential in new areas and further survey work should be carried out where required.

Whereas geological radon potential is the preferred and most spatially precise method of defining the requirement for protective measures in the sedimentary geological environments that cover most of England and Wales, 1 km GRIDRP mapping appears to be the most effective method, based on the use of existing data, in areas where pervasive uranium mineralisation crosses mapped lithological boundaries. So far as has been determined, this applies only to the SW and SX 100 km grid squares of the Ordnance Survey National Grid.

Both geological radon potential mapping and 1 km grid square radon mapping can provide much more detailed maps than the 5 km grid square maps used prior to 1999, and so can allow radon protective measures in new development and radon measurement programmes to be targeted more efficiently. The reliability and spatial precision of both mapping methods is, in general, proportional to the measurement density. It is, however, reassuring to note that even when the measurement density is as low as the minimum for 5 km grid square mapping, 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 map sheets with higher measurement densities.

Lithological variations within geological units can cause geological radon potential mapping in some parts of England to miss significant areas of higher radon potential which are identified by 1 km grid square mapping. Geological and grid square mapping are likely to be most powerful when used in a complementary fashion, by comparing maps produced by the two methods, and by grouping results both by geological unit and by grid square. It is recommended that this line of investigation should be pursued.

Finally, it is important to remember that however indoor radon data are grouped (whether by grid square or geological unit), a wide range of indoor radon levels are likely to be found. 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. Geological radon potential does not indicate whether a building constructed on a particular site will have a radon concentration that exceeds the Action Level. This can only be established through measuring radon in the building.

Radon potential maps for BR211

Revised guidance (BR211, 1999) defines the geographical areas where radon protection is necessary in new dwellings. It incorporates a system for determining the level of protection needed based on two sets of maps that show, as 5km grid squares of the Ordnance Survey National Grid, where protective measures from radon will or may be needed.

The Annex A maps are based on the average estimated percentages of homes above the radon Action Level (200 Bq m^{-3}) whilst the Annex B maps indicate those grid squares which are underlain, completely or in part, by geological units for which the estimated percentages of homes above the Action Level exceed the thresholds for either basic or full radon protection.

When the Annex A maps indicate that no radon protection or the installation of basic protection is required, the Annex B maps should be consulted to establish if underprotection might be possible and whether a geological assessment might allow developers to install a lower level of protection. A geological assessment involves using the BGS Radon Protective Measures GIS to check whether a site is on or close to a geological unit for which either basic or full radon protection is required. The RPM GIS currently comprises 1:250,000 scale data with the more detailed 1:50,000 scale data covering some of the most radon-prone parts of England. The RPM-GIS is being upgraded to 1:50,000 scale over the next 12 months as new digital map data become available through the BGS *DigMapGB* programme. Smaller scale intra-geological map sheet and intra-5-km grid square variations in GEORP will be mapped where sufficient indoor radon measurements are available. The Annex B maps will be amended accordingly, as indicated on page 5 of BR211 (1999). Amended maps will be posted on the BGS web site (www.bgs.ac.uk/radon).

One disadvantage of the current BR211 system is that there are some situations in which a developer will be required by the Annex A maps to provide full or basic radon protection when this would not be required on the basis of geological radon potential. This is because there are frequently major variations in GEORP within individual 5 km grid squares. The Annex A maps were included in the BR211 procedure because it was discovered that approximately eight 5-km grid squares (in which there are sufficient house radon measurements) with GRIDRP's exceeding basic or full thresholds but which were not identified on the Annex B maps. This occurred because of local lateral variations in GEORP. These discrepancies will be resolved once the new 1:50,000 scale digital geological radon potential data and local GEORP information for 5-km and 1-km grid squares has been incorporated into the RPM-GIS. Once this has been done, the Annex A maps may become redundant.

Radon site investigation methods

In general, measurement of soil gas radon in the field provides the most universally applicable geochemical indicator of radon potential. However, 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 water logged soils or when soil gas radon concentrations are abnormally enhanced in some soils due to the sealing effect of soil moisture. These conditions are particularly common in winter. Soil and rock permeability exerts a significant influence on soil gas radon concentrations and permeability normally needs to be taken into account when estimating radon potential from soil gas radon data. However, inconsistent results were observed when the Soil Gas Radon - GEORP - Soil Permeability calibration plot was used to determine GEORP from soil gas radon data so calibration plots clearly need to be refined further.

It may be necessary to devise a series of calibration plots not only for different soil/rock permeabilities but also for different soil moisture levels. Additional research would have to be carried out to investigate this and also to investigate the practicality of making permeability measurements as part of a radon site investigation protocol used prior to the construction of new dwellings. It may be necessary also to measure permeability and moisture content both close to the surface and at the sampling depth of 70 cm. The incorporation of field permeability measurements into a site investigation protocol was not tested during the current research programme. Problems with the determination of permeability and its incorporation into a radon site investigation procedure have been encountered in the Czech Republic where the quality of the permeability classification obtained at a site is very reliant on the personal experience of the technical staff carrying out the site investigation.

Whereas soil gas radon is accepted as being a relatively reliable method for determining GEORP on both a regional and site specific scale, seasonal and temporal variation in soil gas radon concentrations are difficult to deal with. Alternative site investigation protocols might be to (1) carry out measurements on two or three well documented calibration sites prior to carrying out each new survey so that seasonal effects related to soil moisture could be taken into account or (2) measure permeability and soil moisture and use calibration plots to estimate GEORP from soil gas radon data.

Soil gas radon measurements may be used to estimate the radon potential for geological units covering a relatively large area but not necessarily for a small development site. Results indicate considerable variation in radon potential between sites on the same geological unit, which would be expected. In addition, there is often considerable overlap between the soil gas radon ranges for lithological units with significantly different radon potentials (GEORPs).

Whereas the average of 10 soil gas radon measurements taken 25 to 50 m apart in one sector of a 5 km grid square or geological map sheet cannot be expected to correlate perfectly with the 5 km grid or map GEORP, the closeness of the correlation suggests (but does not prove) that it might be possible to use soil gas radon data to indicate radon potential on a site specific as well as a regional scale. An evaluation of the variability of soil gas radon measurements in relation to sample spacing and number of measurements tends to support the standard BGS site investigation protocol in which 10 measurements are taken on a 20 m spacing. However, a rigorously planned field programme would be required to establish the optimum sample number and spacing.

If soil gas radon concentrations cannot be determined because of climatic factors, for example when the soil profile is waterlogged, 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. Different radon site investigation methods may be required dependent upon the specific factors controlling radon emanation from the ground. In some cases no method will be reliable under unfavourable climatic conditions.

With regard to the practical application and effectiveness of soil gas radon site investigation methods as part of a Building Control system, it has not yet been proven that soil gas radon data can be used to discriminate reliably between, for example, 1.0% and 3.0% GEORP taking into account the problems of seasonal and temporal variation in soil gas radon. Soil gas radon site investigation methods are probably precise enough to define the GEORP for a new building site at around the 10% GEORP level as long as soil/rock permeability is taken into consideration.

A more rigorous test of the effectiveness of radon site investigation methods might be to carry out soil gas radon surveys in the immediate vicinity of a representative number of dwellings constructed on a range of geological units with different radon potentials. Approximately 100 sites on each geological unit would be required and radon measurements would need to be made in each dwelling under carefully monitored conditions. Selection of dwellings with similar construction characteristics would reduce the number of confounding factors in the data analysis. Such an evaluation was beyond the scope and financial constraints of the present research project. It should be noted that previous attempts to assess the relationship between radon in dwellings and soil gas radon measured in the immediate vicinity of the dwelling have produced divergent results perhaps because they were based on a relatively small number of dwellings and because of the influence of a building on soil gas radon levels in the ground immediately surrounding the dwellings.

The results of this research programme indicate that in most cases it is impractical to assess the severity of a radon problem on a particular site accurately until the building has been constructed and occupied, therefore precautions should be taken in areas where high radon levels have been predicted by the mapping programme. Radon site investigation techniques are not yet reliable enough to be incorporated into guidance. Many of the problems associated with the development of rigorous and robust site investigation procedures for the determination of methane and carbon dioxide hazard also apply to radon. As with methane, it is likely that a great deal of detailed research will be required before a practical protocol can be devised which can be used to reliably determine radon potential of a development site. In the interim, it is recommended that radon potential mapping is used for delineating those areas where radon protective measures are required in new development.

Contents

Figures

Tables

1. INTRODUCTION

1.1. Radon is a naturally occurring radioactive gas. It 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, and is considered to cause approximately 5% of deaths from lung cancer in the UK. In order to limit the risk to individuals, the Government has adopted an Action Level for radon in dwellings of 200 becquerels per cubic metre (Bq m^{-3}). The Government advises householders that, where the radon level exceeds the Action Level, measures should be taken to reduce the concentration.

1.2. Radon gas comes from uranium that occurs naturally in the ground. The production of radon from rock and overburden, including glacial and fluvial deposits and soil, is affected primarily by the amount of uranium within the rock-forming minerals and their weathering products. The variation in radon levels between different parts of the country is mainly controlled by the underlying geology. Most radon remains in rocks and soils. However, once released from minerals, it can migrate through bedrock and soils and accumulate in buildings.

1.3. Radon enters a building primarily by airflow from the underlying ground. The key routes by which radon enters buildings are through cracks in solid floors or walls below ground level, through construction joints and cavities in walls, or through gaps in suspended concrete or timber floors or gaps around service pipes. In addition, the heating and ventilation systems, and life style of the house occupants are important factors affecting radon accumulation in buildings.

1.4. In radon affected homes, the problem of radon can usually be tackled with simple, effective and relatively inexpensive measures, which are comparable in cost to work such as damp-proofing and timber treatment. The cost of installing radon protective measures in new dwellings is relatively low (£50-150 per dwelling) in comparison with the direct and indirect costs associated with treating lung cancer.

1.5. In the early 1990s, administrative and policy responses to radon problems in new development had limitations in that:

- new development was not adequately covered by existing responses in radon-prone areas which had not been designated as radon Affected Areas.
- the mapping procedures used to identify those areas where protective measures were required in new dwellings in some cases resulted in radon protection not being installed where required, and vice versa.
- they did not adequately cover material change of use or non-domestic development, including workplaces and certain residential institutions
- procedures were not in place to ensure that developers were made aware of requirements for protective measures in new dwellings or of employers' responsibilities with regard to radon under the *Health and Safety at Work etc. Act 1974* and *Ionising Radiations Regulations 1985* at the planning or pre-planning stage
- developers and future occupiers of buildings subject to material change of use (for example from agricultural or workplace to domestic use (e.g. barn conversions)) but not subject to Requirement C2 of Schedule 1 of Building Regulations 1991 were not necessarily made aware of the possible need for protective or remedial measures.

1.6. These limitations have been addressed by the Department of the Environment, Transport and the Regions (DETR) research programme 'Dealing with radon emissions in respect of new development' which aimed to identify the circumstances, if any, where new development may be adversely affected by radon emissions and the appropriate response to such problems.

The objectives of the research were:

a) to identify the circumstances where new development or changes to land use may result in people being exposed to radon emissions which are prejudicial to health or are above the "Action Level";

b) to consider what information is required to enable such radon risks to be assessed and precautions to be targeted more effectively and how this should be collected, collated and presented;

c) to examine what options, including preventive and remedial measures, are available to prevent adverse accumulations of radon within new development; and

d) to present results in forms suitable for both specialists and non-specialists in issues associated with radon.

1.7. Fulfilment of these objectives will help to ensure that occupiers of new domestic and non-domestic developments will be adequately protected against the harmful affects of radon.

1.8. The research programme, carried out by the British Geological Survey (BGS) working in collaboration with the Building Research Establishment Ltd. (BRE), Land Use Consultants (LUC) and the National Radiological Protection Board (NRPB), started in December 1995. The consultation exercise and subsequent revision of the Guidance Document BR211 "Radon: guidance on protective measures in new dwellings" delayed execution of the project. This process extended the research programme from February 1997 until publication of the revised guidance in November 1999.

1.9. The report *Dealing with radon emissions in new development: Summary report and recommended framework for planning guidance* (Appleton et al., 2000) explains the background to dealing with radon in new development. It highlights where improvements to the responses could be made and identifies the available options for dealing with radon in new development, including their relative advantages and disadvantages. The report also identifies the potential role of the planning system and presents conclusions and recommendations on which option(s) would be most appropriate and effective for ensuring that new development is protected against radon emissions.

1.10. Potential options for identifying development sites where radon protection might be required in new dwellings and extensions to dwellings were identified. These are:

A. Mapping defines need for protective measures.
B. Mapping defines need for protective measures. Site investigation might be used to permit relaxation of regulation if the developer wishes to use this option.
C. Universal site investigation defines the need for protective measures.

1.11. Options A and B both require maps that can be readily used by building control bodies, developers and others concerned with radon protective measures. Practical mapping options currently available for identifying areas or sites where new development requires protection include (a) NRPB grid square radon potential maps, (b) geological radon potential maps, and (c) a combination of NRPB grid square and geological radon potential maps. This report summarises the results of a number of studies of the relative advantages and disadvantages of using grid square radon potential mapping and geological radon potential mapping[1] to designate areas where radon protective measures are required. These included an evaluation of mapping options in (1) Derbyshire and Northamptonshire where it was suspected that the level of radon in dwellings was strongly correlated with the distribution of bedrock and drift geological units; and (2) south-west England where it was suspected that the irregular distribution of uranium mineralisation might reduce the effectiveness of geological radon potential mapping. This research programme has also benefited from the results of another DETR study whose main purpose was to use 1:50,000 scale geological radon potential maps and 1 km grid square maps to identify localised areas of England where radon concentrations are most likely to have >5% probability of being above the Action Level (Miles and Appleton, 2000).

1.12. In Option B, which applied to the 1996 interim guidance on radon protective measures for new dwellings, the developer had the option of applying for relaxation of the requirement for measures based on the results of a geological site investigation (incorporating desk studies, ground investigations and soil gas radon measurements). The site investigation and report would have needed to be executed by a suitably qualified geologist. The technical protocols for soil gas radon measurements and assessment of results were not clearly defined in the interim guidance. Indeed, the reliability of radon site investigations was uncertain at that time and was investigated as part of the current research programme.

1.13. This report summarises the results of the evaluations of mapping and site investigation methods for targeting areas where new development requires installation of radon protective measures. The report describes what information is required and how this should be collected, collated and presented.

The report has a further five sections following this introduction:

Section 2 summarises the results of studies of methods used to map radon prone areas;

Section 3 deals with radon site investigation methods;

Section 4 describes the system adopted in revised guidance (BR211, 1999) to determine the level of protection needed in new dwellings.

Section 5 discusses radon potential and radon site investigation costs.

Section 6 presents the main conclusions and recommendations.

[1] In the UK, radon potential indicates the probability that existing dwellings will exceed the radon Action Level (200 Bq m^{-3}). The radon potential of a grid square or any combination of bed-rock and drift (unconsolidated deposit) within a county, map sheet or grid square may be determined by statistical analysis of radon measurements made in existing dwellings.

2. MAPPING RADON PRONE AREAS

Introduction

2.1. The accurate delineation of those areas in which radon exceeds reference levels in buildings is crucially important to the radon policies of many governments (Colgan & Gutiérrez 1996). Accurate mapping of radon-prone areas will help 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. Radon potential maps can be used (i) to assess whether radon protective measures may be required in new buildings; (ii) for the cost-effective targeting of radon monitoring in existing dwellings and workplaces; and (iii) to provide a radon assessment for homebuyers and sellers. It is important, however, to realise 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.

2.2. The principal objective of radon potential mapping is to map the variation in probability that new or existing buildings will exceed a radon reference level. In the UK such maps generally indicate the probability that new or existing houses will exceed a radon reference level, which in the UK is termed the Action Level (200 Bq m^{-3}). In other countries, geological radon potential maps predict the average indoor radon concentration (Gundersen et al. 1992) or give a more qualitative indication of radon risk (e.g. Kemski et al. 1996).

2.3. Two main procedures have been used for mapping radon-prone areas. The first uses radon measurements in existing dwellings to map the variation of radon potential between administrative or postal districts, or grid squares (Cohen et al. 1994, Friedmann et al. 1996, Kunz et al. 1994, Markinowski et al. 1994, Nero et al. 1994, Lomas et al. 1996, Miles 1994, 1998, Miles et al. 1996, Price 1995a, b, RPII 1996, Verger et al. 1994, Voutilainen & Mäkeläinen, 1993). The second is geological radon potential mapping in which each geological feature is assigned to a radon potential class based on the interpretation of one or more of the following data: (i) radon concentrations in dwellings (indoor radon); (ii) concentration, mineralogical occurrence and chemical state of uranium and radium in the ground (radiometric and geochemical data); (iii) rock and soil permeability and moisture content; (iv) concentration of radon in soil gas, and (v) building architecture (construction characteristics). Since the purpose of maps of radon-prone areas is to indicate radon levels in buildings, maps based on actual measurements of radon in buildings are preferable to those based on other data.

2.4. Procedures for monitoring and surveys of radon in dwellings are described in Nazaroff (1988), Wrixon et al. (1988) and Green et al. (1992). In the UK, measurements are made with passive integrating detectors over a period of three months (Green et al. 1992, Miles 1998) whereas short-term "screening" measurements taken over a 2 to 7 day period are commonly used for mapping in the USA (Cohen et al. 1994, Gundersen & Schumann 1996). Recent developments in measurement techniques and equipment are outlined in Janssens et al. (1992) and Hopke (1996). The most common methods for determining radon indoors as well as in soil gas, solids and water rely on the fact that it is the only natural gas that emits alpha particles. Therefore if gas is separated from associated solid and liquid phases, any measurements of its radioactive properties, especially alpha activity, relate to radon or its daughter products. Detector systems include zinc sulphide radiation counting, ionisation chambers, alpha track registration, liquid scintillation counting, and linked absorbers such as activated charcoal. The concentration of radon in air is usually measured in Bq m^{-3}. In Great Britain, the average level in dwellings is 20 Bq m^{-3} and the Government has set a reference level of 200 Bq m^{-3} for existing and future dwellings. A more recent review of the accuracy of different passive measurement techniques (Miles, 2000) showed that the longer a measurement was, the more accurate the estimate of annual average radon concentration. Decisions on remediation of high radon levels should not be based on measurements carried out over a few days, though such short measurements could be used for initial screening. When measurements are carried out over less than a year, they should be corrected for seasonal variations before being used for decisions on remediation or for mapping. Collection of indoor radon data is relatively inexpensive, as passive radon detectors can be distributed by post.

2.5. Indoor radon varies significantly between different types of buildings. Architectural type is one factor within the Radon Index Matrix used to estimate geological radon potential in the USA (Gundersen & Schumann 1996). In the UK, for example, bungalows and detached houses tend to have higher indoor radon than terraced houses or flats in the same area (Gunby et al. 1993). Building material, double glazing, draught-proofing, date of building and ownership were also identified as having a significant impact on indoor radon concentrations (Gunby et al., 1993). In some cases radon potential mapping in the UK is based on indoor radon data which have been normalised to a mix of houses typical of the UK housing stock (Miles et al., 1996, p.14; Miles 1998) thereby removing possible distortion caused by construction characteristics. However, the grid square maps produced in the NRPB Radon Atlases (Lomas et al., 1996, 1998) are based on results that were corrected for temperature but not normalised to a standard house mix. The maps therefore 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 tend to be 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 (Miles and Appleton, 2000). Where the main objective is to obtain an indication of variations in radon potential caused by factors in the ground (such as geology, soil type, permeability etc.), it might be considered logical to normalise the house radon data to a standard dwelling or standard mix of dwellings. A comparison based on house radon data for twenty 1:50,000 scale geological maps sheets demonstrated that the estimated proportion of dwellings exceeding the radon Action Level is, in general, significantly lower if the house radon data are corrected for temperature and normalised to a standard housing mix (Figure 2-1). Whereas it might be logical to produce one set of maps based on temperature corrected data for radon monitoring purposes and another set of maps for building control, the DETR decided on the advice of the NRPB that temperature corrected data should be used for both purposes. Their decision was based on the consideration that (i) using different data sets for different maps could well lead to confusion, and (ii) future houses in a region are likely to be similar to existing houses in that region, rather than similar to a national average house type.

2.6. Requirements for mapping radon-prone areas using house radon data are similar whether the maps are made on the basis of grid squares or geological units. These requirements include:

- accurate radon measurements made using a reliable and consistent protocol;
- centralised data holdings;
- sufficient data evenly spread;
- automatic conversion of addresses to geographical co-ordinates.

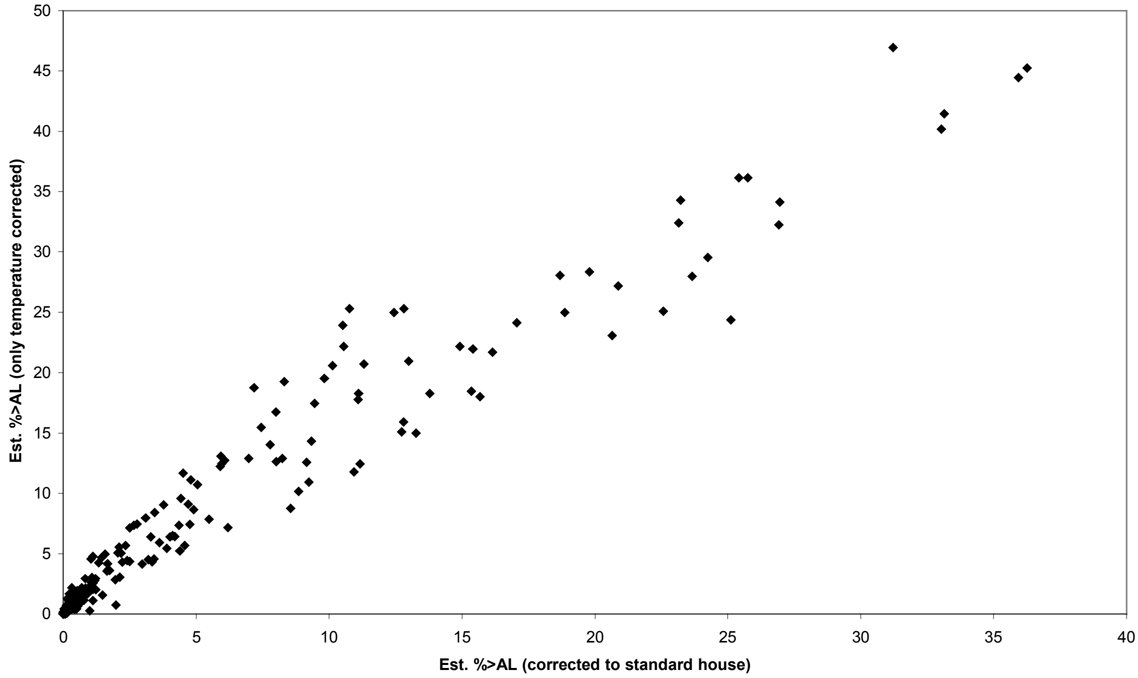


Figure 2-1. Comparison of the estimated proportion of dwellings exceeding the radon Action Level for geological units in twenty 1:50,000 scale geological map sheets in England and Wales based on (i) house radon data corrected for temperature and normalised to a standard house mix (Miles et al, 1996; Miles 1998) and (ii) house radon data corrected only for temperature. (Number of radon measurements per geological unit >50; number of units in plot = 228)

2.7. As far as the authors are aware, it appears that Great Britain is the only country that meets all of these requirements for large areas. In countries where lesser quality or quantity indoor radon data are available, there is greater reliance on proxy data for radon potential mapping (e.g. USA, Sweden and Czech Republic). As Great Britain has a large amount of data that meets these requirements few attempts have been made to map radon-prone areas solely using geological indicators, as in some other countries. Instead, research has been concentrated on such questions as:

- How is the data best analysed and interpreted (particularly where it is sparse)?
- What are the best boundaries to use?
- How can geological information be used to refine maps and extend them into areas where there is little or no data from houses?

2.8. Mapping levels of radon in administrative areas has the advantage of simplifying any subsequent administrative action, and it is usually easier to determine the administrative area in which a building falls rather than its map co-ordinates. However, it has the disadvantages that the areas have shapes and sizes that may not be suitable for the amount of data available, and the variation in shape and size obscures the underlying pattern of variation in radon levels. Use of grid squares allows an appropriate size of area to be chosen and simplifies the analysis, but can make it difficult to apply administrative action. Use of geological boundaries may help to delineate differences in radon potential with greater spatial accuracy than other types of boundary. Use of geological boundaries is not efficient unless these are held in a digital format.

2.9. 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. 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 (Miles et al. 1990, 1992, Ball et al. 1991, Ball & Miles 1993, Appleton & Ball 1995, Ball et al. 1995, Miles & Ball 1996, Appleton & Ball 2000). Similar observations have been made in the Czech Republic (Barnet 1991), Germany (Kemski et al. 1996), Luxembourg (Kies et al. 1996), Sweden (Åkerblom 1987) and the USA (Brown et al. 1992, Gundersen et al. 1992). In the USA, major regional variations may be related to differences in house architecture. In the northern states, for example, most houses have basements and tend to have higher radon than homes in the southern areas, which are mostly slab-on-grade or crawl-space construction (Gundersen and Schumann 1996, Schumann 1993).

Non-geological radon potential mapping

Great Britain

2.10. Non-geological radon potential mapping uses radon measurements in existing dwellings to map the variation of radon potential between administrative or postal districts, or grid squares without taking into consideration the geological controls on radon in dwellings.

2.11. The distribution of radon concentrations in existing houses is presented by the NRPB on maps which show the fraction of the housing stock above the Action Level in each 5 km grid square calculated by lognormal modelling of house radon data (Figure 2-2; Miles et al., 1990, 1992, 1996; Lomas et al., 1996, 1998).

2.12. Because the factors that influence radon concentrations in buildings are largely independent and multiplicative, the distribution of radon concentrations is usually lognormal (Gunby et al., 1993). The lognormal transform employed in interpreting house radon surveys has been criticised by Schwenke and Butine (1994) as it tends to de-emphasise extreme values. They propose alternative statistical analysis methods. However, Miles (1994) showed that the lognormal model produced accurate estimates of the proportion of homes above the action level in the UK. A lognormal modelling procedure has therefore been used by the NRPB to produce the 5 km grid square maps required for the designation of Affected Areas (Miles et al., 1992, 1996). In order to use the lognormal model to estimate the fraction of the housing stock which exceeds the Action Level in each square, estimates of the geometric mean (GM) and geometric standard deviation (GSD) of the radon house values are required for each grid square. Initially the GM and GSD are calculated for the radon results in each square, but in many areas there are too few measurements per square to provide sufficiently accurate estimates for the modelling procedure. If this is the case, a new value for the GM is estimated by pyramidal smoothing with the GMs for the 8 immediately adjacent squares, the weights varying according to the number of results available for each grid square. Where there are insufficient results to estimate the GSD for a square directly, the national average value of 2.5 is used. The distribution of the areas with estimated fractions of <1%, 1-3%, 3-10%, 10-30% and >30% of homes above the Action Level is then plotted (Figure 2-2).

2.13. In order to define radon Affected Areas and delineate areas where protective measures need to be installed in new homes, the computer generated grid square maps were previously manually redrawn (e.g. Miles et al., 1992). The grid square maps were used by the Building Research Establishment and DOE-Building Regulations Division to identify parishes where different levels of protective measures should be installed in new houses (BRE, 1992). Although the contours showing estimated percentages (>3% and >10%) of houses above the Action Level were used by the DOE, the contours were not necessarily followed exactly and other factors may have been taken into account.

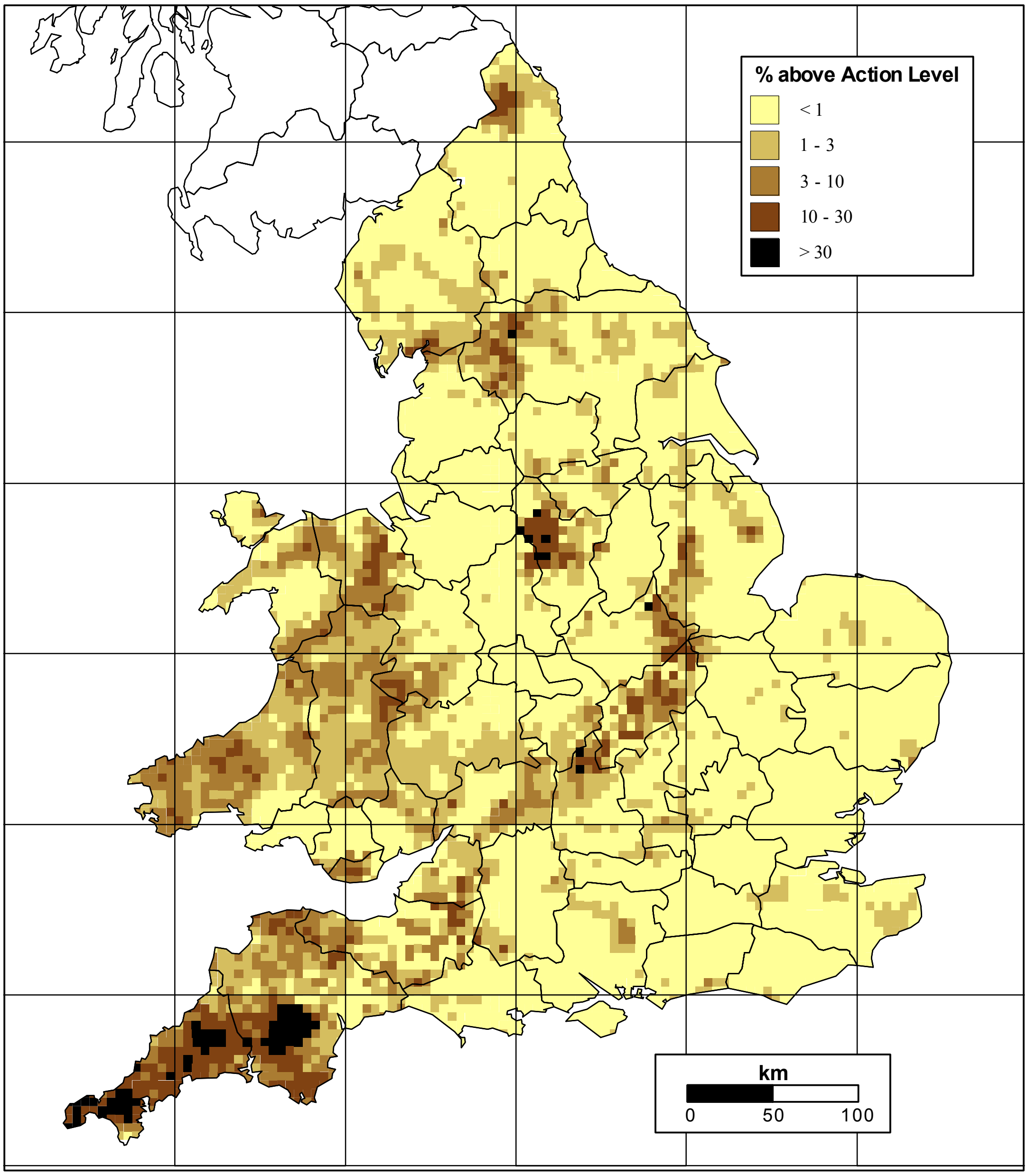


Figure 2-2. Estimated proportion of homes exceeding the Action Level in each 5km grid square of England and Wales (NRPB data, October 1998)

2.14. Some concern was expressed about this procedure on the basis that some parishes are not listed in the BR211 guidance document (BRE, 1992) even though parts of them are clearly underlain by geological units which are known to have high radon potential. These include the Carboniferous and Jurassic Limestones, north of Wells and west of Frome in Somerset (BGS, unpublished data), and some ground underlain by the Northampton Sand Formation in Northamptonshire (Leicester University, unpublished data, 1992).

2.15. Where house radon data is plentiful, maps using smaller grid squares that 5 km can be made. NRPB investigated maps based on 1 km grid squares using the techniques developed for 5 km squares (Miles, in press; Miles and Appleton, 2000). Grouping house radon data by 1 km grid square without making assumptions about the location of boundaries between areas with different radon potential has different advantages from grouping by geology. In some cases, this method can show up variations that are obscured by general geological grouping, such as variations in radon potential within a geological unit (Miles and Appleton, 2000). Investigations in Cornwall and Devon in general revealed that the finer the grid, the closer the correlation with the geological controls of radon in dwellings (see para. 2.43 below).

2.16. Since the purpose of the house radon grid square map is to identify those areas of concern and to indicate the percentage of affected houses, then maps based upon house data largely carry their own in-built verification features. The extent of the problem is represented by the results. Using standard statistical tests the number of repeats required to give the same result from sampling the same population may be calculated. An alternative procedure for testing the accuracy of grid square mapping for large data sets is to select subsets at random from within the main population for statistical treatment (Miles, 1994). Since house data collection may take place over several years, further validation is possible by comparing data sets collected at different times.

2.17. Mapping using postcodes has also been evaluated. Data can easily be grouped and analysed using groupings of postcodes such as sectors, although smoothing is not feasible. Appropriate scales of data grouping have been investigated. Other boundaries, such as parishes, are difficult or impossible to use as the data cannot easily be encoded in this format, and computer-compatible boundary files are not available.

2.18. Some work has been done on kriging (Vincent and Gatrell, 1993), a statistical technique developed for analysing spatial variations in parameters measured in mineral resource evaluation and mineral prospecting. A difficulty with this approach is that kriging assumes that the measured parameter varies with distance in a uniform way across the area mapped. This assumption does not hold for radon levels indoors close to a boundary between two geological units. However, if kriging was restricted to data taken from a single geological formation, it may provide further insight into variations in radon potential both across and laterally within a formation. This is being investigated by the NRPB.

U.S.A.

2.19. In the USA the use of house data for mapping has been investigated by Price (Price 1995a, 1995b, Price et al 1995). Most measurements of indoor radon have been made using short-term charcoal monitors, and so cannot be used directly to estimate long-term average radon levels. Price has been examining ways to supplement the relatively small number of long-term etched track measurements with other data, such as short-term measurements and aeroradiometric data. He shows that although individual short-term measurement results are poor indicators of radon potential, aggregations of them can be corrected for bias and can provide useful information where no long-term results are available. He also uses a statistical technique known as Bayesian analysis to improve estimates of mean radon level in areas where the data are sparse. This method was tested using subsets of the data, and shown to result in significant improvements in accuracy.

2.20. Other parameters, particularly aeroradiometric data, are used by Nero (1993) and Nero et al (1994) to extend the mapping to areas with few or no indoor radon measurements. Kunz et al (1994) use charcoal measurements (uncorrected) and geological information to assign ‘radon risk’ (based on geometric mean radon) for counties in New York state.

2.21. Cohen et al (1994) have also used a variety of sources of results in order to map mean radon levels. Results from short-term measurements were normalised to correct for bias. The maps shown are mean radon levels in 1729 US counties. The statistical treatment seems to have been somewhat cruder than Price’s, but larger areas are covered.

2.22. Markinowski et al (1994) report the EPA survey of radon in homes. This covered about 6000 homes across the USA, all measured using long-term etched track detectors. This is by far the best data set for the USA, though very sparse given the size of the country. It can provide estimates of the mean radon levels and distributions for the whole country and states, but not smaller areas.

2.23. Overall the mapping efforts in the USA have been hampered by the scarcity of high-quality data, and the fact that most data is not collected centrally. None of the workers have attempted to map the proportion of homes with high radon levels. Price, Nero and Markinowski have examined the distribution of radon levels at different scales, and find that it is well fitted by the lognormal model.

Ireland

2.24. Data is being collected on a similar basis to that in most of Europe (long term etched-track), and analysis on a similar basis to that in the UK has been discussed (Madden 1995), though we are not aware of firm plans for publishing. Daly (1994) has examined ways of estimating the proportion of data above a threshold using statistical techniques developed in industry, for instance for estimating the proportion of manufactured parts likely to be outside tolerance limits. This is a possible alternative to techniques used at present, though so far tests have not shown the method to be better for radon mapping than current ones.

Luxembourg

2.25. Kies et al. (1995) has examined results from measurements in about 3000 houses in Luxembourg (a high measurement density) and has related them to underlying geology. He has had to do this by comparing street maps and geological maps, thus illustrating the problems encountered in countries without a detailed postcoding system related to grid references. House radon data was allocated to 13 geological formations (Mesozoic and Palaeozoic). It was found that data for the country as a whole did not fit a lognormal distribution well, possibly because the country is geologically divided into two regions with different characteristics. When data was grouped by lithology, it fitted the lognormal distribution much better. It was found that radon levels in houses increased with the age of the underlying rock, even when the radium content of the rocks did not change.

France

2.26. Verger et al (1994) report results of a survey of 1700 houses using etched-track detectors. Factors affecting results such as house characteristics and seasonal variation are examined in detail, and analysed using a logarithmic model. Because of the scarcity of the measurements, only crude mapping can be carried out.

Geological radon potential mapping

2.27. 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 (Miles & Ball 1996). In the absence of an adequate number of high quality indoor radon measurements, proxy indicators, such as soil gas radon data or information on U content, 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. The relevance, limitations, methods of collection and interpretation of these data for geological radon potential mapping is discussed briefly in the following sections with particular reference to the relationship between each indicator and radon levels in homes. Appleton & Ball (1995, 2000) give a more detailed analysis of data types.

2.28. Since the purpose of maps of radon-prone areas is to indicate radon levels in buildings, maps based on actual measurements of radon in buildings are preferable to those based on radiometric, geochemical or pedological data. Radon potential maps based on indoor radon data grouped by geological unit have the capacity to accurately estimate the percentage of dwellings affected together with the spatial detail and precision conferred by the geological map data (Miles & Ball 1996). In the UK, the BGS and the NRPB have devised a procedure to correlate radon levels in dwellings with geology without prejudicing the confidentiality undertakings given to householders and the Government. Lognormal modelling of the indoor radon data (Miles 1998) produces estimates of the percentage of the housing stock above the UK Action Level for each geological unit within a map sheet, grid square or administrative district.

2.29. Uranium and radium concentrations in surface rocks and soils are a useful indicator of the potential for radon emissions from the ground. They can be estimated by gamma spectrometry either in the laboratory, or by ground, vehicle or airborne surveys. The close correlation between airborne radiometric measurements and indoor radon concentrations has been demonstrated in Virginia (Kline & Mose 1987), New Jersey (New Jersey Dept. of Environmental Protection 1988) and in Nova Scotia, Canada (Jackson 1992). Duval et al. (1989) and Duval & Otton (1990) have confirmed a linear relationship between average indoor radon levels and surface radium content for soils of low to moderate permeability. However, areas with high permeability (>50 cm/hr) had significantly higher indoor radon levels than would otherwise be expected from the $e^{226}Ra$ concentrations, reflecting an enhanced radon flux from permeable ground. Grasty (1997) demonstrated that any estimate of natural gamma-ray flux from the uranium decay series (i.e. radium) in the ground must take into consideration the radon coefficient of the soil as well as its radon diffusion coefficient, which depends largely on soil moisture. Clay soils tend to have higher eU when wet whereas sandy soils have lower eU (Grasty, 1997).

2.30. The first stage of the BGS High Resolution Airborne Resource and Environmental Survey (HiRES) covers an area of the north Midlands stretching from Prestatyn in the west to Sleaford (near Grantham) in the east, and from Shrewsbury in the south to Sheffield in the north. The survey comprised 50,000 line kilometres of magnetic, radiometric and electromagnetic (VLF) data over an area of 14 000 square kilometres. Potassium (Figure 2-3), equivalent uranium (Figure 2-4) and equivalent thorium (Figure 2-5) images of the eastern half of the HiRES-1 survey area have been combined into a ternary gamma-ray (K-eU-eTh) image (Figures 2-5 and 2-6) to aid interpretation. On the ternary image, Sherwood Sandstone (SS, red) is characterised by high K and relatively low eU and eTh. The Mercia Mudstone Group (MM) is represented by white to pale yellow because it has high K, eU and eTh. In the north-west sector of the area, high eU and low K and eTh associated with Carboniferous Limestone (CL) and the overlying uraniferous shales produces a bright blue colour on the ternary image. High eU alluvial deposits derived from the rocks and soils of the High Peak area have been deposited alongside the River Dove (RD). Immediately west of the red Sherwood Sandstone (SS) is an indistinct, north-south trending band of mottled blue-purple-green associated with the Cadeby Formation (CF; dolomitised limestone and dolomite) which has generally low K and variable eU and eTh. Along the eastern border of the survey area, dark blue (moderate eU, low eTh and K) characterise the Lincolnshire Limestone (LL) whilst the turquoise blue associated with the Marlstone Rock Formation (MR) reflects high eTh and moderate eU. The geological radon potential of these major geological units (Figure 2-8) reflects a combination of eU and the permeability of the ground. Very high eU and high permeability associated with the Carboniferous Limestone in Derbyshire results in more than 30% of dwellings exceeding the radon Action Level. High eU and moderate permeability over the Marlstone Rock and moderate eU combined with high permeability over the Lincolnshire Limestone both result in an average of more than 10% of dwellings exceeding the Action Level. These preliminary results confirm the value of airborne gamma spectrometric data for radon potential mapping. A detailed interpretation of the relationship between the HiRES data and geological radon potential is being carried out by the BGS and will be reported in due course.

2.31. After uranium and radium concentration, the permeability and moisture content of rocks and soils is probably the next most significant factor 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. In Great Britain, the most permeable rocks are karstified limestones such as the Carboniferous Limestone, and thick, partly unconsolidated sands and sandstones, such as the Cretaceous Upper and Lower Greensand. Highly permeable unconsolidated materials include terrace, alluvium and gravel deposits and these are frequently associated with high soil gas and indoor radon. Weathering processes can also affect permeability. For example, Devonian rocks in south west England form high ground and retain moderately permeable deep weathering profiles that probably developed during the Tertiary (Ball & Miles 1993). Permeable rocks are more likely to produce high levels of radon in houses than impermeable ones with similar or even higher uranium, radium and soil gas radon concentrations. Enhanced radon in soil gas is also associated with high permeability features such as fractures, faults and joints (Ball et al. 1991, Kemski et al. 1996, Andjelov & Brajnik 1996). 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.

2.32. Use of soil gas radon data for radon potential mapping and estimating the radon risk at a development site are described in Section 3 of this report.

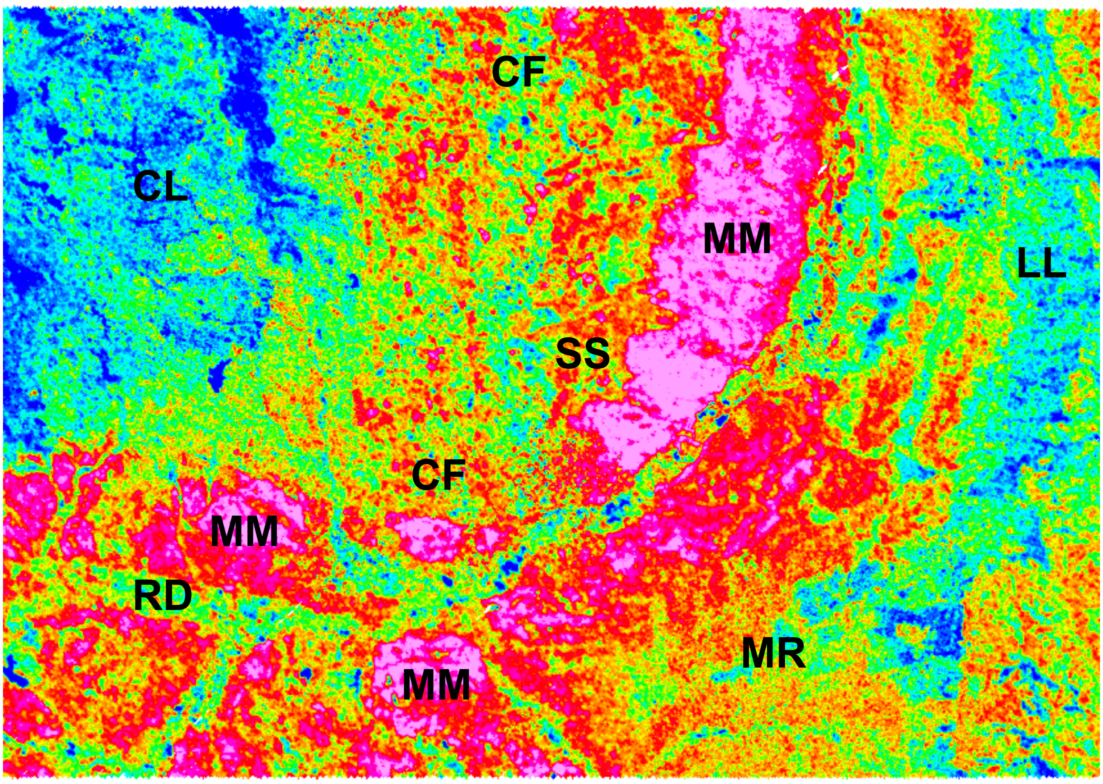


Figure 2-3. BGS HiRES Potassium (K) airborne gamma spectrometry map (Colour scheme: High to Low - pink, red, orange, yellow, green, pale blue, dark blue; CL, MM, RD, SS, MR, LL see text) (Map area 100km by 70km)

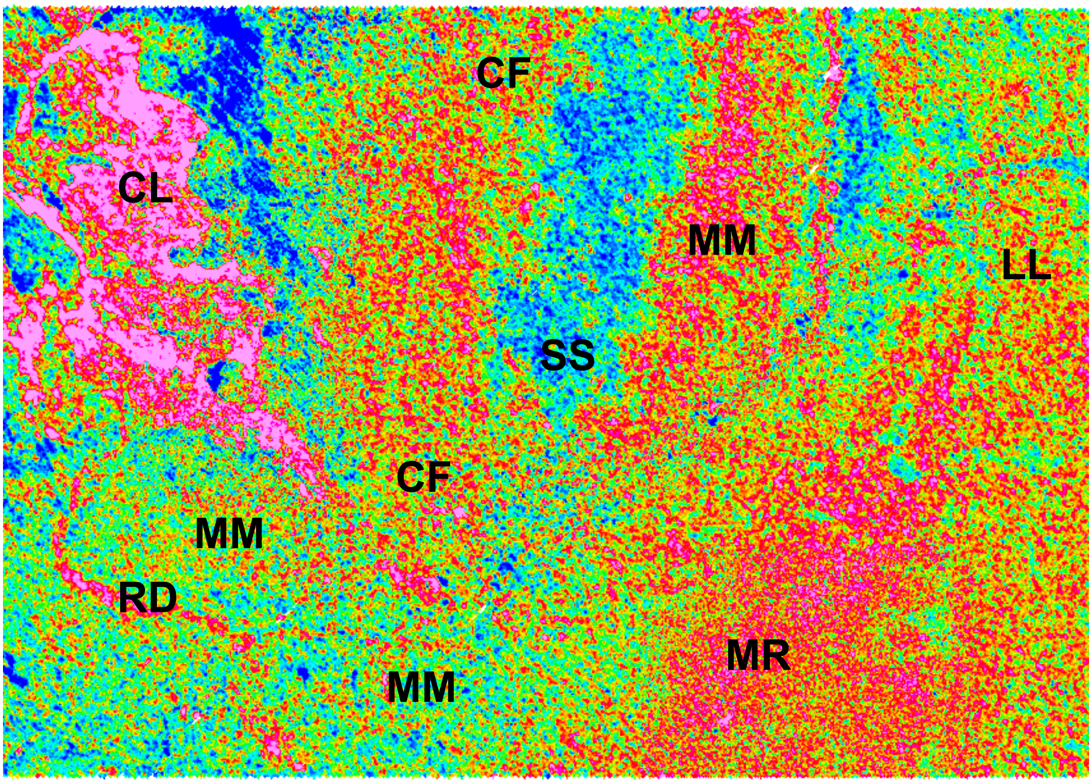


Figure 2-4. BGS HiRES Estimated uranium (eU) airborne gamma spectrometry map (Colour scheme: High to Low - pink, red, orange, yellow, green, pale blue, dark blue; CL, MM, RD, SS, MR, LL see text) (Map area 100km by 70km)

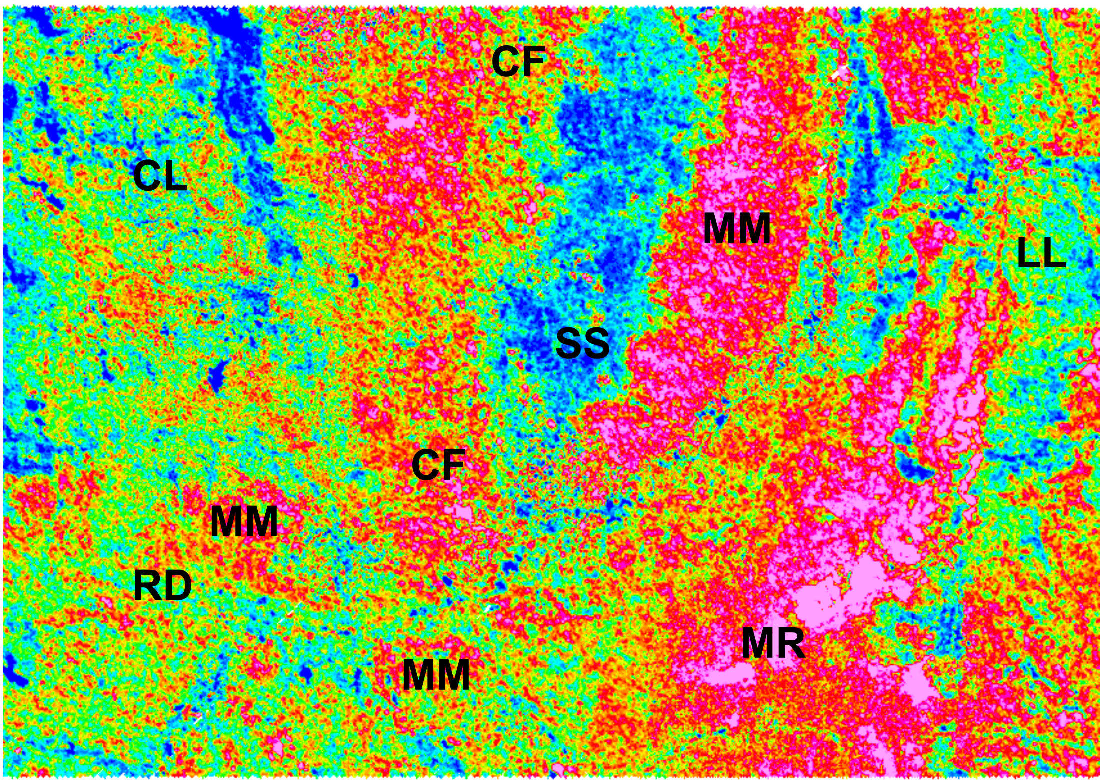


Figure 2-5. BGS HiRES Estimated thorium (eTh) airborne gamma spectrometry map (Colour scheme: High to Low - pink, red, orange, yellow, green, pale blue, dark blue; CL, MM, RD, SS, MR, LL see text) (Map area 100km by 70km)

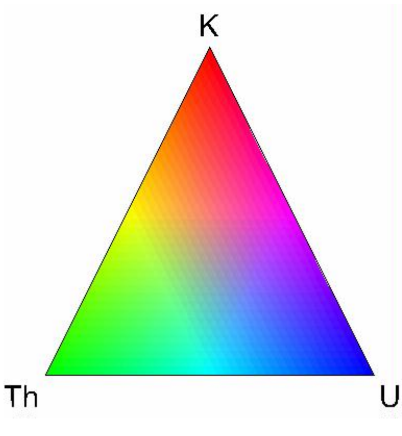


Figure 2-6. Colour chart for airborne gamma spectrometry three component (K= red, eTh = green, eU = blue) map (Figure 2-7).

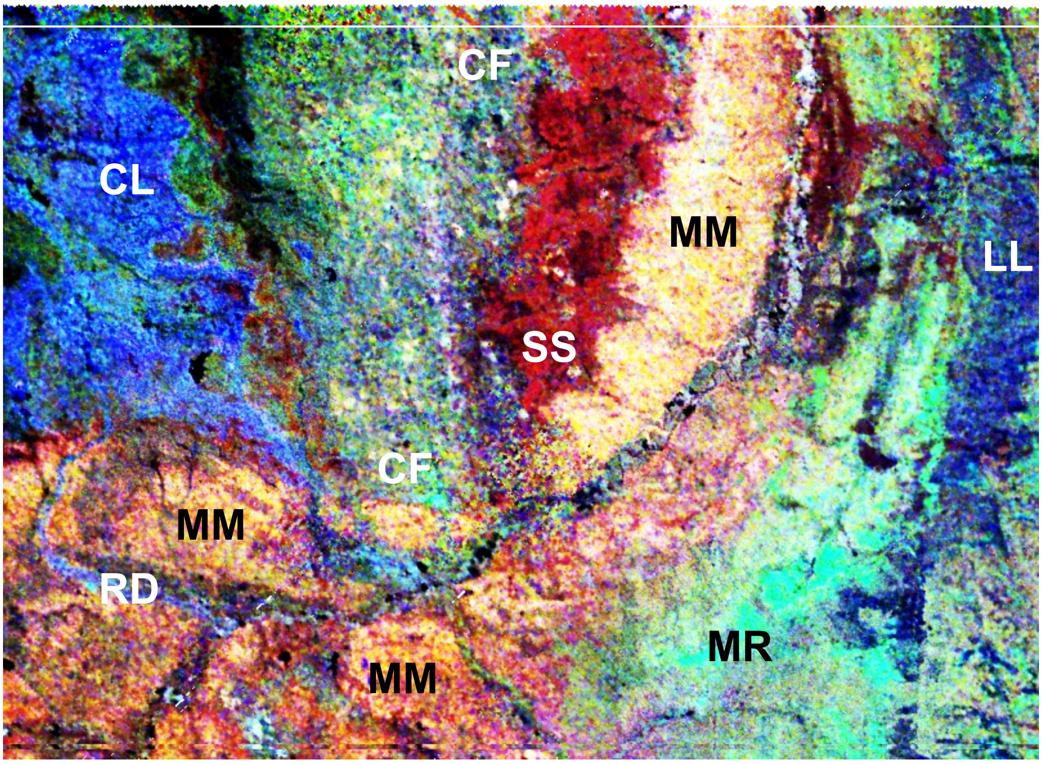


Figure 2-7. BGS HiRES airborne gamma spectrometry three component (K= red, eTh = green, eU = blue) map (white = K, eTh and eU all high; dark = K, eTh and eU all low;CL, MM, RD, SS, MR, LL see text) (Map area 100km by 70km)

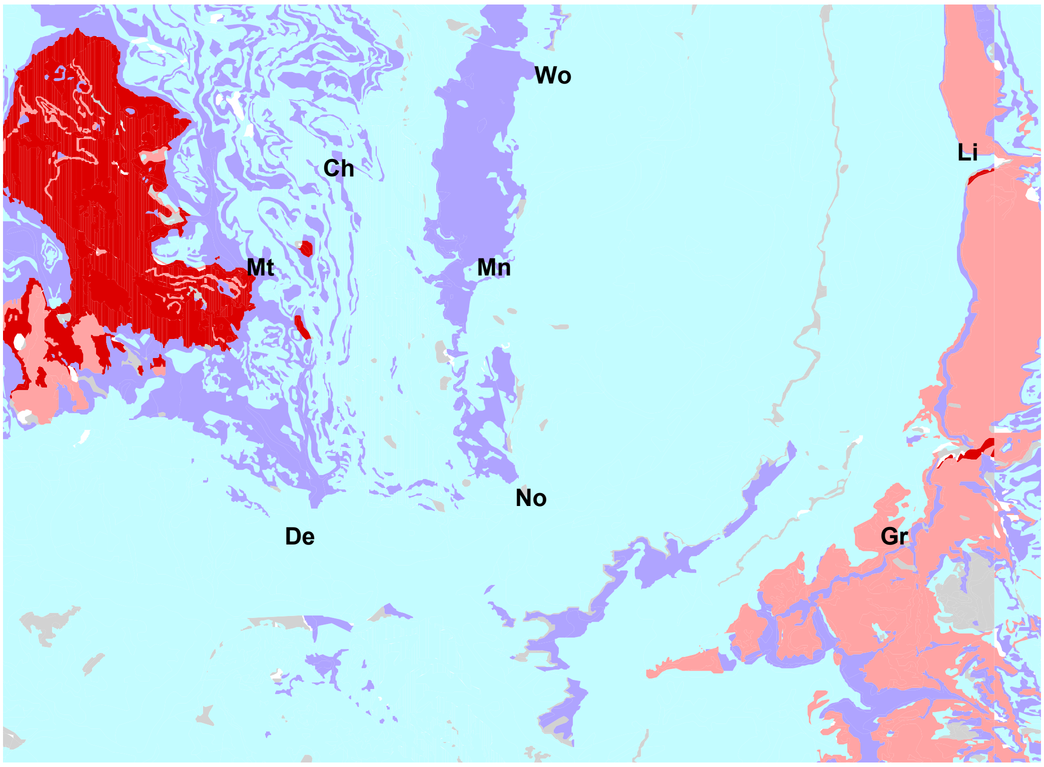


Figure 2-8. Simplified geological radon potential map for the area of Figures 2-3, 2-4, 2-5 and 2-7. (Grey = no data, Pale blue = estimated <3% dwellings exceed AL; Pale purple = estimated 3-10% dwellings exceed AL; Pink = estimated 10-30% dwellings exceed AL; Red = estimated >30% dwellings exceed AL) (Mt=Matlock, Ch=Chesterfield, Wo=Worksop, Mn=Mansfield, De=Derby, No=Nottingham, Li=Lincoln, Gr=Grantham) (Map area 100km by 70km)

Evaluation of radon potential mapping methods (Northamptonshire and Derbyshire)

2.33. In 1996, an evaluation of radon potential mapping in (i) three 1:50,000 scale geological map sheets (171, 185, 186) in Northamptonshire and (ii) the county of Derbyshire was carried out using NRPB temperature corrected house radon data normalised to a mix of houses typical of the UK housing stock (Miles et al.,1996, p.14; Miles 1998). The Royal Mail's PAF® data were used to assign OS National Grid geographical co-ordinates to dwellings at which a radon measurement had been made[2]. Attribution of geological data was carried out manually. The results of this study are summarised in the following paragraphs.

2.34. The evaluation revealed that there is strong contrast between the geological radon potential (GEORP[3]) for different geological units within individual map sheets and 5 km grid squares (Tables 2-1 to 2-3). Geological units have characteristic GEORPs which in general reflect their permeability, uranium content, weathering history and the influence of unconsolidated deposits overlying the bedrock. Relatively few geological units have GEORPs that exceed the threshold percentages designated for either basic (3% >AL) or full (10%>AL) radon protective measures in new dwellings. In Northamptonshire, the principal geological units that exceed the 3% threshold are the Northampton Sand Formation and the Lower Estuarine Series. Whereas this study indicated that in some areas the top section of the Upper Lias Clays has a GEORP greater than 3% (Table 2-1), subsequent studies have demonstrated that this is erroneous and caused by the poor spatial precision of the PAF geographical co-ordinates (Miles and Appleton, 2000). Whereas unconsolidated drift generally reduces the GEORP of these bed rock units, this effect is not totally consistent. In Derbyshire, the Carboniferous Limestones, Longstone Mudstone, Edale Shale and Lower Namurian Shale (below the first grit) have GEORPs greater than 3% (Table 2-2).

2.35. In some cases geological units within 5 km grid squares have GEORPs that exceed the threshold percentages designated for either basic (3% >AL) or full (10%>AL) radon protective measures in new dwellings even though the 5 km GRIDRP[4] is below the thresholds (Tables 2-2 and 2-3; Figures 2-9 to 2-12). In such cases, new development on these high GEORP geological units (large filled squares in Figures 2-9 to 2-12) would be underprotected if the requirement for protective measures was based on the 5 km GRIDRP, as in BR211 (as revised 1992).

2.36. Instances of underprotection were identified both in densely populated urban areas and rural areas. Important examples in urban areas (Table 2-2) include the Wellingborough grid squares (485265 and 490265), the eastern half of Northampton (475260), and also Kettering (485275). In Derbyshire, most instances of underprotection (Table 2-3) are associated with inliers of Carboniferous Limestone (Crich 430350, 435350) or grid squares in which the Carboniferous Limestone comprises a relatively small proportion of the grid square (e.g. 425360 which includes part of Matlock). Other examples, such as the Ashover inlier of Carboniferous Limestone (430360) are suspected, but these could not be confirmed during the current data evaluation as less than 10 house measurements are held by the NRPB for the limestone in this 5 km grid square[5]. Other cases of potential underprotection in Derbyshire (based on GEORP) mainly relate to small pockets of Lower Namurian shales.

---

[2] Recent research (Miles and Appleton, 2000) has demonstrated that the relatively poor spatial accuracy of the PAF data (100 metres) leads to incorrect attribution of geological data to a proportion of house radon measurements. This is likely to be a particular problem where dwellings are situated near geological boundaries and especially in areas of complex geology. Subsequent evaluations of radon potential have been carried out using Ordnance Survey (OS) Code-Point® (formerly Data-Point®) geographical co-ordinates which have a better spatial resolution (Miles and Appleton. 2000).

[3] GEORP = Estimated % of dwellings overlying a combination of bedrock and drift in a specific area (i.e. County, map sheet or 5 km grid square) which exceed the UK radon Action Level (AL) - predicted using lognormal modelling of indoor radon data (Miles, 1998)

[4] GRIDRP = Estimated % of dwellings in a 5-km or 1-km grid square which exceed the UK radon Action Level (AL) - predicted using lognormal modelling of indoor radon data (Miles, 1998)

[5] In order to maintain data confidentiality, grid square data evaluation was carried out only when there were 10 or more measurements for a specific bedrock-drift combination.

2.37. There are many examples of geological units that have GEORPs below the 3% or 10% thresholds in 5 km grid squares with GRIDRP's that exceed the respective threshold (Tables 2-2 to 2-3 and small filled circle in Figures 2-9 to 2-12). New dwellings constructed on these geological units would be overprotected unless relaxation of measures based on geology was permitted.

2.38. This evaluation was carried out before it was fully realised that normalising house radon data to a standard housing mix significantly reduced GRIDRP in rural areas (see paragraph 2.5 above and Figure 2-1). As much of Northamptonshire and Derbyshire are rural, the number of cases of underprotection is likely to be greater than that indicated in Figures 2-9 to 2-12 in which GRIDRP is estimated from temperature corrected radon data and GEORP from fully normalised radon data. If GRIDRP data had been fully normalised, many of the symbols in Figures 2-9 to 2-12 would move to the left, creating more cases of underprotection and fewer cases of overprotection.

2.39. Of the three radon potential mapping methods considered: (i) mapping GEORP within each 50,000 scale geological map; (ii) mapping GEORP within each 5 km grid square; and (iii) mapping GRIDRP by 5 km grid squares, the second of these methods requires a high measurement density to provide accurate results. Sufficient results[6] are required to estimate the radon potential for a geological unit covering part of a 5 km grid square in the case of GEORP. High measurement density is also required for mapping GRIDRP by 1 km grid squares (Miles and Appleton, 2000). In Northamptonshire, such high measurement densities are found only in the major urban centres.

2.40. Whereas the GEORP for a geological unit within a 5 km grid is likely to be reliable if there are many radon measurements, this may not be the case when there are few radon measurements. Use of the GEORP for a larger area, such as for a 1:50,000 geological map sheet should provide a more reliable estimate of the radon potential. Whereas there is clearly lateral variation in GEORP between 5 km grid squares and geological map sheets, there are relatively few instances where the use of the map sheet GEORP would result in under-protection of new dwellings. Instances of possible underprotection are indicated in **bold** in Tables 2-4 and 2-5. The first four instances of possible underprotection in Table 2-4 would not occur now because the current guidance (BRE, 1999) is based on GEORP estimates derived from temperature corrected radon data (see Miles and Appleton, 2000). The current map sheet GEORPs for the Great Oolite Limestone (Sheet 186), the Lower Estuarine Series (Sheet 186) and the Northampton Sand Formation (Sheet 185), based on temperature corrected radon data, are 3.5, 10.0 and 10.1% respectively compared with 1.8, 7.3 and 6.8% (Table 2-4) based on fully normalised radon data.

2.41. Lateral variation in GEORP between geological sheets and between adjacent 5 km grid squares for some geological units is thought to be caused principally by lateral variations in lithology. For example, the Northampton Sand Formation in the Northampton area comprises a lower ironstone, often with an uraniferous nodular horizon at the base, overlain by a massive yellow or brown calcareous sandstone (Variable Beds) which has a lower uranium concentration, less phosphate and lower permeability. The Variable Beds are largely missing from the Kettering and Wellingborough 1:50,000 scale geological map sheets, which may explain why the GEORP for the Northampton Sand Formation is higher in these areas compared with the Northampton sheet.

2.42. In both Northamptonshire and Derbyshire, individual 5 km grid squares frequently contain a mixture of low GEORP units (e.g. Upper Lias Clay with a GEORP ~2%) and high GEORP units (e.g. Northampton Sand Ironstone Formation with a GEORP ~14%). Similar features are shown on 50,000 scale geological maps of many areas underlain by sedimentary strata in England (e.g. Somerset, North Yorkshire). Thus where sufficient measurements are available, GEORP may be

[6] at least 30 radon measurements - see Miles and Appleton, 2000

used to define the requirement for protective measures in different sectors of individual 5 km grid squares and in some situations, even within 1 km grid squares.

2.43. It was concluded that in sedimentary geological terrains such as Northamptonshire and Derbyshire, geological radon potential mapping is the preferred method of mapping areas where radon protective measures should be installed in new dwellings. Geological radon potential mapping may require greater development effort than GRIDRP mapping and it relies on the availability of digital geological maps at an appropriate scale.

Table 2-1. Geological radon potential (GEORP) for a selection of geological units in geological map sheets 171, 185 and 186, Northamptonshire (*based on NRPB normalised house radon data, 1996; n>100*).

Bedrock*	**Drift***	**Map Sheet**		
		171	**185**	**186**
Great Oolite Limestone	Glacial till	**	0.1	0.2
Great Oolite Limestone	No drift	0.3	0.4	1.8
Upper Estuarine Series	Glacial till	**	0.0	0.1
Upper Estuarine Series	No drift	0.5	0.3	1.2
Lower Estuarine Series	No drift	3.1	1.6	7.3
Northampton Sand Formation	Ironstone workings	1.0	3.2	21.6
Northampton Sand Formation	No drift	11.6	6.8	16.4
Top section of Upper Lias Clay	No drift	2.5	13.4	2.9
Upper Lias Clay	No drift	2.8	0.9	0.7

* Stratigraphic units from BGS 1:50,000 Sheets 171, 185, 186
** = less than 100 radon measurements

Table 2-2. Geological radon potential (GEORP) for geological units within a selection of the 5 km grid squares in Northamptonshire (*based on NRPB normalised house radon data, 1996; n>100*).

Bedrock Geology*	**Drift**	**No. of radon measurements in 5-km grid square**	**5-km grid GEORP**	**1:50K map GEORP**
Kettering (485 275; GRIDRP = 9.2%)				
Great Oolite Limestone	No drift	428	1.0	0.3
Upper Estuarine Series	No drift	175	0.5	0.1
Lower Estuarine Series	No drift	230	1.9	3.1
Northampton Sand Formation	No drift	1552	13.6	11.6
Top Upper Lias Clay	No drift	210	2.9	2.5
Upper Lias Clay	No drift	330	2.0	2.8
Wellingborough (490 265; GRIDRP = 5.2%)				
Great Oolite Limestone	Glacial till	111	0.1	0.2
Great Oolite Limestone	No drift	689	1.1	1.8
Northampton Sand with Ironstone	No drift	191	27.9	16.4
Upper Estuarine Series	No drift	222	1.4	1.2
Top section of Upper Lias Clay	No drift	212	2.3	2.9
Upper Lias Clay	Alluvium	115	0.7	0.5
Wellingborough (485 265; GRIDRP = 3.9%)				
Great Oolite Limestone	Glacial till	1480	0.1	0.2
Great Oolite Limestone	No drift	510	0.4	1.8
Lower Estuarine Series	Glacial till	439	1.3	1.8
Lower Estuarine Series	No drift	371	3.9	7.3
Northampton Sand Formation	Ironstone workings	340	23.6	21.6
Northampton Sand Formation	No drift	2007	11.8	16.4
Upper Estuarine Series	No drift	755	0.3	1.2
Upper Estuarine Series Clay	No drift	158	0.1	0.0
Upper section of Upper Lias Clay	No drift	551	0.9	0.8
Northampton (475 260; GRIDRP = 1.4%)				
Great Oolite Limestone	No drift	982	0.1	0.4
Lower Estuarine Series	No drift	879	1.5	1.6
Northampton Sand Formation	No drift	5545	4.3	6.8
Upper Estuarine Series	Glacial till	218	0.0	0.0
Upper Estuarine Series	No drift	2147	0.2	0.3
Upper section of Upper Lias Clay	No drift	468	0.5	0.8
Upper Lias Clay	1st Terrace	183	0.0	0.1
Upper Lias Clay	No drift	520	0.5	0.9
Finedon (490 270; GRIDRP = 10.0%)				
Great Oolite Limestone	Glacial till	269	0.3	0.2
Great Oolite Limestone	No drift	271	1.2	1.8
Northampton Sand Formation	No drift	391	22.2	16.4
Upper Estuarine Series	No drift	134	3.4	1.2

* Stratigraphic units from BGS 1:50,000 Sheets 171, 185, 186

Table 2-3. Geological radon potential (GEORP) for geological units within a selection of the 5 km grid squares in Derbyshire (based on NRPB normalised house radon data, 1996; n>50 except Crich).

Bedrock Geology*	Drift	No. of radon measurements in 5-km grid square	5-km grid GEORP	Derby-shire GEORP
Buxton (405 370; GRIDRP=26.4%)				
Bee Low Limestone	No drift	680	23.2	20.2
Eyam Limestone	No drift	77	40.6	27.1
Lower Namurian Shale	No drift	205	3.4	4.3
Monsal Dale Limestones	No drift	147	32.3	28.6
Hope (415 380; GRIDRP=21.8%)				
Edale Shale	No drift	53	24.0	15.6
Edale Shale	Head	167	11.7	10.4
Monsal Dale Dark Limestones	No drift	78	24.7	25.1
Youlgreave (420 360; GRIDRP=23.6%)				
Eyam Limestone	No drift	124	29.4	27.1
Longstone Mudstone	No drift	76	11.6	20.0
Monsal Dale Dolomite	No drift	69	12.0	12.0
Monsal Dale Limestones	No drift	100	29.9	28.6
Bakewell (420 365; GRIDRP=18.7%)				
Eyam Limestone	No drift	58	19.7	27.1
Lower Namurian Shale	Alluvium	56	21.8	9.0
Lower Namurian Shale	No drift	111	7.9	4.3
Edale (420 375; GRIDRP=19.8%)				
Edale Shale	No drift	60	24.0	15.6
Kinderscout Grit	No drift	83	3.9	2.1
Eyam (Knoll Reef) Limestone	No drift	111	35.3	34.3
Matlock (425 360; GRIDRP=3.7%)				
Eyam Limestone	No drift	66	25.7	27.1
Lower Namurian Shale	Head	166	0.1	1.6
Lower Namurian Shale	No drift	490	1.2	4.3
Crich (430 350; GRIDRP = 2.9%)				
Ashover Grit	No drift	60	1.1	2.0
Eyam Limestone	No drift	10	36.4	27.1
Middle Namurian Shale	No drift	59	0.1	1.1
Crich (435 350; GRIDRP = 3.5%)				
Ashover Grit	No drift	57	0.8	2.0
Eyam Limestone	No drift	10	39.5	27.1
Lower Coal Measures	No drift	127	1.7	0.5
Lower Namurian Shale	No drift	46	0.4	4.3
Middle Coal Measures	No drift	146	0.1	0.2

* Stratigraphic units from BGS 1:50,000 Maps

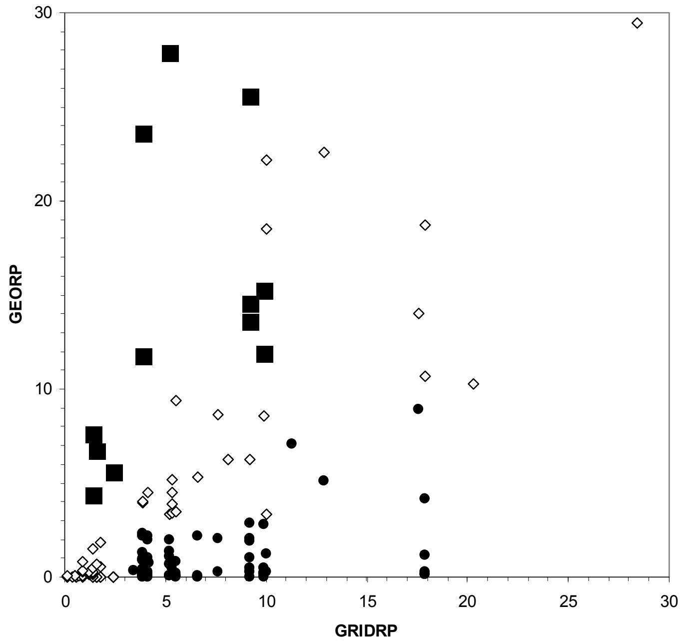


Figure 2-9. Under protection (large filled square) and over protection (small filled circle) of dwellings sited on geological units in Northamptonshire that would occur if the 5 km GRIDRP were used to indicate the level of protection required (small open diamond = dwellings on geological unit correctly protected on basis of GRIDRP; GEORP estimates for geological units in individual 5 km grid squares based on 30 or more radon measurements)

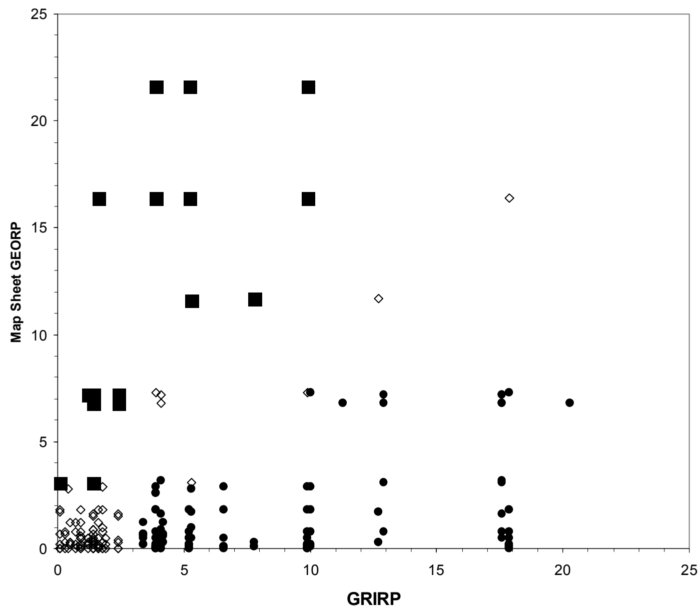


Figure 2-10. Under protection (large filled square) and over protection (small filled circle) of dwellings sited on geological units in three 1:50,000 scale geological map sheets in Northamptonshire that would occur if the 5 km GRIDRP were used to indicate the level of protection required (small open diamond = dwellings on geological unit correctly protected on basis of GRIDRP; GEORP estimates for geological units in individual map sheets based on 30 or more radon measurements)

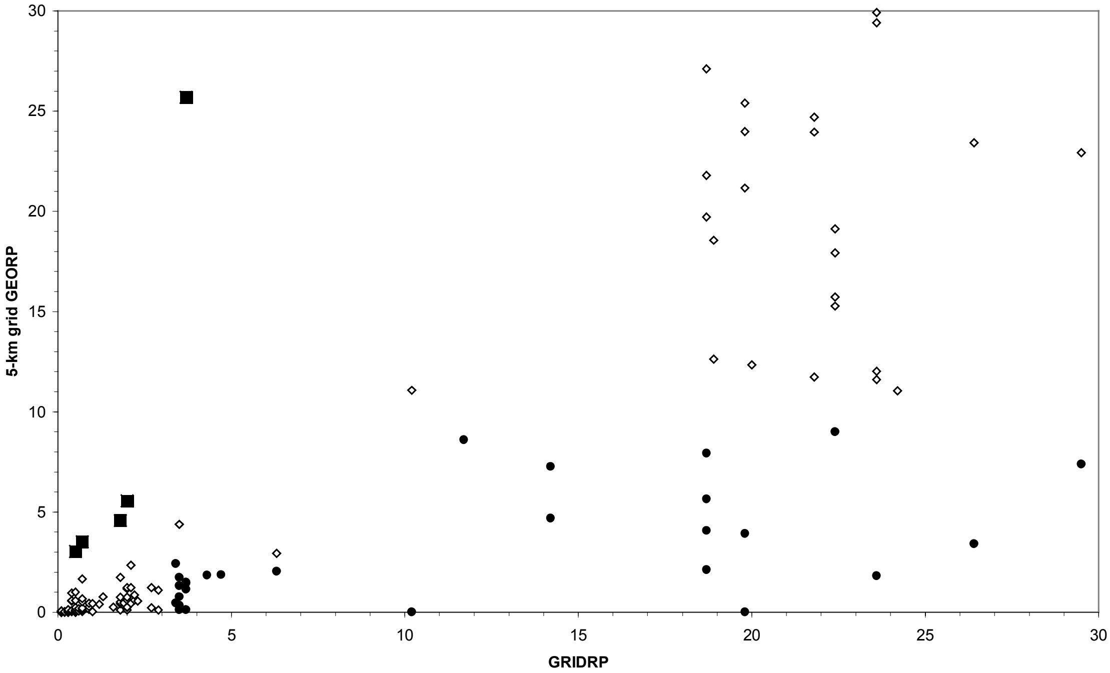


Figure 2-11. Under protection (large filled square) and over protection (small filled circle) of dwellings sited on geological units in Derbyshire that would occur if the 5 km GRIDRP were used to indicate the level of protection required (small open diamond = dwellings on geological unit correctly protected on basis of GRIDRP; GEORP estimates for geological units in individual 5 km grid squares based on 30 or more radon measurements)

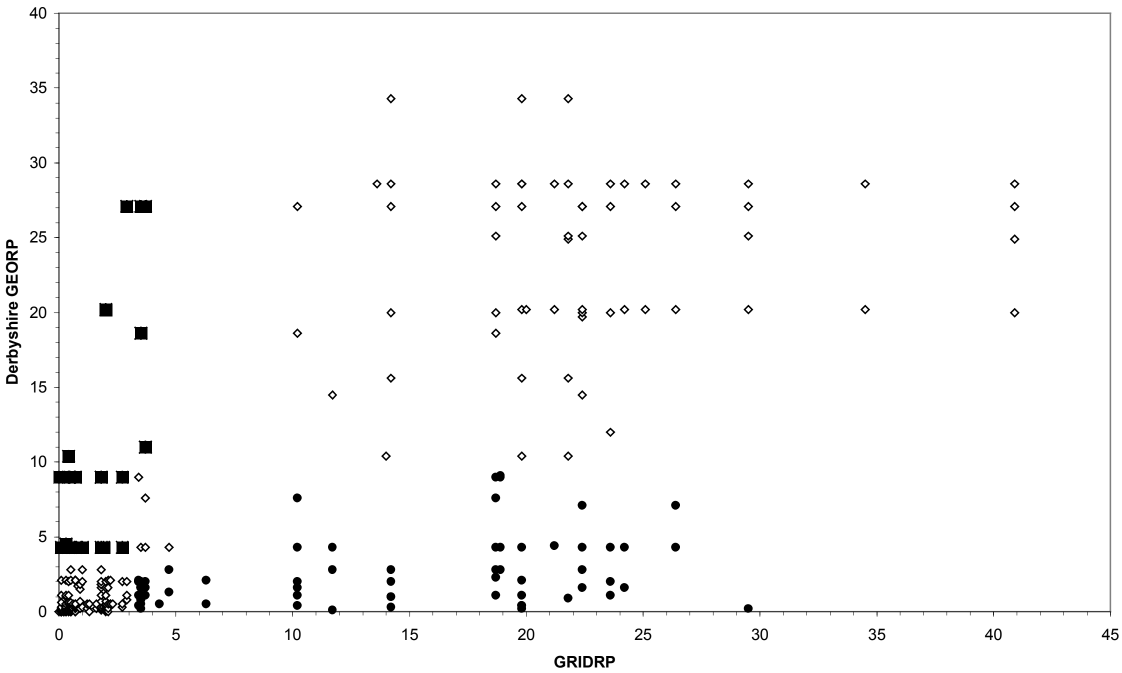


Figure 2-12. Under protection (large filled square) and over protection (small filled circle) of dwellings sited on geological units in Derbyshire that would occur if the 5 km GRIDRP were used to indicate the level of protection required (small open diamond = dwellings on geological unit correctly protected on basis of GRIDRP; GEORP estimates for geological units in Derbyshire based on 30 or more radon measurements)

Table 2-4. Lateral variation in geological radon potential (GEORP) based on estimates for individual 5 km grid squares in Northamptonshire (*based on NRPB normalised house radon data, 1996; ≥ 100 radon measurements*).

Bedrock	Drift	5-km GEORP	Sheet GEORP	Sheet No.	No. radon measurements
Great Oolite Lst.	glacial till	0.0	0.1	185	628
		0.1	0.2	186	1480
		0.1	0.2	186	111
		0.3	0.2	186	269
		0.0	0.2	186	264
Great Oolite Lst.	no drift	0.2	0.3	171	171
		0.3	0.4	185	450
		0.1	0.4	185	982
		0.0	0.4	185	132
		0.4	1.8	186	510
		1.8	1.8	186	382
		1.1	1.8	186	689
		1.2	1.8	186	271
		0.7	1.8	186	374
		5.3	1.8	186	233
Lower Estuarine Series	no drift	0.8	1.6	185	435
		1.5	1.6	185	879
		11.9	7.3	186	210
		3.9	7.3	186	371
Northampton Sand Fm.	ironstone workings	0.5	1.0	171	107
		23.6	21.6	186	340
Northampton Sand Fm.	no drift	3.4	11.6	171	133
		4.5	6.8	185	3311
		10.3	6.8	185	137
		14.0	6.8	185	297
		4.3	6.8	185	5545
		5.6	6.8	185	251
		15.2	16.4	186	502
		11.8	16.4	186	2007
		18.7	16.4	186	773
		27.9	16.4	186	191
		22.2	16.4	186	391
U. Estuarine Series	glacial till	0.0	0.0	185	190
		0.0	0.0	185	218
		0.0	0.0	185	259
U. Estuarine Series	no drift	0.2	0.3	185	877
		0.2	0.3	185	2147
		0.3	0.1	186	755
		1.4	0.1	186	222
		3.4	0.1	186	134
Upper section of U. Lias Clay	no drift	0.5	0.8	186	184
		0.9	0.8	186	551

Table 2-5. Lateral variation in geological radon potential (GEORP) based on estimates for individual 5 km grid squares in Derbyshire (*based on NRPB normalised house radon data, 1996; >50 radon measurements except Grit and Limestone ≥ 60 measurements*).

Bedrock	Drift	5 km GEORP	Derbyshire GEORP	No. of radon measurements
Ashover Grit	No drift	1.1	2.0	60
		0.5		72
		0.8		130
		4.4		140
Bee Low Limestone	No drift	21.2	20.2	69
		12.3		85
		23.4		680
Eyam Limestone	No drift	19.7	27.1	58
		25.7		66
		40.6		77
		29.4		124
		17.9		183
Lower Coal Measures	No drift	0.8	0.5	102
		1.7		127
		0.4		130
		0.1		169
		0.1		188
		1.9		189
		3.0		197
		0.9		211
		0.1		351
		0.1		352
		0.3		411
Lower Namurian Shale	No drift	7.9	4.3	111
		3.4		205
		8.6		389
		1.2		490
Mercia Mudstone Group	No drift	0.0	0.0	137
		0.1		202
		0.0		558
		0.0		749
		0.0		979
Middle Coal Measures	No drift	0.1	0.2	146
		0.1		155
		0.1		207
		0.1		243
		0.1		348
		0.1		348
		0.1		407
		0.4		523
Monsal Dale Limestones	No drift	27.1	28.6	76
		29.9		100
		32.3		147
		22.9		187

Evaluation of radon potential mapping methods (Cornwall and Devon)

Introduction

2.44. Miles (in press) developed a method to make use of high house radon measurement densities where they are available. The method is based on mapping at 1 km grid square resolution - the map has high resolution where there are many results and is smoothed where few data are available. Miles (in press) observed that the 1 km grid map correlates well with identifiable geological features.

2.45. Under the current research contract, a geological evaluation was carried out in 1997 of house radon measurements located within the BGS 1:50,000 scale Geological Sheets 325, 335/336, 337, and 338 covering parts of Cornwall and Devon (Figure 2-13). Radon potential mapping methods need to be effective in a range of geological environments so the principal aim of the study was to ascertain whether the conclusions based on the testing of radon potential mapping options in Northamptonshire and Derbyshire are also applicable to the geologically distinctive radon affected areas of Cornwall and Devon.

2.46. Log-normal modelling of fully standardised house radon data was used to determine radon potential (Estimated % of dwellings exceeding the radon Action Level) for geological units within the BGS 1:50,000 scale geological map sheets 325, 335/336, 337, and 338, and also within individual 5 km grid squares in these map sheets. OS National Grid geographical co-ordinates were assigned to dwellings at which a radon measurement had been made using the Royal Mail's PAF® data. Attribution of geological data was carried out digitally. Recent research (Miles and Appleton, 2000) has demonstrated that the relatively poor spatial accuracy of the PAF data (100 metres) leads to incorrect attribution of geological data to a proportion of house radon measurements. This is likely to be a particular problem where dwellings are situated near geological boundaries and especially in areas of complex geology. In order to preserve confidentiality undertakings to the DETR and householders, radon data were provided to the BGS only where there were at least 10 measurements for a specific geological unit in a map sheet or 5 km grid square. House radon data were corrected for outdoor levels, temperature and standardised to a 3 bedroom semi-detached house so that differences in radon potential between geological units and 5 km grid squares are not distorted by these factors. Log-normal modelling was also used to produce a trial 1 km grid square radon potential map based on standardised house radon data with the estimated proportion of dwellings above the Action Level derived from grid square geometric means using a geometric standard deviation of 2.5 (Miles, in press). These maps were then compared with the radon potential (GEORP) for geological units. The reliability of the estimated radon potential, both for geological units (GEORP) and 5 km grid squares (GRIDRP), increases with the number of house measurements. Estimates based on <30 measurements should be treated with considerable caution (Miles & Appleton, 2000).

Geology, geochemistry and uranium mineralogy of south-west England [7]

2.47. A granite batholith intrudes folded and faulted Devonian and Carboniferous sedimentary rocks which are dominantly argillaceous and arenaceous with minor volcanic rocks and limestones (Figure 2-13: letters on map refer to geological units mentioned in the below; see also Table 2-6). There is a transition in the Devonian sequence from flysch type sediments in the west to deeper water mudstones interbedded with volcanics and limestone lenses in the east and a thick shallow water marine shale-siltstone-sandstone sequence of the Gramscatho Group (DG) and Mylor Slate Formation (DMs) in the south. The Lower Devonian (LD) comprises mainly sandstones of the Meadfoot Group and argillaceous rocks of the Dartmouth Group, whilst the Middle Devonian (MD)

[7] summary from Ball and Miles (1993)

is mainly slates, followed further north by a predominantly argillaceous sequence of Upper Devonian and Lower Carboniferous rocks (DC). The lower part of the Carboniferous sequence (Tournasian and Visean; LC) comprises dark grey to black shales and slates with sandstones, basic volcanic rocks (narrow, purple coloured bands on Figure 2-13), lenticular limestones and cherts. The Upper Carboniferous is represented by the sandstones and mudstones of the Crackington Formation (CF) overlain by the thick, massive sandstones, siltstones and mudstones of the Bude and Bideford Formation (BB). Permo-Triassic red-bed sediments (comprising sandstones and breccias of the Exeter Group (PE) and argillaceous rocks of the Aylesbeare Mudstone Group, TA) were deposited upon eroded land surfaces following a period of folding, faulting and tectonic uplift.

2.48. Present day granite outcrops (bmG = Bodmin Moor Granite, dG = Dartmoor Granite, saG = St Austell Granite, cG = Carnmenellis Granite, leG = Land's End Granite) reveal only the uppermost few hundred metres of the intrusion. The granitic rocks are uraniferous with concentrations ranging from 6-25 mg/kg although higher values occur rarely. There are extensive areas of alteration within the granites; tourmalinisation, greisening, haematitisation, and kaolinisation all affect substantial volumes of rock. Of these, kaolinisation is the most important because it was very widespread and usually resulted in a substantial decrease in the uranium concentration. The greatest proportion of the uranium in the granites occurs in the mineral uraninite, which is often weathered near the surface. The uraninite is pseudomorphed by aggregates of a variety of mineral phases including plumbogummite, clay minerals and secondary iron oxides. Much of the uranium is removed by weathering but a large part of the radium remains in the relict minerals and, because of the greater specific surface area, these minerals in the weathered rock become more efficient radon generators than expected from the remnant uranium.

2.49. Uranium mineralisation has been known in the area for at least a century and the minerals were mined, originally for glass colouring, before reworking of some deposits for their radium content. Two types of uranium occurrence are recognised: (a) within high temperature tin/tungsten/copper lodes and (b) in later "crosscourses". Most of the known uranium vein mineralisation occurs within about 2 km either side of the granite contact. Uranium mineralisation ranges from small, high-grade, to more disseminated occurrences. In south Devon small uraniferous mineral occurrences near Start Point and the uraniferous/vanadiniferous nodules in the Permo-Trias are not related to the granite contact.

2.50. Uranium concentrations in Devonian rocks range from <1 to 11 mg/kg with mean concentrations of 1.3 to 5.7 mg/kg. Higher concentrations of 5-21 mg/kg have been recorded for the Visean Meldon Chert Formation and high total gamma has been recorded over Lower Carboniferous black shales to the north of the Dartmoor Granite (BGS, unpublished data).

2.51. The granites are surrounded by a zone in which uranium in stream sediments is high (orange brown to brown colour in Figure 2-14 is generally 3-30 mg/kg U, with a maximum of 2077 mg/kg). Uranium is also high in the stream waters and sediments derived from the Permo-Triassic rocks to the east of the Dartmoor Granite. The area, corresponding to the suboutcrop of the Littleham Mudstone Formation (part of the Aylesbeare Mudstone Group, TA) gives high values for uranium related to extensive zones of uranium/vanadium mineralisation.

Table 2-6. Simplified geological sequence for the area covered by 1:50,000 map sheets 325, and 335 to 338.

Age	**Lithology**	**1:50,000 map units *(units in italics also used on the 1:250,000 maps)***
Triassic - U. Permian	mudstone and sandstone	*Aylesbeare Group,* Littleham Mudstone
L. Permian	sandstone	Thorverton Sandstone.
L. Permian	breccia	Alphington and Heavitree Breccias
U. Carboniferous (Westphalian)	sandstone and shale	*Bude Formation*
U Carboniferous (Namurian)	dark shales and turbiditic sandstones	*Crackington Formation*
L. Carboniferous (Dinantian; Visean + Tournasian)	dark & black shale, chert, limestone, sandstone.	Lydford Fm, Meldon Chert Fm, Brendon Fm, Meldon Shale, Brendon Formation, Cotehele Sandstone. Fm., Greystone Fm.
L. Carboniferous (Dinantian; Visean + Tournasian)	basaltic lavas	Meldon Volcanics; Milton Abbot Fm., Tintagel Volcanic Fm
L. Carboniferous - U. Devonian (L. Tournasian, Famenian and Frasnian)	slates, black shales with thin sandstones and limestones.	Kate Brook Slate, Tredorn Slate Fm, Woolgarden Slate Fm. Trevose Slate Fm. Gurrington Slate
U. and Middle Devonian	limestones	Chercombe Bridge Limestone
Middle Devonian	slates with thin limestones	Bedruthan Fm
Lower Devonian (Emsian)	slates, siltstones, massive sandstone and few limestones.	*Staddon Grit Fm*
Dolerite	dolerite	
Granite	granite and microgranite	

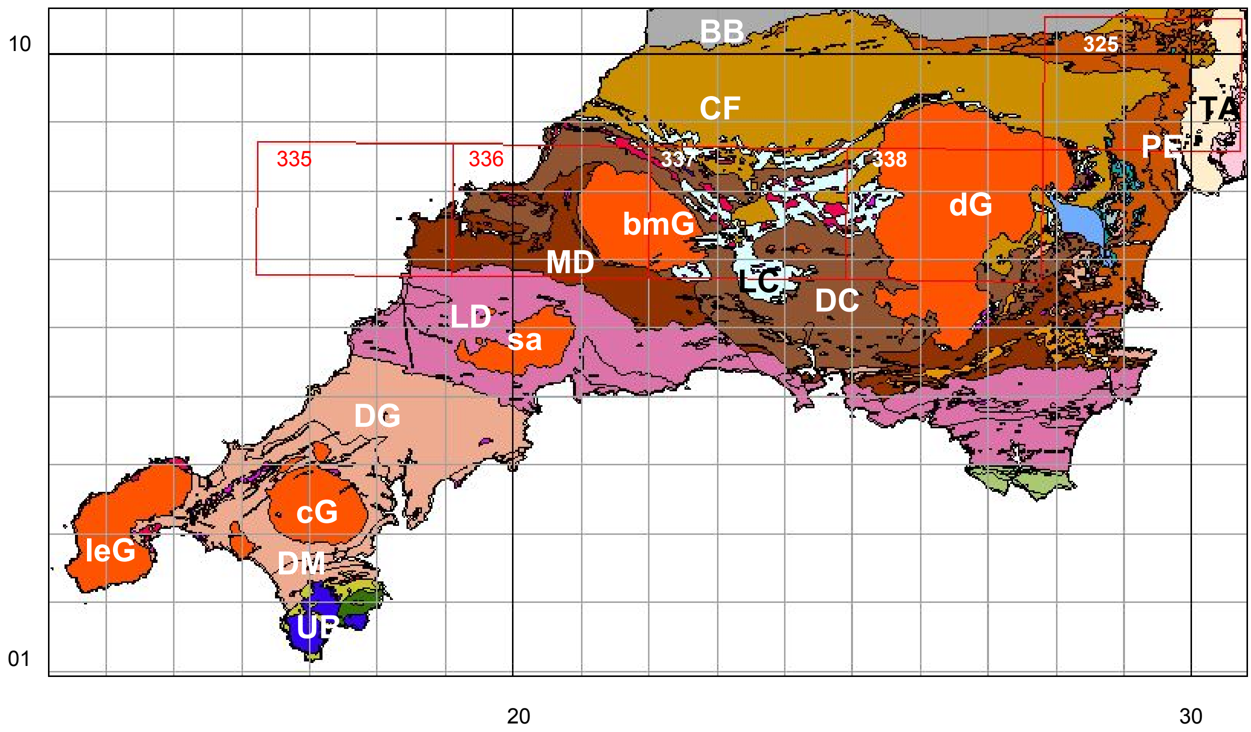


Figure 2-13. Simplified bedrock geological map of south west England derived from BGS 1:250,000 lithostratigraphic data; see text for explanation)

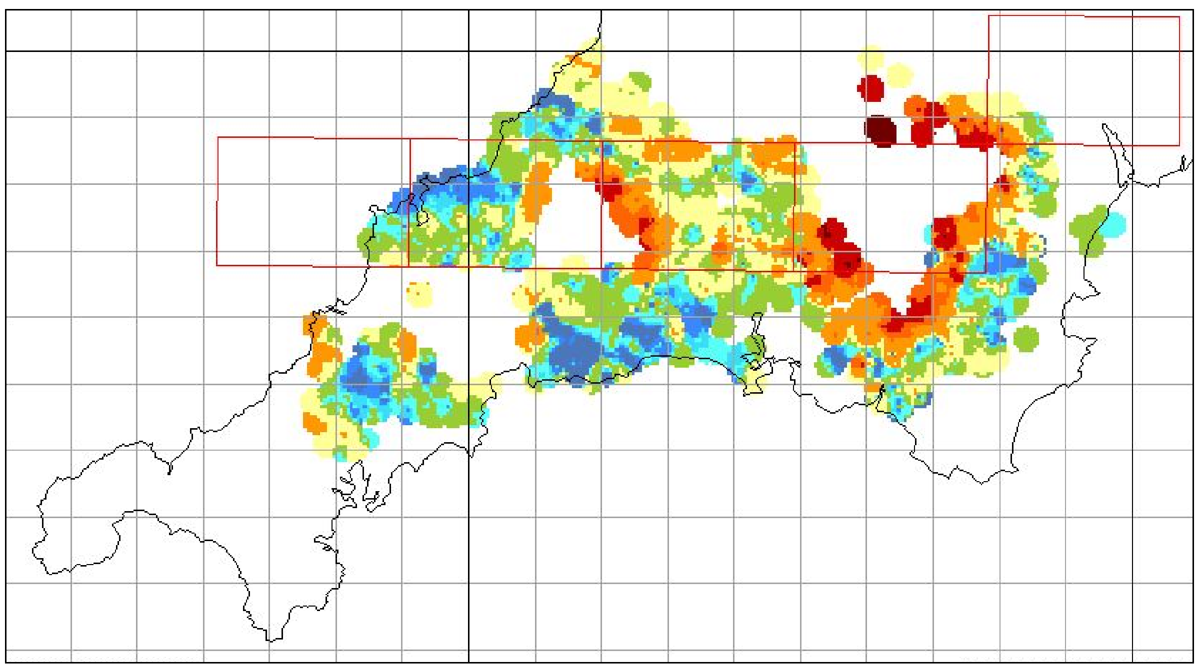


Figure 2-14. Uranium geochemical map of south west England (BGS unpublished in stream sediment data; blue = low; brown = high; see text for explanation)

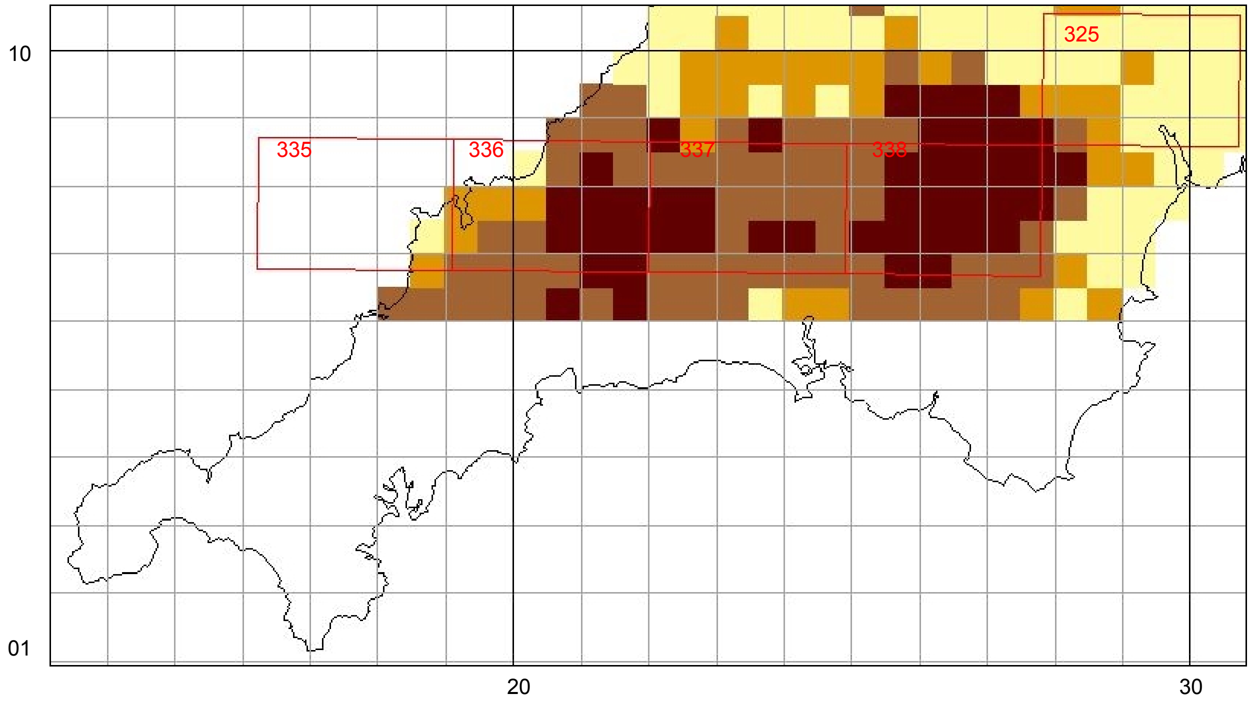


Figure 2-15. 5-km grid radon potential (GRIDRP) map of the south west England study area (boundaries of 1:50,000 geological map sheets indicated in red; GRIDRP classes: yellow = <3%, pale brown = 3-10%, medium brown = 10-30%, dark brown = >30%>AL)

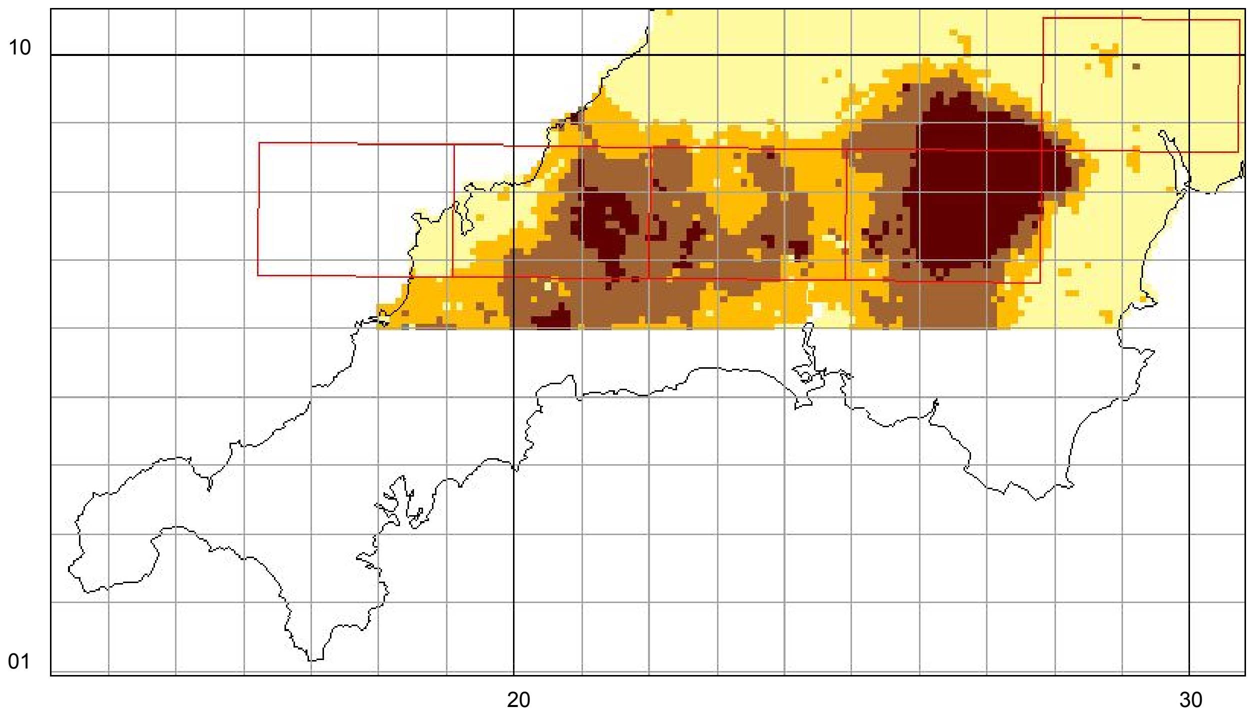


Figure 2-16. 1-km grid radon potential (GRIDRP) map of the south west England study area (boundaries of 1:50,000 geological map sheets indicated in red; GRIDRP classes: yellow = <3%, pale brown = 3-10%, medium brown = 10-30%, dark brown = >30%>AL)

Relationship between 5 km GRIDRP, 1 km GRIDRP, geology and stream sediment geochemistry

2.52. On **Sheet 325**, comparison of the 5 km and 1 km GRIDRP maps (Figures 2-15 & 2-16) with the 250,000 scale geology map (Figure 2-13) shows that the >30% (dark brown) and 10-30% (medium brown) zones have a very restricted extent and are closely associated with the outcrop of the Dartmoor Granite and the U mineralised zone of the granite aureole. Some subtle differences exist between the 5 km and 1 km GRIDRP maps. For example, 5 km grid square 285090 is classified as 3-10% on the 5 km GRIDRP map whereas on the 1 km GRIDRP map most of the 25 km^2 is classified as <1%. High uranium concentrations occur in geochemical samples related to sub-zones within the Permo-Triassic Littleham Mudstone, part of the Aylesbeare Mudstone Group (Figure 2-13, Table 2-7; BGS unpublished data). However, the proportion of houses above the action level is only about 1%, probably because the mudstones are relatively impermeable and the radon flux into dwellings is low despite the high U, radium and radon content of the rocks.

2.53. The sector of the 5 km GRIDRP map covering **Sheet 335/336** shows that the >30% grid squares (dark brown) approximate to the outline of the Bodmin Moor Granite (bmG) with a surrounding zone, generally one grid square wide, of 10-30% declining to 3-10% for most of the remainder of the map sheet. The >30% zone of the 1 km GRIDRP map is associated with the central part of the Bodmin Moor Granite with 10-30% characterising the margin of the Granite and the uranium mineralised zone of the contact aureole (Ball and Miles, 1993). Moving west away from the granite contact, GRIDRP decreases rapidly through 3-10% to a 1-3% zone (not shown on Figure 2-16) which characterises most of the coastal strip.

2.54. The sector of the 5 km GRIDRP map covering **Sheet 337** shows that the Bodmin Moor Granite and small bosses of granite in the Gunnislake area (Figures 2-13 and 2-15) have a GRIDRP of >30% surrounded by a 10-30% zone associated with Devonian and Carboniferous sedimentary and volcanic envelope to the granite. The 1 km GRIDRP map (Figure 2-16) shows that the eastern sector of the Bodmin Moor granite is generally 10-30% with small patches of >30%. Small granite bosses in the Gunnislake area have GEORPs exceeding 30%. Most of the granite aureole and the zone of higher U concentrations in stream sediments (Ball and Miles, 1993; and Figure 2-14) is 10-30%>AL with the remainder of the map sheet being 3-10%. The 1 km GRIDRP map (Figure 2-16) has a distinct belt with 10-30% >AL running NNW along a line from Gunnislake, E of the Tamar valley to the northern boundary of the map, just to the east of Launceston. This zone is traversed by many NNW to NW trending faults and underlain in part by Lower Carboniferous dark and black shales, which would be expected to have relatively high U concentrations. The NNW fault set in this area is known to have late uranium mineralisation and this, together with the enhanced gas flux along fault and fracture zones (Gregory et al., 1986), might explain why this zone is characterised by relatively high radon in dwellings. However, the lack of a corresponding stream sediment uranium anomaly (Figure 2-14) contradicts this interpretation. Lower GRIDRP (3-10%) occurs to the west and east of this NNW trending high (10-30%). As expected, the 1 km GRIDRP map shows a more precise relationship to geology than the 5 km grid map, and some features, such as the NNW trending belt of 10-30% to the east of the Tamar river, only appear on the 1 km GRIDRP map.

2.55. The sector of the 5 km GRIDRP map covering **Sheet 338** (Figure 2-15) shows that granite is >30%>AL whereas the Devonian and Carboniferous sedimentary and volcanic envelope to the granite is 10-30%>AL. The 30%>AL threshold boundary on the 5 km GRIDRP map shows a relatively poor spatial correlation with the geological boundaries (Figures 2-13 and 2-15). As would be expected the 1 km GRIDRP map (Figure 2-16) shows a much closer spatial agreement with the geological map. The granite and its immediate aureole in the SE has a GRIDRP of >30%, whereas some of the western sector of the granite is 10-30%>AL with isolated highs of >30% in the SW sector. In the SE corner of the 1 km GRIDRP map, GRIDRP decreases rapidly through 10-30%

over the Crackington Formation (CF) and the U. Devonian (Kate Brook Slate) to 3-10% over the Lower Tournasian (Gurrington Slate) and Middle Devonian (Chercombe Bridge Limestone). In the west of the map, the 10-30% belt is wider and the 3-10% belt covers a range of lithological units outside the granite aureole.

2.56. In summary, there is a close correspondence between areas where more than 30% of the house radon levels are above the 200 Bq m^{-3} Action Level, and the outcrop of granite. The granites are characterised by high uranium concentrations, a deep weathering profile, and uranium in a mineral phase that is easily weathered. However, whereas uranium may be removed, the radium can remain *in situ*. Radon is thus easily emanated from the host rock and high values of radon have been detected in ground and surface waters and soil gases. One of the zones where 10-30% of houses exceed the Action Level surrounds the >30% contour and is broadly coincident with rocks in which sub-economic grade uranium mineralisation is common. This usually occurs as small discrete high-grade veins but there are also numerous disseminated uranium occurrences. This area is underlain by microgranitic intrusions and small granite plugs which also contribute to the overall moderate to high levels of radon. This zone is also characterised by high values of uranium in stream sediments (Figure 2-14).

2.57. The approximate areas assigned to GRIDRP classes on the 5 km and 1 km GRIDRP maps covering geological maps sheets 336 and 337 are very different (Table 2-7). If the threshold for full measures (10%) and the 5 km GRIDRP map was used to define the need for the installation of protective measures, then full measures would be required for 840 km^2 (76% of the total area) on these two map sheets. If the 1 km GRIDRP map is closer to the "truth" (and the GEORP data suggests that this is the case) then full measures would be required only on 485 km^2 (44% of the two map sheets).

2.58. The difference between the 1 km GRIDRP map and the 5 km GRIDRP map cannot be an artefact of smoothing, as there is virtually no smoothing in Cornwall and Devon apart from interpolation into the uninhabited parts of Dartmoor. There is more than sufficient house radon data in these counties for smoothing to be necessary. Apart from the effects of the different data sets used to compile the two maps (5 km map based on data available in 1995; 1 km map based on data available in 1996), it is suggested that averaging within a 5 km grid square is one of the main reasons for the difference in areas covered on the 1 km and 5 km GRIDRP maps. For example, in a 5 km grid square with several geological units of strongly contrasting GEORP, such as 5 km grid square 250070 (Figure 2-17), of which 6 km^2 is underlain by Granite with GEORP = 43% and 15 km^2 is underlain by the Kate Brook Slate Formation with GEORP = 12%, the GRIDRP is high (30%) because of the influence of the very high radon measurements associated with the dwellings sited on Granite. Another major contributory factor is likely to be the corrections applied to the radon measurements used to produce the 5 km and 1 km grid maps. The 5 km grid map is based on temperature corrected data (Lomas et al., 1996) whereas the 1 km map is based on a fully normalised data set. In general, fully normalised radon data are significantly lower than temperature corrected data (see para. 2.5 and Figure 2-1, above).

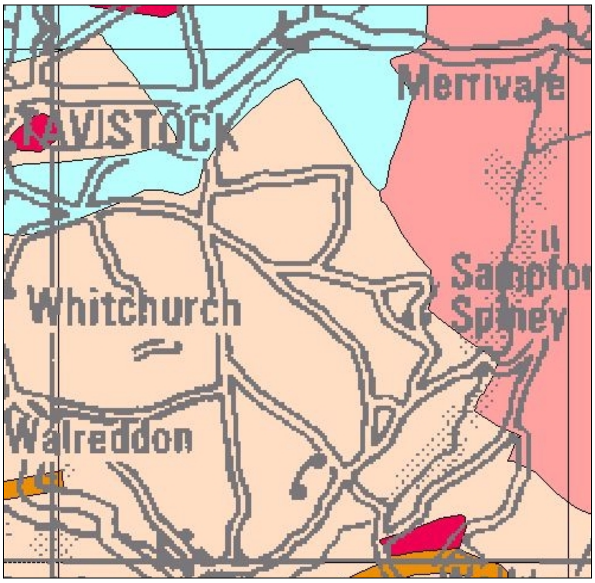


Figure 2-17. Geology of the 250070 5 km grid square (1:250,000 geological boundaries (pink = Granite, fawn = Kaye Brook Slate Formation; 5-km grid lines; 1:250,000 scale topography reproduced with permission from Ordnance Survey Licence No. GD272191/2000, © Copyright. All rights reserved)

2.59. The area under study has one of the steepest radon potential gradients in the whole of the country so averaging over 5 km grid squares will tend to enhance the area apparently affected by high radon potential. For this reason the 1 km GRIDRP map provides a much better indication than the 5 km GRIDRP map of the extent of the area where new dwellings would require protective measures. This problem of enhancement of 5 km GRIDRP should not be encountered in other sectors of south-west England, away from the granite intrusions and uranium mineralised areas, where the radon potential gradients are much less.

Table 2-7. Comparison of approximate areas assigned to different classes on 5 km and 1 km GRIDRP maps that cover BGS geological map sheets 336 and 337.

GRIDRP	Area on 5 km GRIDRP map (km2)	Area on 1 km GRIDRP map (km2)
>30%	340	95
10-30%	500	390
3-10%	260	615

Geological radon potential of map sheets 325 and 335 to 338

2.60. Drift free solid geological units in **Sheet 325** with GEORP >3% (Table 2-8) are:

- Crackington Formation (Namurian) within the Granite contact aureole - uranium mineralised zone in the SW corner of the map sheet (GEORP 10%)
- Bude Formation (Westphalian), which comprises massive sandstones with thin interbedded siltstones and mudstones and has a GEORP of 8.5% (Max. house radon measurement 934 Bq m^{-3}). Ball et al. (1992) reported that soil gas radon over the Bude Formation to the north of the Dartmoor Granite was 20 Bq/l and that the average GEORP for the Bude Formation in SW England was 2%>AL. Westphalian sandstones are known to have elevated GEORPs in other parts of the UK, mainly reflecting their relatively high permeability.

2.61. The Alphington Breccia in the Exeter city area and to the SW of the city has a low GEORP (0.4-1.0%) but is characterised by 5 dwellings with 400-600 Bq m^{-3}. Occasional houses would be expected to exceed the Action Level, for example where faults cut the permeable breccia leading to an enhanced radon flux.

2.62. The GEORP data for 5 km grid squares confirms that the Crackington Formation has 13%>AL in grid square 280085 in the uranium mineralised zone marginal to the Granite (U-zone). There are only 5 measurements available for the Granite in Sheet 325 so they have not been released to BGS. Interpolation from the adjoining sheet 338 would suggest a GEORP of >30% for the Granite.

2.63. The Aylesbeare Group, which includes the Littleham Mudstone Formation in the SE sector of Sheet 325, has a GEORP of <0.1%. Whereas extremely high uranium values have been reported to be associated with the Littleham Mudstone Formation (Ball and Miles, 1993), its permeability is low and Appleton and Ball (1995) reported that only 1 house out of the 467 measured up to March 1994, that are sited on Littleham Mudstone in Devon, exceed the AL. This low GEORP may result from the low permeability of the Littleham Mudstone Formation.

2.64. GEORP data for **Sheet 335/336** (Table 2-9) indicate that:

- GEORP for the Bodmin Granite is 25%>AL
- The Devonian Tredorn Slate Formation located mainly in the northern contact zone of the Bodmin Granite has a GEORP of 18-20% whereas the Trevose Slate Formation, which crops out in a zone going from the granite contact to the coast has a GEORP of 21% in the U mineralised contact zone to an average of 4% outside the U-zone.
- Superimposition of alluvium on the solid rocks does not reduce the GEORP either inside or outside the U-zone.
- The Staddon Grit Formation has a GEORP of 3% inside the U-zone reducing to 1% outside the U-zone whereas the Bedruthan Formation reduces from 16% in the U-zone near Bodmin to <10% outside the U-zone. Other Devonian formations cropping outside the U-zone include the Polzeath Slate Formation and the Harbour Cove Slate Formation, which have GEORPs of 2-3%.

2.65. GEORP data for 5 km grid squares show that :

- Only the Trevose Slate Formation may be used to monitor the progressive decrease in GEORP from 30% in the contact zone with the Bodmin Granite to 0.6% in the coastal zone (Table 2-10).
- The GEORP data confirms that high radon potential in this map sheet, as in sheets 337 and 338, is predominantly associated with uranium mineralisation within the granite, the granite contact aureole and a zone continuing as far west as Wadebridge, where the GEORP of the Trevose Slate is still 5% (195070). Neither uranium mineralisation nor uranium stream sediment anomalies are a noted feature as far west as this (Ball and Miles, 1993) so it must be assumed, that as in Map Sheet 337, there are zones of low grade pervasive uranium mineralisation (or relict radium anomalies derived from weathered U mineralisation) which generate sufficient radon to produce a GEORP or 1 km GRIDRP exceeding 3%.

Table 2-8. Geological radon potential (GEORP) for geological units in the Exeter geological map sheet (No. 325) (based on NRPB normalised house radon data, 1996; n>30).

Bedrock*	**Drift**	**No. radon measurements**	**Max. radon**	**GEORP Est. %>AL**
Alphington Breccia	Alluvium	192	610	0.6
Alphington Breccia	Head	197	425	1.0
Alphington Breccia	No drift	761	462	0.5
Alphington Breccia	River Terrace	314	456	0.6
Ashton Shale Member	No drift	94	126	1.0
Aylesbeare Group	No drift	271	103	0.2
Aylesbeare Group	Older Head	36	79	0.1
Basalt	No drift	50	305	2.8
Bude Fm	No drift	34	934	8.5
Budleigh Salterton Pebble Beds	No drift	52	59	0.0
Cadbury Breccia	No drift	125	302	1.2
Crackington Fm	Alluvium	67	145	0.8
Crackington Fm	Head	119	353	1.2
Crackington Fm	Made ground	76	146	0.4
Crackington Fm	No drift	1161	312	0.4
Crackington Fm (U-zone)	No drift	63	765	10.0
Crackington Fm	River Terrace	63	212	0.6
Crediton Breccia	No drift	231	319	0.6
Creedy Park Sandstone	No drift	125	247	0.9
Dawlish Sandstone	Marine deposits	64	201	1.0
Dawlish Sandstone	No drift	152	140	0.1
Dawlish Sandstone	River Terrace	284	150	0.2
Heavitree Breccia	No drift	401	298	0.5
Heavitree Breccia	River Terrace	124	97	0.5
Monkerton Fm	Head	31	195	1.5
Monkerton Fm	No drift	53	134	0.5
Newton St Cyres Breccia	No drift	39	141	0.5
Thorverton Sandstone	No drift	80	677	0.9
Whipton Fm	Alluvium	93	310	2.3
Whipton Fm	Head	113	82	0.0
Whipton Fm	No drift	511	221	0.6
Whipton Fm	River Terrace	38	40	0.0

* Geological units from BGS Sheet 325

Table 2-9. Geological radon potential (GEORP) for geological units in the Trevose Head and Camelford geological map sheet (No. 335/336) (based on NRPB normalised house radon data, 1996; n>30).

Bedrock*	**Drift**	**U****	**No. radon measurements**	**Max. radon Bq m^{-3}**	**GEORP Est. %>AL**
Bedruthan Fm	No drift	U	51	1314	15.7
Granite	No drift	U	137	1189	25.1
Harbour Cove Slate Fm	No drift	NU	55	401	2.9
Polzeath Slate Fm	No drift	NU	150	224	1.6
Staddon Grit Fm	No drift	NU	337	546	1.2
Tredorn Slate Fm	No drift	NU	194	1685	18.1
Tredorn Slate Fm	No drift	U	80	1844	21.0
Trevose Slate Fm	Alluvium	NU	95	233	4.6
Trevose Slate Fm	Alluvium	U	58	693	27.0
Trevose Slate Fm	Blown Sand	NU	76	262	1.0
Trevose Slate Fm	No drift	NU	1018	721	4.3
Trevose Slate Fm	No drift	U	426	2748	20.5

* Geological units from BGS Sheet 335/336; **U = inside U-zone; NU = outside U-zone.

Table 2-10. Lateral variation in geological radon potential within the Trevose Slate Formation (data for 5 km grid squares in Sheet 335/336)

Easting	**Northing**	**U-zone***	**Number of radon measurements**	**GEORP**
185	70	NU	95	0.6
190	70	NU	108	0.6
195	70	NU	289	5.3
200	70	NU	50	6.8
205	70	NU	53	11.5
210	70	U	73	21.9
190	75	NU	102	2.0
200	75	NU	22	5.7
205	75	NU	114	8.0
205	75	U	40	22.9
195	80	NU	26	0.3
200	80	NU	17	0.2
205	80	NU	82	7.1
210	80	U	121	15.8

*U = inside U-zone; NU = outside U-zone.

2.66. Within **Sheet 337** (Table 2-11) :

- the GEORP for Granite (42%) is reduced to 23-27% when it is covered by Alluvium, Head and Peat.
- the Crackington Formation crops out only outside the U-zone and has an 8% GEORP where drift free. This is reduced to 4 and 2% respectively when covered by Alluvium and Head deposits. None of the Crackington Formation is located within the Granite aureole, being mainly in an E-W belt running through Launceston. This relatively low GEORP contrasts with

the much higher GEORP where the Crackington Formation lies close to the granite margin in Sheet 338.

- the Brendon Fm (Visean) has a very wide lateral extent running east from the aureole of the Bodmin Granite to the edge of Tavistock on the eastern margin of the map sheet. The average GEORP is 15%, being slightly higher when covered by Head (19%) and lower when covered by Alluvium (11%).
- the Devono-Carboniferous Basic Tuff has a GEORP of 15% in the U-zone, 7% outside the U-zone, and 6% in the U-zone when covered by Alluvium. The GEORP of the closely associated (Visean) Milton Abbott Formation is 9%, which is reduced to 6% when covered by Alluvium.
- GEORP for the Kate Brook Slate Formation is 12-13% for drift-free and alluvium covered ground both within and outside the U-zone.

2.67. GEORP data for 5 km grid squares indicate that:

- The eastern sector of the Bodmin Granite has a GEORP of 25-32%. Two small bosses of granite crop out at, and 5 km to the west of, Gunnislake. House radon data for the Gunnislake area indicate a GEORP of 45% and this is reduced only slightly to 34% when bedrock is covered with Head.

- Both the Bodmin and Gunnislake Granites have metamorphic aureoles characterised by uranium mineralisation and elevated radon levels. The sedimentary rocks in the zone marginal to the Bodmin Granite (5 km grid squares 220065, 225065, 225070, 225075, 220080) fall within the zone of the uranium mineralisation and geochemical stream sediment anomalies (Ball and Miles, 1993). Within this zone, high GEORPs characterise a range of geological units of very different lithologies (Brendon Fm, Tintagel Volcanic Group, and Woolgarten Slate Formation). The GEORPs range from 10 to 36% with an average of about 15%, which agrees with the 1 km GRIDRP, map (Figure 2-16). Further to the east and north-east, away from the granite margin, the GEORPs in a range of lithological units decreases progressively from around 8%>AL closest to the granite (230065) reducing to 2% in 5-km grid square 230075, furthest from the granite, although this is still within the U-zone. At the northern margin of the map sheet (grid squares 230080, 235080, 235085) much of which is reported by Ball and Miles (1993) to be outside the U-zone, high GEORPs ranging from 6 to 32% occur in a range of geological units. These are predominantly slates, but include shales (Crackington Formation) and cherts, black shales and limestone (Meldon Chert Formation). This suggests the presence of unrecorded uranium mineralisation or, as in Derbyshire, uraniferous black shales and permeable limestone.

2.68. Indoor Within On the 1 km GRIDRP map (Figure 2-16) there is a NNW trending zone with 10-30% running between the Gunnislake area to the previously mentioned high zone (230080, 235080, 235085). This follows a relatively heavily faulted zone that is not noted for uranium mineralisation in its central and northern sectors. Enhanced radon in dwellings in this zone may reflect enhanced permeability in the faulted zone or an unrecorded zone of relatively weak uranium mineralisation. Uranium mineralisation has been reported to be associated with NNW and NW trending faults elsewhere in Cornwall and Devon (K Ball, personal communication, 1997).

2.69. Indoor Along the eastern margin of the map sheet (grid squares 245065, 245070, 245075, 245080) sandstones of the Brendon Formation, and Cotehele Sandstone Formation have higher GEORPs (14%) than volcanics and slates of the Milton Abbott Formation and Kate Brook Slate Formation (5-8%). This may reflect differences in permeability and fracturing or concentration of low grade uranium mineralisation in the rocks more susceptible to open fracturing (such as sandstones). All this area is within the U-zone.

Table 2-11. Geological radon potential (GEORP) for geological units in the Tavistock geological map sheet (No. 337) (based on NRPB normalised house radon data, 1996; n>30).

Bedrock*	**Drift**	**U**	**No. radon measurements**	**Max. radon**	**GEORP Est. %>AL**
Basic Tuff	Alluvium	U	44	247	5.5
Basic Tuff	No drift	NU	54	249	7.4
Basic Tuff	No drift	U	97	1038	15.1
Bealsmill Fm	Alluvium	U	52	834	8.1
Bealsmill Fm	No drift	U	52	291	11.1
Brendon Fm	Alluvium	U	908	1213	11.3
Brendon Fm	Head	U	217	2977	19.2
Brendon Fm	No drift	U	457	1201	14.8
Burraton Slate Fm	No drift	U	44	663	3.4
Cotehele Sdst Fm	Alluvium	NU	49	887	15.9
Cotehele Sdst Fm	Alluvium	U	42	175	3.4
Cotehele Sdst Fm	No drift	NU	56	541	7.6
Cotehele Sdst Fm	No drift	U	255	897	14.1
Crackington Fm	Alluvium	NU	128	422	4.0
Crackington Fm	No drift	NU	696	1795	8.3
Dolerite	Alluvium	U	180	406	2.6
Granite	Alluvium	U	36	2220	25.3
Granite	Head	U	134	1268	26.8
Granite	No drift	U	224	2613	42.5
Granite	Peat	U	35	434	23.1
Greystone Fm	No drift	U	38	303	1.4
Kate Brook Slate Fm	Alluvium	NU	37	328	12.9
Kate Brook Slate Fm	Alluvium	U	531	919	11.8
Kate Brook Slate Fm	No drift	NU	205	2050	12.8
Kate Brook Slate Fm	No drift	U	1473	1457	12.0
Lezant Slate Fm	Alluvium	U	32	137	1.5
Lezant Slate Fm	No drift	U	97	380	2.3
Liddaton Fm	No drift	NU	53	527	8.1
Lydford Fm	No drift	U	40	549	11.0
Meldon Chert Fm	No drift	NU	36	320	16.9
Milton Abbot Fm	Alluvium	U	102	354	6.4
Milton Abbot Fm	No drift	U	193	2125	8.6
Stourcombe Fm	No drift	NU	62	395	6.5
Tintagel Volcanic Fm	No drift	U	39	595	20.3
Woolgarden Slate Fm	Alluvium	U	49	678	17.6
Yeolmbridge Fm	No drift	NU	33	956	32.2

*Geological units from BGS Sheet 337; U = inside U-zone; NU = outside U-zone

2.70. Within **Sheet 338** (Table 2-12) :

- Granite is 51-54%>AL and alluvium has little effect on the GEORP.
- The Crackington Formation has an average GEORP of 40%>AL probably because a high proportion of the Formation is located within the aureole of the Granite in the SE sector of map.

- Lower Carboniferous Basic Tuff has a GEORP of 16%. This unit is not in the Granite aureole but is located in the U mineralised/anomalous zone.
- GEORP for the Kate Brook Slate Formation is 7% (no drift). A higher GEORP (10%) occurs where the Kate Brook Formation is overlain by alluvium possibly because dispersion of uranium from the adjacent Granite produces a higher GEORP for the U enriched alluvium than for the underlying bedrock.
- Most of the map sheet is drift free. Alluvium has no effect on Granite GEORP and enhances it over the Kate Brook Slate Formation.

2.71. GEORP data for Sheet 38 grouped by 5 km grid square indicate that:

- Granite in the west (260075 - Princetown) has a GEORP of 30% whereas the remainder of the granite is 52-75% (Table 2-13). This may be geologically controlled or it may reflect different construction characteristics in the Princetown area. Whereas the use of radon data corrected for dwelling type should iron out differences due to house type, the fine details of house construction may exert a significant control on radon and may not be corrected for by the normalisation process.
- The GEORP for the Crackington Formation in three 5 km grid squares in the SE of the map (270065, 270070, and 275075) are all similar (37, 45, 49% respectively). 270065 is mainly outside the granite aureole and has a slightly lower GEORP.
- The Kate Brook Slate Fm in the SW corner of the map has a GEORP of 8-12% (with the same GEORP for drift-free and alluvium covered terrain) whereas in the SE, GEORP is 3-7%. A relatively smaller portion of the ground in the SE is within the granite aureole, which probably explains the lower GEORP.
- In the west and NW of the map sheet, the Greystone Formation (Tournasian) GEORP is 3-8%>AL (250075, 250085) and the Dolerite 4% (250075).

Table 2-12. Geological radon potential (GEORP) for geological units in the Dartmoor Forest geological map sheet (No. 338) (based on NRPB normalised house radon data, 1996; n>30; all data in U-zone; explanation of geological units on BGS Sheet 338).

Bedrock	**Drift**	**No. of radon measurements**	**Max. radon**	**GEORP Est. %>AL**
Basic Tuff	No drift	53	565	15.9
Chercombe Bridge Lst.	No drift	96	273	3.4
Crackington Fm	No drift	162	1893	40.0
Dolerite	No drift	91	448	3.7
Granite	Alluvium	71	1839	54.1
Granite	No drift	671	3293	51.2
Greystone Fm	No drift	82	330	4.3
Kate Brook Slate Fm	Alluvium	181	1645	9.8
Kate Brook Slate Fm	No drift	940	1557	6.7
Lydford Fm	No drift	40	987	17.9
Milton Abbot Fm	No drift	53	228	3.6

Table 2-13. Lateral variation in geological radon potential within the Dartmoor Granite (data for 5-km grid squares in Sheet 338; 34 to 126 radon measurements per 5 km grid square)

Easting	**Northing**	**GEORP Est. %>AL**
255	70	32
265	75	61
270	70	52
270	75	52
270	80	75
275	80	53
275	85	65

Use of 5 km GRIDRP map to define the requirement for installation of protective measures in new dwellings

2.72. There are many grid squares in the zone surrounding the granite where new dwellings might be overprotected if the 1996 version of the 5 km GRIDRP map (Lomas et al., 1996) was used to define the requirement for protective measures. Attention is drawn in particular to the relationship between 5 km GRIDRP and GEORP for Launceston (230080, 230085) and Tavistock (245070) (Table 2-14). As mentioned previously, this contrast will in part be related to differences in the corrections applied to house radon data used for the 5 km grid maps (temperature corrected) and the geological radon potential assessments (temperature corrected and normalised). Fully normalised radon data tend to be significantly lower than temperature corrected data (see para. 2.5 and Figure 2-1 above).

2.73. In other 5 km grid squares, the GEORPs are so high that protection would be required on all geological units within a 5 km grid square. This is illustrated by the data for 5 km grid square 240070 (Table 2-15) which has a GRIDRP of 35.9%. Although the combinations of solid and drift geological units within the grid square have very different GEORPs these are very close to or comfortably exceed the current 10% threshold for installation of full protective measures. In this case the 5 km GRIDRP provides a good guide to the requirement for protective measures throughout the grid square. It can be seen that GEORP is reduced when solid geological units are overlain by drift.

2.74. Unlike in the Northamptonshire and Derbyshire area, there appear to be no significant situations in map sheets 335-338 where underprotection would be a problem if the 5 km GRIDRP map was used to define the need for installation of protective measures.

Conclusions: Cornwall and Devon

2.75. The area covered by geological map sheets 335/6, 337, and 338 includes zones with the steepest radon potential gradients in Great Britain. This reflects the very high GEORP of the uranium mineralised granites (30 to 55%), which are intruded into an envelope of Devonian and Carboniferous sedimentary and volcanic rocks of much lower GEORPs. The zone of known uranium mineralisation and uranium stream sediment anomalies outlined by Ball and Miles (1993) is generally characterised by GEORPs of >10 to 20%. Thus both this zone and the areas underlain by Granite require full protective measures as they exceed the 10% threshold.

2.76. There are a number of exceptions where GEORPs less than 10% occur in a few sectors of the uranium enriched (U) zone and GEORPs greater than 10% occur in the zone not affected by uranium enrichment. The most prominent example of a high radon potential zone identified by the 1-km grid mapping, which was not identified on geological and geochemical evidence nor on a geological assessment of the house radon data, is the belt of 10-30%>AL that extends NNW from Gunnislake to a point a few kilometres east of Launceston (Figure 2-16). It appears that high radon in dwellings is probably related to disseminated uranium mineralisation (or remnant radium left behind following removal of the uranium) in a NNW- to NW-trending fault zone along which radon flux could be enhanced above the fractured rocks. Although there is a geological explanation for this feature, it had not been identified prior to the production of the trial 1 km GRIDRP map.

2.77. The 5 km GRIDRP maps show a broad but imprecise relationship to the geological features controlling radon potential. Because of the very steep radon potential gradient, averaging produces grid squares with anomalously high GRIDRP values in the zone surrounding the Granites. Use of the 5 km GRIDRP maps to define the requirement for protective measures would lead to overprotection in some areas.

2.78. The 1 km GRIDRP map exhibits a close relationship to the geological features controlling radon potential. In addition, because there are many house radon measurements available, 1 km GRIDRP mapping has the capability of defining areas of high radon potential which have not been identified on the basis of geology and geochemistry. In the areas surrounding the Granites, radon potential is generally controlled by the distribution of pervasive uranium mineralisation which in some areas appears to have been weathered away, leaving radon generating radium in the rock strata without a strong uranium geochemical signature. Thus although the boundary of the U-zone defined by Ball and Miles (1993) corresponds quite closely with the 10% threshold for installation of full protective measures, there are exceptions to this relationship.

2.79. In the part of Cornwall and Devon evaluated in this study, the major controls on radon potential at the 10% threshold is the boundary of the U-zone but it appears that the 3% threshold cannot be defined on the basis of readily mappable lithological controls. Whereas GEORP is the preferred and most spatially precise method of defining the requirement for protective measures in sedimentary geological environments not characterised by cross-cutting uranium mineralisation, 1 km GRIDRP mapping appears to be the most effective method, based on the use of existing data, for defining the need for protective measures in the four map sheets studied in Cornwall and Devon. This judgement applies to the SW and SX 100 km grid squares of the Ordnance Survey National Grid. In contrast, Ball and Miles (1993) earlier concluded that the most efficient method of identifying zones of high radon potential (in Cornwall and Devon) is the soil gas radon survey. Whereas this may be true, it would require the collection of additional soil gas radon data.

2.80. The controls on radon potential in the four map sheets studied differ significantly from most of the rest of Great Britain where a strong lithological control has been demonstrated (e.g. in Northamptonshire, Derbyshire, Somerset, and all other areas underlain by the Carboniferous Limestone and stratigraphic units within the Jurassic and Permian characterised by high radon potential (>3%)). In such areas, geological units have characteristic GEORPs, which in general reflect their permeability, uranium content, weathering history and the influence of unconsolidated deposits overlying the bedrock. In areas of lower measurement density, GEORP based on a larger area may be used with greater reliability than 1 km GRIDRP. In sedimentary geological terrains such as Northamptonshire and Derbyshire, GEORP is the preferred method of mapping. Where sufficient measurements are available, GEORP may be used to define the requirement for protective measures in different sectors of individual 1 km grid squares.

2.81. A less detailed assessment of the relationship between radon and geology in SW England (Varley & Flowers, 1998a) based on approximately 250 indoor and 2000 soil gas radon measurements confirmed (1) that geology is the most important factor defining radon potential, (2) a correlation between high indoor radon and granitic areas and (3) that the metamorphic aureole around the granite had a significant impact on indoor radon (mainly because of the occurrence of uranium mineralisation within the aureole).

Table 2-14. Comparison of GEORP with 5 km GRIDRP for a selection of grid squares in Sheets 335-338 (No. of radon measurements >30; U = inside U-zone; NU = outside U-zone).

5 Km Grid	Solid Geology	Drift Geology	U-zone	No.	GEORP	GRIDRP
Launceston						
230080	Basic Tuff	No drift	NU	39	6.4	14.7
230080	Crackington Fm	Alluvium	NU	68	2.3	14.7
230080	Crackington Fm	No drift	NU	363	5.3	14.7
230080	Lezant Slate Fm	No drift	U	40	2.8	14.7
230080	Liddaton Fm	No drift	NU	35	9.4	14.7
230080	Stourcombe Fm	No drift	NU	62	6.4	14.7
230080	Yeolmbridge Fm	No drift	NU	33	32.2	14.7
Tavistock						
245070	Basic Tuff	No drift	U	99	14.7	15.2
245070	Brendon Fm	Alluvium	U	48	2.5	15.2
245070	Brendon Fm	No drift	U	84	14.5	15.2
245070	Burraton Slate Fm	No drift	U	44	3.4	15.2
245070	Cotehele Sandstone Fm	Alluvium	U	42	3.4	15.2
245070	Cotehele Sandstone Fm	No drift	U	270	13.5	15.2
245070	Kate Brook Slate Fm	Alluvium	U	138	5.8	15.2
245070	Kate Brook Slate Fm	No drift	U	736	4.4	15.2
245070	Milton Abbot Fm	Alluvium	U	103	6.2	15.2
245070	Milton Abbot Fm	No drift	U	230	7.8	15.2

Table 2-15. GEORP data for 5-km grid square 240 070 (Gunnislake 1:50,000 Geological Map Sheet 337).

Solid Geology	Drift	No. of radon measurements	Max. radon (Bq m^3)	GEORP (Est. %>AL)
Granite	Head	26	787	34
Granite	No drift	185	2613	45
Kate Brook Slate Formation	Alluvium	51	353	9
Kate Brook Slate Formation	No drift	536	1457	20

Evaluation of radon potential mapping methods (1998-2000)

2.82. The NRPB and the BGS carried out research for the Radioactive Substances Division of the DETR in 1998-2000 with the objective of identifying localised areas of England where radon concentrations are most likely to have >5% probability of being above the Action Level (Miles and Appleton, 2000). An abridged summary of the main results and recommendations is given in the following paragraphs.

2.83. The NRPB has the results of more than 400,000 measurements of radon levels in houses in England, mostly funded by the DETR. Under the contracts reported in Miles and Appleton (2000), these results were used to map radon potential, and in particular to identify areas where 5% or more of houses are above the UK Action Level for radon (200 Bq m^{-3}). This work was undertaken since not all the houses in England above the Action Level have yet been identified. Two approaches to mapping using house radon data were used: (i) grouping data by geological boundaries (carried out by the BGS), (ii) grouping the data by 1 km grid square (carried out by NRPB).

2.84. When using house measurement data for mapping, the distribution of radon results must be taken into account. No matter how small an area is chosen, a wide range of indoor radon levels is found, following the lognormal distribution. It is possible to estimate the proportion of the distribution above any threshold using the parameters of a lognormal distribution and standard mathematical formulas. In general, the accuracy of these estimates is proportional to the number of radon measurements.

2.85. For radon potential mapping it is necessary to assign national grid geographical co-ordinates to each postal address at which a radon measurement has been made. There are currently three sources of address-linked geographical co-ordinates: Royal Mail's PAF® (Postcode Address File, a registered trademark of Royal Mail), Ordnance Survey (OS) Address-Point™ and OS Data-Point® (now marketed as Code-Point®). An evaluation of the relative spatial accuracy of these three co-ordinate systems confirmed that:

(i) a more reliable estimation of geological radon potential can be achieved using OS Data-Point® and OS Address-Point™ co-ordinates compared with the spatially less accurate PAF® co-ordinates. The results highlighted the problems associated with attributing geological codes to house co-ordinates in areas where the geology is complex and changes rapidly over relatively short distances.

(ii) the OS Data-Point® co-ordinates are a very significant improvement on the PAF co-ordinates and, on the basis of this limited evaluation, are considered to be the most appropriate co-ordinate system to use when funding is restricted. Whereas, the accuracy of statistical analysis would undoubtedly be improved by using OS Address-Point™ co-ordinates, especially in rural areas, their high cost was beyond the financial budget of the project. The potential spatial error of about 50m using OS Data-Point® co-ordinates and 1:50,000 scale digital geological maps is likely to result in the misattribution of a relatively small numbers of houses.

2.86. Recent research initiated under the BGS Natural Environmental Radioactivity Survey (NERS) programme and further developed under the current contract has shown that the estimated probability of houses above the "Action Level" varies significantly according to the method of estimation. Simulations were carried out to assess how the accuracy and range of geological radon potential estimates varies with the number of radon measurements (n) and the computational method used. The following conclusions were derived from the simulations:

- GM + GSD2.5[8] tends to underestimate GEORP (%>AL) because the GSD for the geological units studied (Northampton Sand Formation (4, 9 &12%>AL); Lower Namurian Shale (3%>AL) and Bee Low Limestone (25%>AL) was greater than 2.5 (range 2.7 to 3.0)
- the range of estimates decreases as the number of measurements increases
- the range of estimates is generally less using GSD2.5
- when n = 100, GM + GSD provides the most accurate estimate
- when n is low (say <30), estimates based on using a constant GSD (such as 2.5) in general provide a more reliable estimate than GM + GSD
- for intermediate populations (n = 30 - 100) the outcome is less certain
- the percentage of estimates that fall outside the range of ±1.5 x Popn. GEORP (Est. % >AL) is less for GSD2.5 when n=10, equal when n=30 and greater for GSD2.5 when n=100.
- estimates tend to be low when n is low (e.g. 10) for both computational methods (Miles and Appleton, 2000).

2.87. In the areas of sedimentary strata studied, grouping house radon data by geological boundaries appears the most logical way of grouping data, as radon potential clearly differs between geological units. Geological radon potential is determined from house radon measurements grouped according to the solid and drift geological units underlying the houses. Statistical analysis of house radon measurements for the 5-km grid squares illustrated the strong contrast between GEORP for different combinations of bedrock and drift. Taking the 5 km grid square (475260) that encompasses the north-east sector of the city of Northampton as an example (Table 2-16 and Figure 2-18), it was demonstrated that whereas most of the GEORP values calculated for this 5-km grid square are similar to GEORP estimates for the 1:50,000 scale map sheet, GEORP estimates for the Northampton Sand Formation are different. Lateral variation in GEORP both within and between map sheets is not an unusual feature. This reflects lateral variations in the chemistry and permeability of the solid and drift geological units, as well as lateral variations in housing mix and construction style. In the Northampton 1:50,000 map sheet, the two predominantly urban 5-km grid squares (475260 and 475265) have lower than average GEORPs (6-9%>AL) whereas all except one of the predominantly rural 5-km grid squares have higher than average GEORPs (12-25%>AL) (Table 5.4 in Miles & Appleton, 2000). This may in part reflect differences in housing mix between urban and rural areas, but Figure 2-19 shows that lateral variations in GEORP are still apparent even after the house radon data have been fully normalised.

[8] GM = geometric mean; GSD2.5 = geometric standard deviation of 2.5 used to estimate the GEORP; GSD = calculated GSD for sample population used to estimate GEORP

Table 2-16. Geological radon potential (GEORP*) for geological units within the east Northampton 5-km grid square (475 260**; SP76SE) compared with estimates for the 1:50,000 map area (Sheet 185). (based on NRPB temperature corrected house radon data, 1998).

Solid***	Drift***	No. in 5-km grid	No. >AL 5-km grid	GEORP* 5-km grid	GEORP* 50k map	No. in 50k map
Blisworth Limestone Fm.	No drift	1024	9	1.1	0.9	1812
Blisworth Limestone Fm.	Till	82	0	0.1	0.1	704
Grantham Fm.	No drift	1220	33	1.9	1.5	2653
Grantham Fm.	Till	75	1	1.7	0.6	149
Northampton Sand Fm.	Calcareous tufa	31	0	0.4	0.4	31
Northampton Sand Fm.	No drift	5430	319	5.9	10.1	13397
Northampton Sand Fm.	Till	102	6	5.5	3.6	531
Rutland Fm.	No drift	2203	11	0.2	0.2	3174
Rutland Fm.	Till	324	0	0.1	0.2	738
Wellingborough Member in Rutland Fm	No drift	478	2	0.1	0.4	848
Whitby Mudstone Fm.	Alluvium	41	0	0.1	0.4	478
Whitby Mudstone Fm.	Calcareous tufa	52	0	<0.1	<0.1	52
Whitby Mudstone Fm.	First River Terrace Deposits	153	1	0.1	0.1	347
Whitby Mudstone Fm.	Glacial Lake Deposits	35	0	<0.1	0.1	366
Whitby Mudstone Fm.	No drift	1614	19	0.5	1.1	5466
Whitby Mudstone Fm.	Second River Terrace Deposits	92	1	0.4	0.4	92
Whitby Mudstone Fm.	Till	88	0	<0.1	0.2	229

No. = number of radon measurements; * GEORP = Estimated % of dwellings overlying geological unit which exceed the UK radon Action Level (AL) - predicted using lognormal modelling (Miles, 1998); ** 5 km grid square radon potential (GRIDRP) = 1-3% > AL; *** Stratigraphic units from BGS 1:50,000 Sheet 185

2.88. Twenty geological maps at 1:50,000 scale were used to map radon potential of different rock types. This work requires the boundaries of geological units to be available in digital form. Lognormal modelling of the indoor radon data produced estimates of the percentage of the housing stock above the UK Action Level for each combination of bedrock (solid geology) and drift (unconsolidated deposits, such as glacial sand and gravel, till, etc). Twenty new geologically based radon potential maps were produced.

2.89. The reliability of a geological (and grid square) radon potential map is, in general, proportional to the house measurement density. Measurement densities vary significantly between the twenty map sheets so it was anticipated that the mapping method might not function very effectively in six of the map sheets. It is reassuring that even when the measurement density is low, geological radon potential mapping clearly discriminates between geological units in a logical way.

2.90. Grouping house radon data by 1 km grid square without making assumptions about the location of boundaries between areas with different radon potential has different advantages from grouping by geology. This method can show up variations that are obscured by geological grouping, such as variations in radon potential within a geological unit, or variations caused by mineralisation cutting across geological units. The method used was to allocate a radon potential to a 1 km grid square on the basis of the nearest ‘n’ measurements to that square, where ‘n’ is a number found experimentally or on statistical grounds to be sufficient for an accurate estimate of radon potential.

Figure 2-18. Geological radon potential map of the 5 km grid square (475260) that encompasses the north-east sector of the city of Northampton. The 1:50,000 scale map illustrates the distribution of geological units with geological radon potentials of <3% (white), 3-5% (blue) and 10-20% >AL (pink). The 5-km grid square has an average radon potential of 1-3% (based on NRPB temperature corrected house radon data, 1998). *Topography based on Ordnance Survey 1:50 000 Scale Colour Raster data with permission of The Controller of Her Majesty's Stationery Office © Crown Copyright. Ordnance Survey licence number GD272191/2000.*

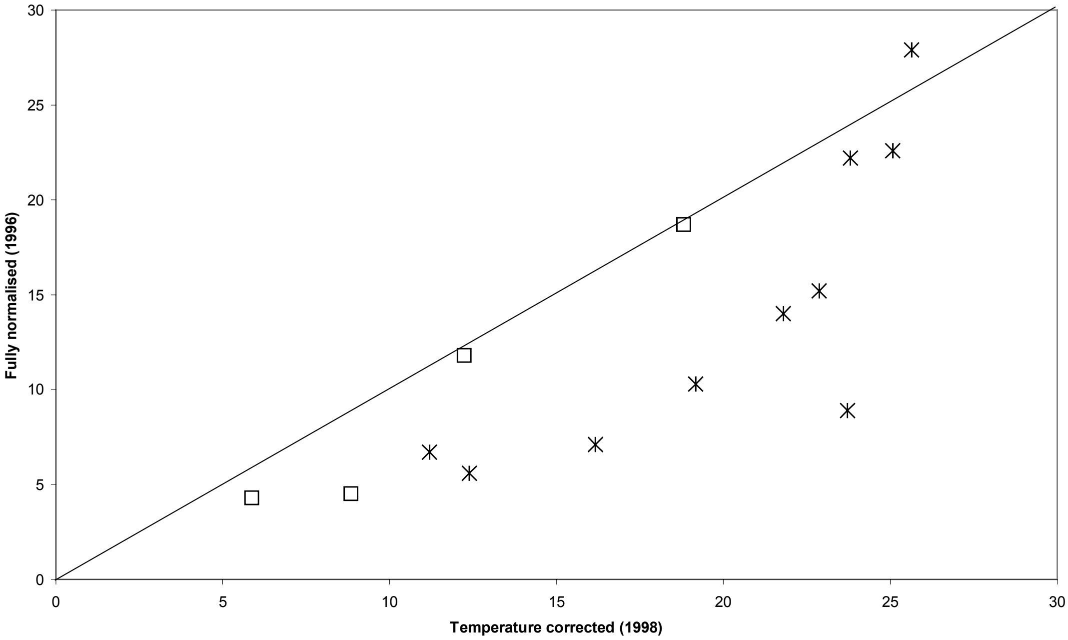


Figure 2-19. Geological radon potential (Estimated % of dwellings >AL) for the Northampton Sand Formation in a range of urban and rural 5 km grid squares in Northamptonshire. Estimates derived from temperature corrected (1998 data) and fully normalised (1996) house radon data (square = predominantly urban 5-km grid squares, star = predominantly rural 5-km grid squares).

2.91. A sample of 20,000 simulated radon results were used to compare the accuracy of distance-weighted and unweighted means in 1 km mapping. The tentative conclusion from this work is that unweighted means give errors that are smaller than or equal to the errors on weighted means if 'n' is chosen appropriately. Unweighted means were therefore used in the study. After trials with artificial data, a value of 'n' = 30 was chosen for consistency with earlier work and to provide an acceptable uncertainty. The 1 km mapping method was applied to the house radon data in England south-west of the grid co-ordinate 300 100, and the percentage of homes above the Action Level calculated and mapped for each target square using the lognormal model (Figure 2-20)[9]. It is interesting to note that the belt of high radon potential (10-30%>AL) that extends NNW from Gunnislake to a point a few kilometres east of Launceston on the trial 1-km grid map (para 2.11 above and Figure 2-16) does not appear on the most recent 1-km grid map (Figure 2-20). This is probably because fully normalised house radon data were used for the trial map whereas the temperature corrected data were used to derive the map in Figure 2-20. In addition different mapping algorithms were used.

2.92. The research allowed a comparison of grid square mapping and geologically based mapping in some areas, the strengths and weaknesses of the two methods to be understood more clearly, and to suggest how the two methods could be combined to give more accurate mapping than either separately.

2.93. A comparison was made between the geological radon potential mapping for parts of Somerset and 1 km mapping for the same area. The comparison showed that the known radon hot spot of Street was identified as having high radon potential in the 1 km mapping, but not in the geologically based mapping. It was shown that this was caused by significant variation in the radon potential of the Lower Lias (no drift) within a single 1:50,000 geological map sheet. It is clear that there would be significant advantages in being able to evaluate and map lateral variations of radon potential not only between 1:50,000 scale geological map sheets, as was done in the current project, but also within map sheets.

[9] The BGS has recently completed digitisation of airborne radiometric survey data collected in 1957/9 (Kimbell et al., 2000). The most striking regional features on the total gamma map (Figure 21) are the large hollow-centred (doughnut shaped) highs relating to the granite outcrops. Thick peat deposits and kaolinisation probably cause the lows in the centres of the Dartmoor and Bodmin granites. High total gamma along the western border of the Dartmoor granite is not reflected in high radon potential on the 1 km grid map (Figure 18). This may reflect the absence of house radon measurements in this part of the granite - the gridding algorithm will interpolate grid squares with no measurements using high values from the east sector of the granite and lower values from the area to the west of the granite. Other notable features on the total gamma map (Figure 20) are the pronounced low over the Lizard complex and a number of linear features related to bedrock geology, such as the boundary between the Lower Devonian (LD) sandstones and argillaceous rocks and the Middle Devonian (MD) slates (Figure 13).

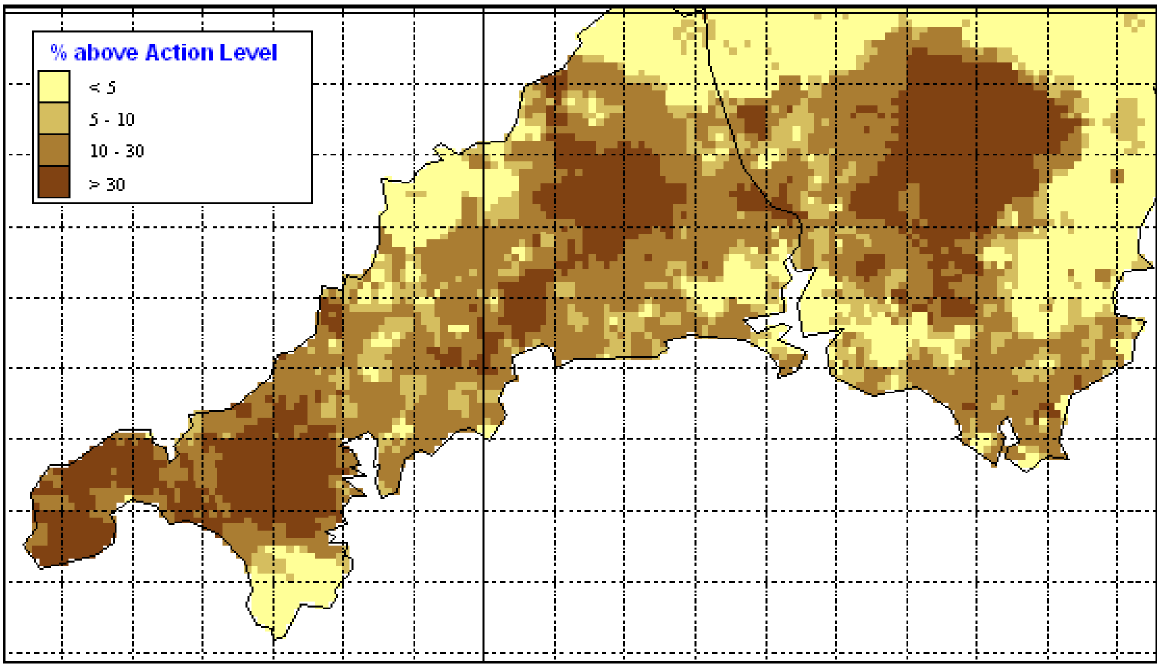


Figure 2-20. 1-km grid radon potential (GRIDRP) map of south-west England showing the estimated percentage of homes above the Action level (minimum 30 results, unweighted, using measured GSD for each grid square; Fig 6.4 Miles and Appleton, 2000)

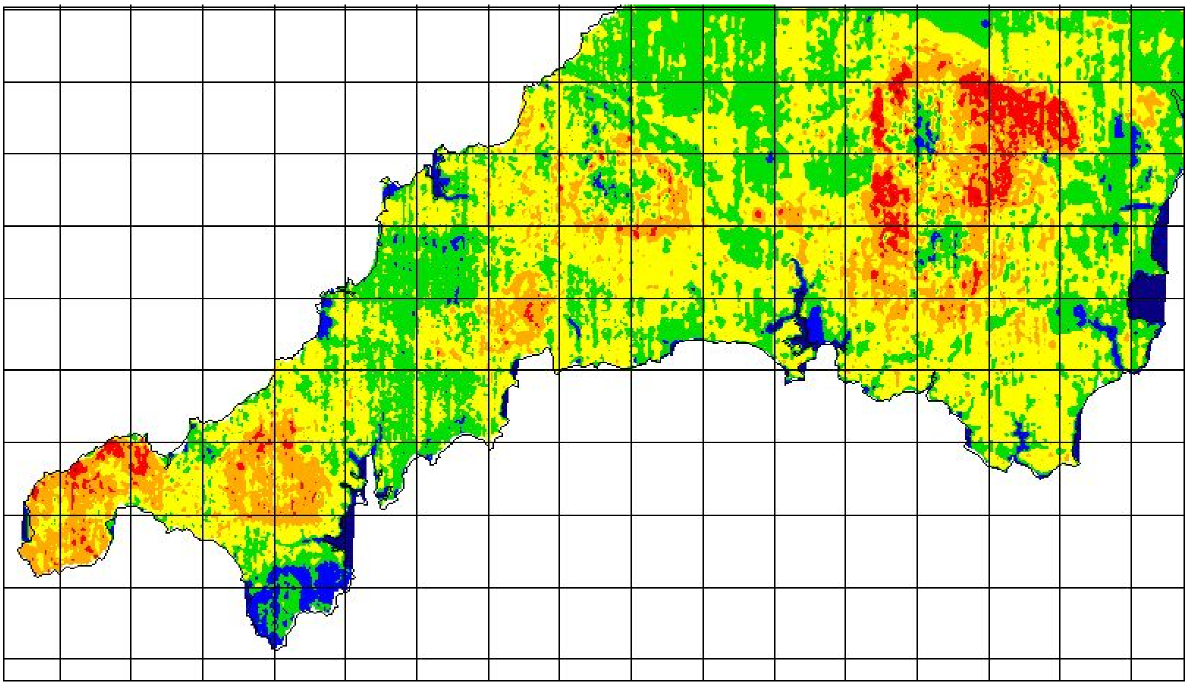


Figure 2-21. Airborne total gamma radiometric data for south-west England (redrawn from Kimbell et al., 2000; blue = low, red = high)

Summary and recommendations

2.94. Geological radon potential maps are designed for a wide range of users including local Government planners, building control and environmental health officials as well as consultants. However, it is important to ensure that the geological radon potential maps are used correctly and that users are aware of their limitations. The data on which the maps are based are not always comprehensive and their quality and density are variable; the maps reflect the limitations of both the geological and indoor radon data. Localised or anomalous features may not be represented, and any boundaries shown are approximate. Areas of lower or higher radon potential are likely to occur within areas given a specified classification because of the occurrence of sub-units of contrasting lithology and permeability or unmapped shear and fracture zones. The scale of the maps frequently precludes the identification of such areas. The categorisation of a group of rocks or unconsolidated deposits as having high levels of radon potential does not imply that there is any problem. That would depend on whether pathways, locations for accumulation, and protracted exposure occur. Therefore the map does not give any direct guide to the level of radon in individual buildings or underground spaces. However, there is, in general, a higher likelihood that problems may occur at specific sites within areas of high radon potential. The maps only provide general indications of radon potential and must not be relied upon as a source of detailed information about specific sites, or as a substitute for house radon monitoring.

2.95. Both geological radon potential mapping and 1 km grid square radon mapping can provide much more detailed maps than the 5 km grid square maps used prior to 1999, and so can allow radon protective measures in new development and radon measurement programmes to be targeted more efficiently.

2.96. The reliability and spatial precision of both mapping methods is, in general, proportional to the measurement density. It is, however, reassuring to note that even when the measurement density is as low as the minimum for 5 km grid square, 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 map sheets with higher measurement densities.

2.97. Conversely, variations within geological units can cause geological radon potential mapping in some parts of England to miss significant areas of higher radon potential which are shown up on 1 km grid square mapping.

2.98. The two methods are likely to be most powerful when used in a complementary fashion, by comparing maps produced by the two methods, and by grouping results both by geological unit and by grid square. It is recommended that this line of investigation should be pursued (Miles and Appleton, 2000).

3. RADON POTENTIAL SITE INVESTIGATIONS

Introduction

3.1. The main potential options for targeting radon protective measures in new dwellings and extensions to dwellings through the Building Control system (Appleton et al., 2000) are:

BC-1: Universal application of radon protective measures.
BC-2: Mapping defines need for protective measures.
BC-3: Mapping defines need for protective measures. Site investigation used to permit relaxation of regulation if the developer wishes to use this option.
BC-4: Universal site investigation defines the need for protective measures.

3.2. Two of these four options depend partly or totally on radon potential site investigation, which may comprise one or more of the following procedures:

- measurement of soil gas radon concentration, sometimes in combination with soil permeability;
- measurement in the laboratory of radon emanation from soil samples;
- determination of ^{214}Bi (and hence eU) in the field by gamma spectrometry.

3.3. 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 which supports the hypothesis that soil gas radon is a relatively reliable indirect indicator of indoor radon levels (Åkerblom et al. 1984, Åkerblom 1987, Reimer & Gundersen 1989, Ball et al. 1991, Sharman 1991, 1992, McAulay & Moran 1988, O'Connor et al. 1992, Reimer 1992, Ball & Miles 1993, Schwartz & Vulkan 1997, Barnet et al. 2000). Soil gas radon measurements combined with an assessment of ground permeability give the most useful indication of radon potential when insufficient indoor radon measurements are available (Åkerblom et al. 1984, Gundersen et al. 1987, 1988, Gates & Gundersen 1989a, 1992a, 1992b, Reimer & Gundersen 1989, Gundersen & Schumann 1996, Ball et al. 1992, 1995, Mose et al. 1992, Kemski et al. 1996, 2000, Barnet et al. 2000, Friedmann 2000, Siehl et al. 2000, Zhu et al. 2000). In Germany, Kemski et al. (1996) developed an empirical ranking classification for radon potential based on median soil gas radon and permeability measured by air injection through the soil gas probe.

3.4. In cases where low correlations have been measured between radon in soil gas and radon in adjacent houses (Nason & Cohen 1987, Ennemoser et al. 1995, Varley & Flowers, 1998b) the probable causes include: (i) the small number of houses of variable design in the study, (ii) single or restricted number (e.g. only 5) rather than multiple (10-15) soil gas measurements, (iii) short term indoor radon measurements, and (iv) a mixture of summer and winter measurements. Ennemoser et al. (1995) confirmed this by demonstrating a much better correlation between indoor and soil gas radon if the average for July and February measurements were used. Varley & Flowers (1998b) concluded that in south-west England, soil gas radon data is of little value for predicting the indoor level of an individual house, mainly because the construction characteristics of the dwellings and the lifestyle of the inhabitants have such a major impact on the indoor radon concentration. Varley and Flowers (1998b) observed that meteorological conditions and soil permeability exert a significant impact on indoor radon but that soil permeability may not always assist evaluation of soil gas radon data, especially in areas with highly cracked clay soils.

3.5. 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 (Schumann et al. 1992, Washington & Rose 1992, Schutz & Keller 1994, Hubbard & Hagberg, 1996, Winkler et al. 1999) and variations in soil gas radon on a scale of a few metres (Ennemoser et al. 1995, Durrani & Badr 1995, Oliver & Badr 1995, Durrani et al. 1997, Durrani, 1999). The former problem may be overcome by sampling at a depth greater than 70 cm (Rose et al. 1990, Ball et al. 1991, Gates & Gundersen 1992b, Bunzl et al. 1998) 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. Hutter & Knutson (1998) demonstrated that the coefficient of variation for soil gas radon measurements decreased from 120% at 0.4-0.5 m to 36% at 0.6-0.75m and 27% at 0.9-1.0 m. Small-scale variability in soil gas radon may be overcome by taking 10 to 15 soil gas radon measurements to characterise a site or geological unit (Ball et al. 1992, 1995). Neznal et al. (1996, 1997) assessed spatial variability of soil gas radon and concluded that a 0.8 m sampling depth is an acceptable compromise between reduction of weather effects and the practicability of the method under field conditions. They concluded that a single soil gas radon measurement is generally invalid and recommended that 15 measurements for evaluation of a site should normally be taken within a 10 x 10 m grid (2 m interval). Bunzl et al. (1998) cautioned that soil gas radon measurements made only once in a given month (especially January and February) cannot be used to derive a reliable estimate of mean annual radon concentration, even if a large number (ca. 20) of radon measurements are taken in the field.

3.6. Radon in soil gas in general varies with climatic changes including soil moisture, temperature, and atmospheric pressure. Seasonal climatic variations in soil gas radon have been reported by a number of workers (Rose et al. 1990, Schumann et al. 1992, Schumann and Gunderson 1996, Shi & Xu 1995, King & Minissale 1994, Strutt et al. 1995, Hubbard & Hagberg, 1996, Bunzl et al. 1998, Varley & Flowers, 1998b). Hubbard & Hagberg (1996) reported strong correlations between soil gas radon, barometric pressure and outdoor temperature, and , in agreement with Varley & Flowers (1998b) that maximum soil gas concentrations occurred during the summer months. As would be expected, diffusion of radon through the soil decreases with an increase in soil moisture whereas it increases with soil porosity (Shweikani et al. 1995). Sesana et al. (1999) also observed a link between radon concentration and variations of atmospheric pressure. Ek (1996) demonstrated that freezing does not generally cause capping of the soil profile although it may add to capping caused by high soil moisture. Freezing can, however cause an increase in radon content within the frozen soil. Weather conditions should be as stable as possible during the course of a soil gas radon survey. In the UK, it is recommended that radon in soil gas measurements are made during spring to autumn, when soils are relatively dry and thus more permeable (Ball et al. 1992). Talbot (1994) proposed a laboratory-based method that involves the measurement of radon emanation from soil samples to overcome these problems.

3.7. In the USA, Mose et al. (1992) concluded that both soil radon and soil permeability data are required to predict radon potential on a development site for new housing and hence act as a guide to the need for appropriate protective measures in a new home. Whereas Mose & Mushrush (1999a) confirmed that indoor radon can be predicted using soil radon and soil permeability for homes within a geographically small area, Mose & Mushrush (1999b) have also recommended caution when using soil gas and soil permeability measurements to characterise the radon potential of established communities and of areas not yet developed for housing. It is very important to note that the evaluation of building sites made on the basis of a single or few soil gas radon determinations could be very misleading if temporal (seasonal and day-to-day weather) variations were not considered (Schumann et al., 1992). Hutter (1995) observed that autumn radon concentrations could be up to ten times higher than in the winter at a site in New Jersey, USA and that spatial variations up to an order of magnitude exist over distances of a few metres. Three alternative radon site investigation methods were suggested by Yokel and Tanner (1992). In the first, an undisturbed soil sample is collected for dry density, gamma spectrometric and particle size analysis as part of the Standard Penetration Test used during geotechnical investigations. In the second method, radium is either determined by gamma spectrometry on a soil sample collected by auger or at the site by gamma ray spectrometry, whilst permeability is determined by percolation tests or visual estimation. The third method comprises the determination of radon in soil gas extracted using a pump monitor device in conjunction with in situ determination of dry density and water content.

3.8. In the UK, the BGS established a provisional geological radon potential classification on the basis of soil gas radon, permeability and indoor radon data for a range of geological units (Appleton & Ball 1995). Thus if the geometric mean radon concentration in soil over a bedrock unit with high permeability is >19 kBq m^{-3}, the geological unit was assigned to the 'High' geological radon potential class (Table 3-1). The validity of this classification was confirmed by investigations of the relationship between the fraction of houses above the Action Level and the radon potential class based on soil gas and permeability for the major geological units in the Somerset area (Cliff & Miles 1997).

Table 3-1. Provisional geological radon potential classification based on soil gas radon and permeability (adapted from Appleton & Ball 1995).

Predicted geological radon potential (GEORP*)	Rock and Soil Permeability		
	High	Moderate	Low
	Observed geometric mean radon concentration in soil gas (Bq/l)		
High (>10%)	>19	>26	nd
Moderate (3-10%)	9 - 19	19 - 26	26 - nd
Low (<3%)	<9	<19	<26

nd = no data available
* GEORP = Estimated % of dwellings overlying geological unit which exceed the UK radon Action Level of 200 Bq m^{-3}

3.9. Instruments for the determination of soil gas radon are 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). The establishment of national or regional reference sites for soil gas radon may be required for quality control (Matolín 1996). Appleton & Ball (1995) review soil gas radon survey and measurement procedures.

3.10. Gas permeability at a specific site can be estimated by a range of methods such as controlled gas extraction, air injection procedures or water percolation tests (Gundersen et al. 1988, Mose et al. 1992, Yokel & Tanner 1992, Steck et al. 1996, Kemski et al. 1996, Matolin et al. 2000, Neznal et al. 2000). *In situ* measurement and modelling of soil permeability at the Riso site, Denmark (Cliff and Miles, 1997, p.55-56) revealed that soil permeability varied over four orders of magnitude and that the effective permeability was considerably higher than the measured values. Modelling indicated that the effective permeability (related to cracks and macropores) probably controls radon movement through soil and into buildings. The presence and density of cracks and macropores may exert a greater influence on indoor radon concentrations than the micropore permeability determined by conventional *in situ* single probe permeability measurements (Anderson et al., 1994).

3.11. 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. Information on rock and overburden permeability in Great Britain can be obtained from various published and unpublished sources including Geological Survey memoirs and hydrogeological reports. In the UK, soil permeability closely reflects the permeability of the underlying rock and unconsolidated overburden (Ball et al. 1992). In England, the overall permeability and water saturation of soil associations are described by the system of Wetness Classes, grading from Wetness Class I (well drained) to Wetness Class VI (almost permanently waterlogged) (Findlay et al. 1984).

Radon site investigation procedures used prior to construction

Sweden

3.12. The Swedish National Board of Housing, Building and Planning has adopted a ground classification based on geology, permeability and soil gas radon measurement (Table 3-2). This procedure is used to predict radon emissions expected on a particular construction site. Local building boards are responsible for deciding which protective measures should be installed according to radon risk determined from site investigations. In normal situations, when the concentration of radon in soil air is 10,000 to 50,000 Bq m^{-3} the house has to have a radon protective construction whereas when the concentration is higher than 50,000 Bq m^{-3}, a radon safe construction has to be used. Below 10,000 Bq m^{-3} no radon protection is required although open penetrations to the ground below the house have to be sealed.

Table 3-2. Classification of ground according to the risk of radon gas. Recommendations issued by the National Swedish Board of Urban Planning and Building, 1982 (after Åkerblom, 1987, 1994)

Radon Risk Class	Types of Ground
High	Uranium rich granites, pegmatites and alum shale. Highly permeable soils, for example gravel and coarse sand. Rn concentration in soil gas >50 Bq/l
Normal	Rocks or soils with low or normal uranium content and average permeability. Rn concentration in the soil gas 10-50 Bq/l
Low	Rocks with very low uranium content, for example limestone, sandstone and basic igneous and volcanic rocks. Soils with low permeability, for example, clay and silt or soils where the radon concentration in the soil gas is <10 Bq/l

3.13. Where the soil cover is less than 2 metres thick over bedrock-geology that is deemed to be high risk, ground measurements are made of radon concentrations, even if the airborne survey reveals little radioactivity. The inclusion of limestones in the Swedish low radon risk class contrasts strongly with the situation in Great Britain where the Carboniferous Limestone is usually associated with a high proportion (>10%) of homes above the Action Level and Jurassic limestones frequently have >3% of homes exceeding the Action Level.

3.14. The general classification given in Table 3-2 is not adequate for site investigations in some situations when a more detailed classification is required (Table 3-3). This classification also covers the situation of a building founded on bedrock or fill and takes into consideration the permeability of the overburden (Åkerblom, 1987). Separate risk classifications, based on radium, uranium and soil gas radon concentrations, have been established for situations where buildings are to be constructed on unconsolidated sediments or directly onto bedrock (Åkerblom, 1987; 1994). The radon risk classification also takes into consideration the permeability of the overburden (Table 3-3).

Table 3-3. Criteria used in Sweden for classifying high-radon and low-radon ground (after Clavensjö and Åkerblom, 1994)

Bed-rock or overburden	Ra-226 (Bq/kg)	Rn-222 in soil gas (Bq/l)
High radon ground.		not relevant
Bare rock	>200	
Gravel, sand, coarse till	>50	>50
Sand, coarse silt	>50	>50
Silt	>70	>60
Clay, fine till	>110	>120
Low radon ground		
Bare rock	<60	
Gravel, sand, till	<25	<20
Silt	<50	<20
Clay, fine till	<80	<60

3.15. Whereas site investigations at the planning stage of construction work provide information of direct relevance to radon protection requirements, they are relatively expensive. In addition, scientific analysis has shown that radon (and other soil gas) measurements taken from boreholes may give inaccurate results. When the soil is disturbed by bore holes the emanation rate is changed and strong lateral and vertical variations in soil properties means that there is a need for many boreholes across the site in order to obtain an accurate estimate of soil gas radon concentrations (C. Samuelsson, personal communication). Measurement of radon in the ground is carried out by municipal authorities and also by private companies. The Swedish Radiation Protection Institute (SSI) is responsible for calibration of equipment (Snihs, 1992).

Finland

3.16. Finland has adopted a similar radon risk classification of building ground based on radioactivity and permeability (Slunga, 1988). The measurement of radon emanation coefficients and radium concentrations in soil by gamma spectrometry is used to investigate radon characteristics of soil in new building areas (Markkanen and Arvela, 1992).

Czech Republic

3.17. Following recommendations by the Czech Ministry of Public Health, radon risk has to be estimated at new building sites using radon site investigation and mapping procedures similar to those adopted in Sweden (Burian et al., 1993). All new development sites in the Czech Republic require, under Building Regulations, a site investigation comprising a geological survey and measurement of radon in soil gas (Barnet, 1994; Matolín, 1996; Neznal et al. 1996, Matolin et al. 2000). Radon concentrations in dwellings are generally proportional to concentrations in soil gas (Neznal et al., 1996; Barnet & Mikšová, 1999, Barnet et al. 2000). In the Czech Republic it was found that neither the normal nor the lognormal model was applicable to soil radon data. Firstly the median and subsequently the 75th percentile of the soil gas radon measurements for a site were recommended as the statistical parameter for the evaluation of soil gas radon site investigation data (Barnet, 1994).

3.18. The broad relationship between radon emission potential, radon concentration in soil gas and rock/soil permeability has been demonstrated also in the Czech Republic (Barnett, 1991; Matolin et al. 2000; Barnet et al. 2000) where information on rock and soil permeability are obtained from hydrogeological and pedological maps and reports.

3.19. Barnett (1991) established a radon emission risk classification based on data from the Czech Republic, Sweden and the USA. The Czech radon risk classification is based upon soil gas limits and is broadly similar to the BGS classification derived from radon potential studies in Somerset (see Table 3-1).

Table 3-4. Czech Republic radon risk classes based on radon in soil gas and rock-overburden permeability (after Barnet, 1991, 1994)

Radon Risk	**Rock-Overburden Permeability**		
	High	**Medium**	**Low**
	Radon concentration in soil gas (Bq/l)		
High	>30	>70	>100
Medium	10-30	20-70	30-100
Low	<10	<20	<30

3.20. There is a close correspondence between the soil gas radon concentrations at which basic radon protective measures are recommended in Sweden and the Czech Republic and the provisional threshold values suggested for England and Wales (Table 3-1).

Table 3-5. Comparison of soil gas radon concentrations (Bq/l) indicating that basic radon protective measures may need to be installed in new dwellings (compiled from Tables 3-1 to 3-4)

	Ground Permeability		
	High	**Medium**	**Low**
Country	Radon concentration in soil gas (Bq/l)		
England & Wales	9	19	26
Czech Republic	10	20	30
Sweden	10	20	60

Methodology for evaluation of site investigation procedures

Introduction

3.21. If radon site investigation procedures are to be effective for the determination of the requirement for radon protective measures in new buildings, any procedures used need to produce consistent and readily interpreted results in a wide range of geological environments and under a range of climatic conditions. The following sections of the report describe an evaluation of radon site investigation procedures in two contrasting geological environments in the counties of Northamptonshire and Derbyshire, both of which are important radon affected areas in central England (Lomas et al., 1996; Miles et al, 1996). This is followed by an evaluation of historical soil gas radon data that were collected principally for radon potential mapping .

Field sampling

3.22. Radon site investigations were carried out at 19 locations in Northamptonshire and 15 locations in Derbyshire during the summer (June 1996 and June-October 1996, respectively). One third of the sites were re-sampled in the winter (March 1996 and December 1996, respectively) to assess seasonal variations in soil gas radon. Locations were chosen to encompass geological units with a range of GEORPs[10] (from less than 1% of dwellings exceeding the Action Level (AL) to >10%>AL). Drift-free and boulder clay covered locations were investigated to assess the influence of superficial deposits.

3.23. At each of the sample sites a series of ten individual points were sampled using the following procedures: (1) radon and thoron concentrations in soil gas was determined using a 'Lucas cell' type scintillation counter by standard BGS procedures (Appleton & Ball, 1995) following extraction by pumping from a depth of 60-70 cm; (2) the permeability of the soil was determined qualitatively based on published wetness class data; (3) gamma spectrometric measurements for ^{214}Bi (^{238}U), ^{208}Tl (^{232}Th) and ^{40}K were made using an *Exploranium GR-256* gamma ray spectrometer equipped with a 3x3 inch NaI crystal; (4) radon emanation from a soil sample collected at a depth of 60-70 cm was determined in the laboratory (Talbot, 1994; Appleton and Ball, 1995).

3.24. The gamma spectrometer is used to measure the intensity of gamma radiation from Bi-214 in the U-238 decay series, Tl-208 in the Th-232 decay chain and a prompt gamma ray from K-40. Both the bismuth and thallium isotopes are daughter products of radon isotopes. The radon isotope in the thorium decay series (thoron, Rn-220) has a half-life of less than one minute. The other daughter products of Th generally have short half-lives, so consequently the Tl-208 gamma photopeak usually gives an accurate measure of the amount of Th in soils.

3.25. The situation is different for the uranium series because the early-formed daughters have long half-lives and their chemical properties are often different to the parent. Because of these chemical properties, uranium may become totally separated from its decay products. If this occurs then secular equilibrium in the decay chain can take up to 1.6 Ma to become re-established (91% in 1 Ma). Furthermore the radon isotope (Rn-222) has a 3.82 day half life so that it is capable of moving from its generation location. The Bi-214 photopeak, since it is a daughter of radon and radium, may therefore represent the total radon present in the soils better than many other measurements, especially those for uranium. Unfortunately there is no means of determining, in the field, the proportion of radon daughters referable to the labile component. The apparent uranium and thorium concentrations are usually given as eU (equivalent uranium) and eTh (equivalent thorium).

[10] GEORP = geological radon potential (Est.%>AL) for a specific combination of solid and drift in a specific area (i.e. County, map sheet or 5 km grid square)

3.26. A grid sampling pattern was used with a 20-25 m spacing, apart from four sites where this was not practicable due to access problems. At these sites, a linear pattern with a sample spacing of 10-25 m was adopted. A full suite of measurements were collected at all sites during the summer whereas only soil gas radon was measured at a third of the sites under winter conditions to assess seasonal variations.

Laboratory determination of radon emanation

3.27. Laboratory determination of radon emanation utilised a recently developed method based on liquid scintillation counting (LSC; Talbot, 1994). Approximately 20g of dried soil is mixed with water in a 215 ml glass bottle. This is then sealed and allowed to stand for four weeks to allow radon released into the water to reach equilibrium. The bottle is shaken daily to facilitate radon release. After four weeks, a 10 ml aliquot of water is extracted by syringe and injected into the bottom of an LSC vial which already contains 10 ml of a toluene-based LSC cocktail and the vial is tightly capped. Shaking the vial for 30 seconds quantitatively extracts any radon present in the water into the organic phase. By using a liquid scintillation counter with an α - β discrimination capability, such as the LBK Wallac 1219 operated by BGS, and selection of a suitable counting window, it is possible to measure directly the α spectrum of the organic phase of the sample and hence determine the radon concentration in the water phase (Figure 3-1), which is recalculated to give the radon release (emanation) of the soil in Bq/kg.

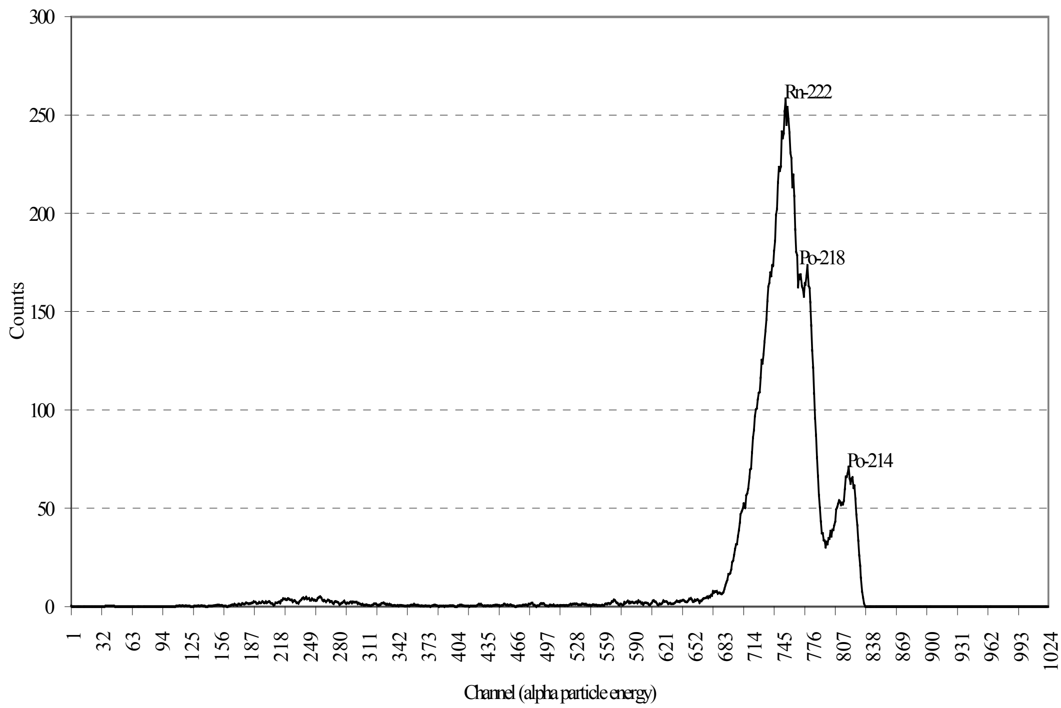


Figure 3-1. LSC spectrum of radon.

Evaluation of effectiveness of site investigation procedures

3.28. The effectiveness of these radon site investigation procedures has been evaluated by studying the relationship between the soil gas radon, gamma spectrometry and radon emanation data with an independent estimate of the radon potential. For this study, the geologic radon potential (GEORP), which is the proportion of existing dwellings which exceed the Action Level for a particular combination of solid and drift geology within a defined geographic area, has been used as the independent estimate of radon potential. In Northamptonshire, GEORP was calculated for each combination of solid and drift geology for three 1: 50 000 scale geological map sheets on the basis of approximately 63 000 house radon measurements. In Derbyshire, which is a more rural area and has a lower density of indoor radon measurements available, the county average GEORP for each combination of solid and drift geology was calculated on the basis of approximately 27 000 house radon measurements. Where an adequate number of house radon measurements were available, GEORP was also estimated for each combination of geologies within 5 km grid squares. Soil gas geological radon potential (SG-GEORP) was also estimated from radon in soil gas data using a calibration plot, which takes into account the estimated permeability of the ground.

Evaluation of Site Investigation Procedures I: Northamptonshire

Site characteristics

Geological Radon Potential (GEORP)

3.29. Jurassic geological units evaluated included the Upper Lias Clay (Low GEORP <0.1 to 2.8%>AL), the Blisworth Limestone (formerly known as the Great Oolite Limestone; Low GEORP 0.3 to 1.8%>AL) and the Northampton Sand Formation (High GEORP 6.8 to 16.4%>AL). Adjoining sites covered by Boulder Clay were also sampled for each bedrock to assess the influence of drift. The same combinations of bedrock and drift were investigated in the Kettering, Northampton and Wellingborough areas. In addition, a site on the Middle Lias Silts and Clays (Low GEORP 1.2%>AL) was selected in the Northampton area because it was difficult to identify a site upon the Blisworth Limestone. The Middle Lias Silts and Clays do not crop out within the Wellingborough and Kettering Sheets. In addition, a site with Glacial Sands and Gravels overlying the Middle Lias Silts and Clays was sampled.

Geology

3.30. *Low GEORP:* The *Upper Lias Clay Formation.* This formation in the Northampton area is 47-60 m thick and comprises mainly mudstones with a number of thin argillaceous limestones near the base. The middle and upper parts are composed of blue-grey mudstones with calcareous and ferruginous nodules.

3.31. *Low GEORP: The Middle Lias Silts and Clays Formation* crops out on the Northampton Sheet only. It comprises mostly siltstones, with subordinate mudstones and sandstones along with thin silty limestones. The formation is 16-30m thick. *Blisworth (Great Oolite) Limestone*: In the Northampton area this geological unit consists of 2-7 m of shelly and oolitic limestone with marls and clays near the base whereas in the Wellingborough area the formation is 4-8 m thick and is overlain by 1-5 m of the Blisworth Clay. In the Kettering area the Blisworth Limestone is about six metres thick and comprises a basal soft limestone occupying the lower one third of the succession overlain by more massive limestone.

3.32. *High GEORP:* The *Northampton Sand Formation* in the Northampton area is 4-23 m thick and consists of a lower ironstone, often with an uraniferous nodular horizon at the base, overlain by a massive yellow or brown calcareous sandstone (the Variable Beds) which has a lower level of uranium, less phosphate and lower permeability. The Variable Beds are largely missing from the Kettering and Wellingborough areas where the Northampton Sand Formation is only 0-7m thick.

3.33. *Boulder Clay* covering parts of these bedrock units in Northamptonshire is locally classified as "Chalky Boulder Clay" since it usually contains small clasts of chalk in the clay matrix. However, much of the clasts and matrix are locally derived. Boulder Clay over the Northampton Sand Formation, for example, contains abundant clasts of ferruginous sandstone in addition to chalk.

3.34. *Glacial Sands and Gravels* are widespread over the western part of the Northampton sheet. They mostly pre-date the Chalky Boulder Clay and again are mostly locally derived.

Land Use

3.35. Because of the potential effect that different cropping regimes may have upon the behaviour of the radioelements a summary of land use for the various sites is given in Appendix 1. Permanent pasture usually has residual ridge and furrow structure and the surface has not been significantly disturbed since the enclosure of the open fields which took place about 200 years ago. Modern ploughing destroys the ridge and furrow structure within about three years. As in most of lowland Britain, much of the existing farmland is developed on forest brown-earths of various stages of maturity. The soil structure has largely been maintained by ploughing.

Soil

3.36. Soils over the Upper Lias Clay and the Boulder Clay are usually water retentive. These soils have been classified as "argillic pelosols", following the description of Avery (1973). Some gleying (iron mottling) was observed in boulder clay overlying the Northampton Sand Formation. According to the Soil Survey, these soils have a typical Wetness Class of 3 and a related Integrated Air Capacity of about 50-70 mm/m. Under winter conditions it was difficult or impossible to extract soil gas from the soils. This is a major operational limitation of the soil gas radon site investigation procedure.

3.37. Soils over the Blisworth Limestone contain clasts of chalky limestone and buff coloured sandstone in a clay matrix. They are tentatively classed as rendzinas with a Wetness Class of 3.

3.38. Soils over the Northampton Sand Formation are usually well drained and may be classed as Brown Earths (brunisols), with a Wetness Class of 1 and an Integrated Air Capacity of about 200 (+/- 10) mm/m.

3.39. The Middle Lias Silts and Clays generally give rise to argillic brown earths with a Wetness Class of 2 and an Integrated Air Capacity of 80-100 mm/m.

3.40. It has been demonstrated (Appleton and Ball, 1995) that it is essential to take soil and rock permeability into account when using soil gas radon measurements to assess the GEORP of a site. In this study, soil Wetness Class information obtained from Soil Survey publications was used as a measure of permeability. Other site investigation studies have determined soil permeability at each site but no allowance was made for such measurements to be made during the present investigation.

Results

3.41. A statistical summary of the results for the summer site investigations is presented in Table 3-6 and a comparison of summer and winter data in Table 3-7.

Table 3-6. Summary of summer site investigation results for Northamptonshire (median values).

Site	50K Sheet	Bedrock Geology	Drift Geology	WC	GEORP Map	GEORP Soil Gas	SG Radon Bq/l	SG Thoron Bq/l	Lab Radon Bq/kg	eK %	eU ppm	eTh ppm
T17	171	Blisworth Limestone	Boulder Clay	3	0.1	1.7	7.6	19.4	6.8	1.2	1.2	9.4
T24	186	Blisworth Limestone	Boulder Clay	3	0.2	0.5	3.6	11.6	6.2	1.6	1.6	7.0
T16	171	Blisworth Limestone	No drift	3	0.3	0.6	4.1	14.6	7.4	1.4	1.5	7.2
T23	186	Blisworth Limestone	No drift	3	1.8	0.8	4.8	19.3	6.8	1.1	1.3	5.1
T11	185	Middle Lias Clay (g2)	GS&G	2	0.6	3.2	10.4	22.3	3.8	0.9	0.7	8.4
T09	185	Middle Lias Clay (g2)	Boulder Clay	2	0.2	2.2	8.5	20.9	8.4	1.3	1.2	7.0
T10	185	Middle Lias Clay (g2)	No drift	2	1.2	1.4	6.8	21.7	5.1	1.1	1.0	7.1
T12	186	Northampton Sand (g5)	Boulder Clay	2	2.6	0.5	3.6	13.9	9.3	1.5	1.5	6.0
T18	185	Northampton Sand (g5)	Boulder Clay	2	3.1	0.8	4.8	19.7	5.1	1.2	1.0	8.6
T25	171	Northampton Sand (g5)	Boulder Clay	2	0.7	1.4	6.8	21.0	8.0	1.4	1.4	7.1
T13	186	Northampton Sand (g5)	No drift	1	16.4	15.9	14.3	47.1	7.1	1.1	1.5	12.6
T19	185	Northampton Sand (g5)	No drift	1	6.8	2.5	5.8	28.2	5.8	0.9	1.0	14.8
T20b	185	Northampton Sand (g5)	No drift	1	6.8	13.6	13.2	45.8		0.9	1.1	13.3
T26	171	Northampton Sand (g5)	No drift	1	11.6	16.5	14.6	41.6	6.6	0.7	1.3	8.1
T07	171	Upper Lias Clay (g3)	Boulder Clay	3	0	1.1	5.9	16.5	4.9	1.2	1.2	10.2
T14	186	Upper Lias Clay (g3)	Boulder Clay	3	2.6	0.8	4.9	11.3	9.1	1.4	1.5	7.9
T22	185	Upper Lias Clay (g3)	Boulder Clay	3	0.2	1.2	6.2	20.5	7.8	1.1	1.2	7.5
T08	171	Upper Lias Clay (g3)	No drift	3	2.8	1.2	6.3	18.5	5.3	1.2	1.1	8.9
T15	186	Upper Lias Clay (g3)	No drift	3	0	2.5	9.1	24.9	9.4	1.4	1.6	7.6
T20a	185	Upper Lias Clay (g3)	No drift	3	0.9	0.6	4.2	25.0		1.1	1.5	10.6
T21	185	Upper Lias Clay (g3)	No drift	3	0.9	0.2	-0.1	10.0	8.1	1.1	1.5	6.7

Lab. = laboratory determination of radon emanation; SG = soil gas; GEORP Map = geological radon potential for 1:50,000 scale geological map; GEORP Soil Gas = geological radon potential estimated from calibration plot (Figure 3-8); WC = soil wetness class from Soil Survey of England and Wales (1984); K, eU, eTh determined by gamma spectrometry

Table 3-7. Comparison of winter and summer data for Northamptonshire (median values)

Site	Date	50K map sheet	Bedrock	Drift	GEORP	WC	SG radon Bq/l	SG thoron Bq/l	eK %	eU ppm	eTh ppm
T01	March 96	185	Upper Lias Clay (g3)		0.9	3	0.3	0.5	0.9	1.5	7.3
T21	June 96	185	Upper Lias Clay (g3)		0.9	3	-0.1	10.0	1.1	1.5	6.7
T02	March 96	185	Upper Lias Clay (g3)	Boulder Clay	0.2	3	13.8	5.2	0.9	1.6	6.4
T22	June 96	185	Upper Lias Clay (g3)	Boulder Clay	0.2	3	6.2	20.5	1.1	1.2	7.5
T04	March 96	185	Northampton Sand (g5)		6.8	1	21.6	17.3	0.8	1.1	9.9
T19	June 96	185	Northampton Sand (g5)		6.8	1	5.8	28.2	0.9	1.0	14.8
T03	March 96	185	Northampton Sand (g5)	Boulder Clay	3.1	2	5.1	7.2	1.0	1.2	5.7
T18	June 96	185	Northampton Sand (g5)	Boulder Clay	3.1	2	4.8	19.7	1.2	1.0	8.6
T06	March 96	171	Blisworth Limestone		0.3	3	6.7	9.0	0.8	1.9	10.4
T16	June 96	171	Blisworth Limestone		0.3	3	4.1	14.6	1.4	1.5	7.2
T05	March 96	171	Blisworth Limestone	Boulder Clay	0.1	3	0.0	4.9	1.2	1.8	11.6
T17	June 96	171	Blisworth Limestone	Boulder Clay	0.1	3	7.6	19.4	1.2	1.2	9.4

Lab. = laboratory determination of radon emanation; GEORP = geological radon potential for 1:50,000 scale geological map; WC = soil wetness class from Soil Survey of England and Wales (1984); K, U, Th determined by gamma spectrometry

Seasonal variations

3.42. Largely because of the waterlogged nature of some of the soils and the water retentiveness of others it is clear that under winter conditions it is only practicable to sample a limited number of environments using field-based soil gas methods. A full complement of soil gas samples was only obtained over the Northampton Sand Formation. During winter conditions only one adequate sample of soil gas was obtained over the Upper Lias Clay. However the situation improved slightly over the nearby Boulder Clay with about half the locations yielding sufficient soil gas for analysis. Even over the potentially well-drained Blisworth Limestone it was difficult to obtain a reliable soil gas sample at a number of locations. Therefore the radon in soil gas median values for the Upper Lias Clay and Blisworth Limestone (and also for the sites where these two units are covered with boulder clay) should be treated with caution (Table 3-7).

3.43. The Northampton Sand Formation was characterised by higher soil gas radon concentrations in winter than in summer (Duplicate site T04-T19; Table 3-7) due to the sealing effect of soil moisture which prevents the escape of radon from the soil. A similar relationship is seen at site T02-T22. When gas samples are taken below the moisture saturated upper layer, the collected soil gas has aged slightly with a consequential in-growth of radon and decay of short lived thoron. The general increase in soil moisture may also retard the migration of thoron due to its short half life.

3.44. The values over the Northampton Sand Formation in the Northampton Sheet (Sites T04-T19) are the only ones to show a very marked decrease in radon levels in summer time. This was the only site with close-to-mature oil-seed rape (Appendix 1). Along with the dry conditions and the nature of the root and stem systems of the plant, it is possible that the permeability of surface samples was substantially increased thus allowing the reduction in soil gas radon through dilution with the atmosphere. It should be noted, however, that compared with the other sites over Northampton Sand Formation sampled during the summer (Table 3-6) that site T19 is unusual in that soil gas radon, thoron and eU are all lower than for the other three sites (T13, 20b, 26; Table 3-6).

3.45. The main conclusion to be drawn from the comparison of winter and summer site investigation is that soil gas radon measurement during the winter period is not practicable over many geological units due to waterlogging of impermeable soils.

3.46. Because of the problems associated with site investigation data collected during the winter period, the evaluation of soil gas radon, laboratory radon emanation and gamma spectrometry site investigation procedures is based largely on the data collected during the drier summer period.

Soil gas radon

3.47. During summer conditions, soil gas samples were obtained from most of the sites. For the Upper Lias Clays the mean Rn in soil gas value remained low with a median of 5.0 Bq/l. Similar values were obtained over the Boulder Clay covered areas (6.4 Bq/l; Table 3-8). Although previous site investigation data indicate that the Upper Lias Clay can produce moderate amounts of radon (Sharman, 1991) it is unlikely to enter houses because of the low permeability of the mudstones. Much higher concentrations typify the Lower Lias Clays (Sharman, 1995; and Table 3-14 below) but low permeability reduces the radon risk in houses.

3.48. Over the Blisworth Limestone a median of 4.4 Bq/l was obtained with a similar value where the limestone is covered with Boulder Clay (5.9 Bq/l).

3.49. The Northampton Sand Formation (median 11.7 Bq/l; Table 3-8) has a summer radon concentration that is significantly higher than the other three geological units investigated. The median decreases to 5.6 Bq/l where the Northampton Sand Formation is covered with Boulder Clay.

3.50. With the exception of the Northampton Sand Formation, there appear to be no significant differences between the median values for drift free and drift covered sites when the site results are grouped together (Table 3-8). However, when pairs of drift free and drift covered sites from the same map sheet are considered separately, significant differences emerge. Statistical examination of the data using a variety of tests (one way analysis of variance; Students T test; non parametric Kruskaal - Wallis and Kolmogorov-Smirnoff tests) show that significant differences are observed between the concentrations of radon in soil gas for the Boulder Clay and non-drift covered areas for the Blisworth Limestone as well as the Northampton Sand Formation. However, no significant difference exists between Boulder Clay covered and uncovered sites over the clay rich rocks of the Middle and Upper Lias. These results reflect the reduction of radon flux caused by the superimposition of relatively impermeable boulder clay on permeable limestones and sandstones.

3.51. The median soil gas radon concentrations for the four geological units samples during the present investigation are similar to median concentrations reported by Sharman, 1995 (Figure 3-2).

Table 3-8. Summary statistics for geological units in Northamptonshire (medians)

Bedrock Geology	Drift Geology	GEORP (Map)	Wetness Class	GEORP* (Soil gas radon)	Soil gas Radon Bq/l	Soil gas Thoron Bq/l	Lab. Radon Bq/kg	eK %	eU ppm	eTh ppm
Blisworth Limestone (g7)	Boulder Clay	0.2	3	1.1	5.9	16.3	6.6	1.4	1.4	8.2
Blisworth Limestone (g7)		1.1	3	0.7	4.4	17.0	7.2	1.4	1.4	8.2
Middle Lias Clay (g2)	Boulder Clay	0.2	2	2.2	8.5	20.9	8.4	1.3	1.2	8.1
Middle Lias Clay (g2)		1.2	2	1.4	6.8	21.7	5.1	1.1	1.0	6.4
Northampton Sand (g5)	Boulder Clay	2.1	2	1.0	5.6	18.7	8.1	1.4	1.3	8.5
Northampton Sand (g5)		9.7	1	10.7	11.7	42.6	6.3	0.9	1.2	12.0
Upper Lias Clay (g3)	Boulder Clay	0.9	3	1.1	5.9	16.5	7.3	1.2	1.3	7.7
Upper Lias Clay (g3)		1.2	3	0.9	5.4	18.6	6.7	1.2	1.5	8.1

* derived from calibration plot (Figure 3-8)

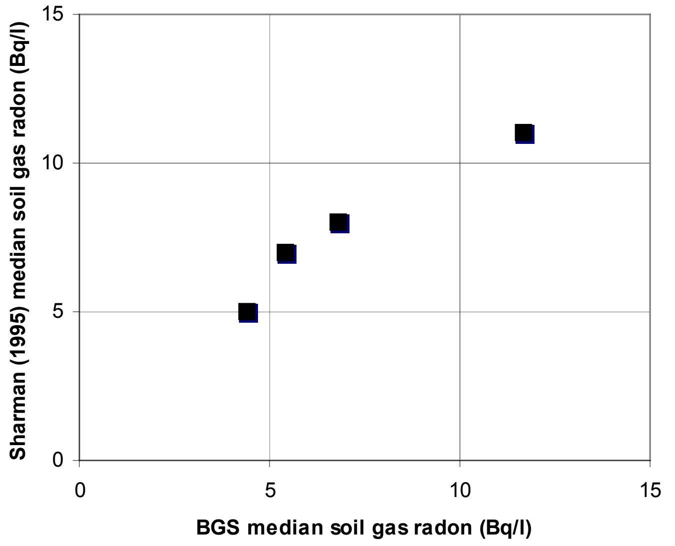


Figure 3-2. Comparison of BGS (this report) and Sharman (1995) median soil gas radon for four geological units in Northamptonshire

Soil gas thoron

3.52. Thoron concentrations are particularly high in summer conditions compared to winter (Table 3-7) and are also higher in permeable soils than in relatively impermeable soils (Tables 3-6, 3-8 and Figure 3-3). Whereas thoron concentrations in soil gas have been used previously to give a rough estimate of relative permeability for areas that have a similar concentration of thorium, higher thoron in the permeable soils overlying the Northampton Sand Formation probably reflects higher Th in the bedrock and soil (see eTh data in Table 3-8 and Sutherland, 1991).

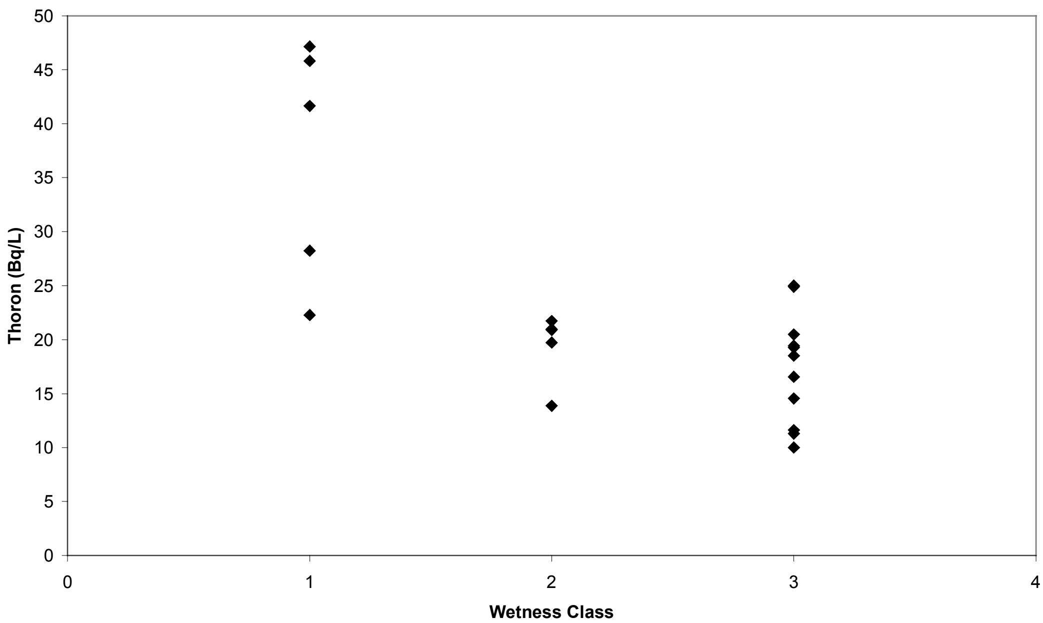


Figure 3-3. Relationship between Thoron (Bq/L) in soil gas and Soil Wetness Class in Northamptonshire

K, eU and eTh

3.53. eTh is significantly higher over the Northampton Sand Formation than over the other geological units investigated (Tables 3-6, 3-8) reflecting higher bedrock concentrations (Sutherland, 1991). eTh is depressed to background values (7-8 ppm) where the Northampton Sand Formation is covered with boulder clay (Table 3-8).

3.54. There appears to be little difference between median K and eU values for the different geological units investigated (Table 3-8) apart from the lower K associated with the Northampton Sand Formation, which probably reflects lower clay concentrations in the soils over this arenaceous (sandy) geological unit.

3.55. Uranium is often associated with, or is contained in, thorium minerals. In such a case the emanation coefficient for Rn-222 is lower than if uranium occurs in a separate mineral phase. Thorium-rich minerals are usually resistant to weathering and therefore retain their integrity in the weathering zone. The resultant low specific surface area and high density of the thorium mineral reduces the amount of radon that can escape from the mineral. The eTh/eU ratio may be used to give a rough estimate of the amount of uranium located in the thorium bearing minerals. If the eTh / eU ratio is greater than four, then it can reasonably be assumed that much of the uranium is contained in a thorium mineral. The median eTh/eU ratio for most sites is approximately 6 with the Northampton Sand Formation (no drift) reaching 10. It is concluded that significant amounts of uranium are contained in thorium rich minerals. In the case of the Northampton Sand Formation U and Th are likely to be concentrated principally in iron oxides.

Radon emanation from soil samples (laboratory data)

3.56. The values for radon emanation data in Tables 3-6 and 3-8 are laboratory determined and indicate the maximum available labile radon. This is the maximum radon that could be obtained from the mineral fraction of the soil that is available to pass into the gas phase if the soil was completely dry or into the water phase if the soil was completely water-logged. In practice this gives an imprecise correlation with the soil gas radon because of the varying nature of the water content of the soils, the partition coefficient between water and air, and the likely migration of radon bearing ground gas from deeper levels. However, previous work (Talbot, 1994) demonstrated that the correlation between soil gas radon measured in the field and radon emanation measured in the laboratory (Figure 3-4) is sufficiently good for the analysis of the radon emanation from soils to be considered an appropriate method for estimating radon potential. Talbot (1994) concluded that the method was relatively low cost and rapid and could be used at all times of year as the results were not affected by climatic conditions, unlike field measurement of soil gas radon. Talbot's conclusions were based on a field programme in Derbyshire and Figure 3-4 clearly shows that the majority of the geological units investigated could not be distinguished from each other. Only the Carboniferous Limestone units that produce very high levels of soil gas radon (90-100 Bq/l in the field determinations) also produce high levels of radon in laboratory emanation tests (Figure 3-4).

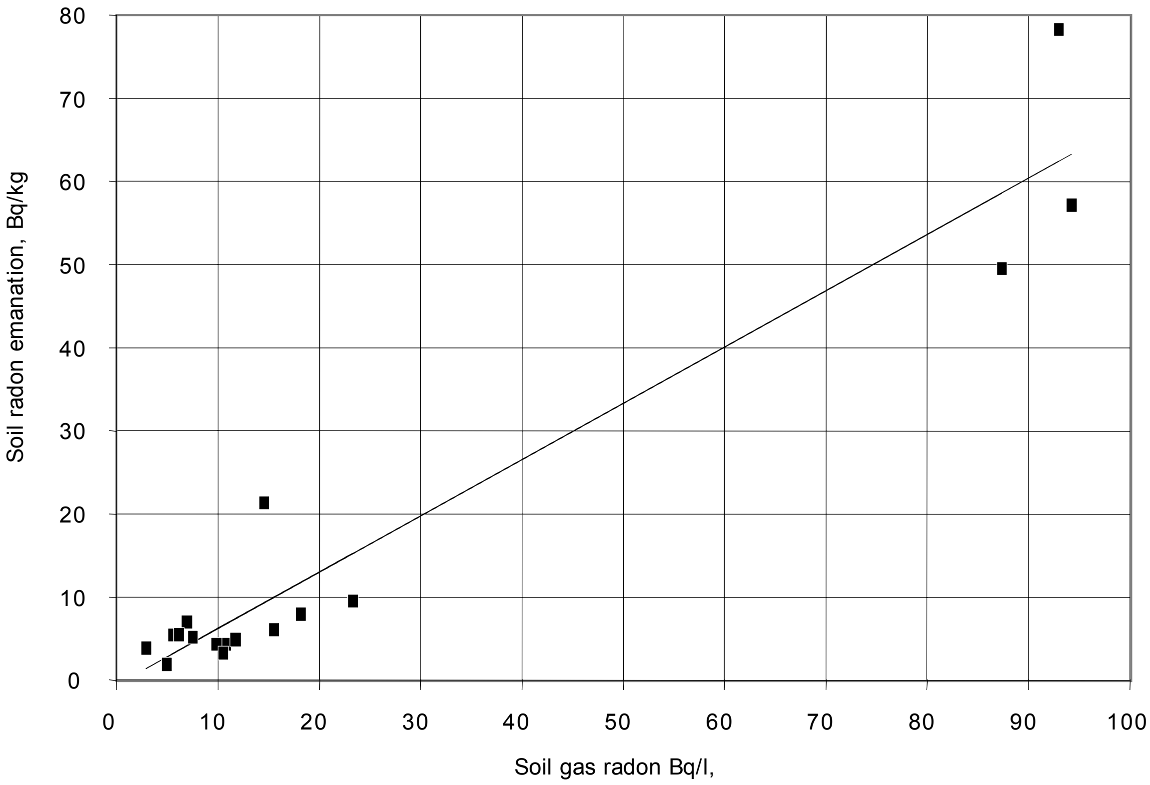


Figure 3-4. Relationship between soil gas radon (Bq/L) and soil radon emanation measured in the laboratory (samples grouped by geology, Talbot, 1994)

3.57. The results obtained for the Northamptonshire sites indicate that it is not possible to use the laboratory radon emanation data to distinguish between sites of low, moderate and high radon potential (Tables 3-6 and 3-8). The Northamptonshire results plot at the bottom left corner of the plot shown in Figure 3-4. It appears that the radon emanation procedure does not appear to be capable of indicating radon potential when the overall radon in soil gas concentrations are low (<20 Bq/l).

Soil gas radon, laboratory radon emanation and eU as indicators of radon potential

3.58. The geological radon potential calculated from existing house radon measurements for the map sheet in which each site is located (GEORP(Map)) is compared with the selected site investigation radon potential indicators (soil gas radon, laboratory soil radon emanation, eU and GEORP(Soil Gas radon) derived from soil gas radon results) in Table 3-9 and Figures 3-5, 3-6, 3-7 and 3-9.

3.59. Soil gas radon shows a strong correlation with GEORP(Map) significant at the 99.5% but neither eU nor laboratory radon emanation correlate significantly with GEORP(Map). Although soil gas thoron correlates significantly with GEORP(Map) at the highest level (99.9%) this reflects the co-incidental high permeability and eTh in the Northampton Sand Formation. Therefore thoron concentrations cannot be used to give a direct indication of GEORP(Map).

3.60. It has been demonstrated previously (Appleton and Ball, 1995; Sharman, 1995) that it is necessary to take soil and rock permeability into account when using soil gas radon measurements to predict GEORP. Appleton and Ball (1995) set out a provisional classification that has been refined to produce a new soil gas radon calibration plot (Figure 3-8). This illustrates the relationship between soil gas radon and the percentage dwellings estimated to exceed the Action Level and comprises two general calibration lines for permeable and impermeable soils and rocks. Conversion of the soil gas radon to an estimate of GEORP using the soil gas radon - soil permeability calibration improves the predictive value of the soil gas radon data (Figure 3-9 and Table 3-8).

3.61. As there is no significant difference in eU or laboratory radon emanation between the four geological units evaluated (Table 3-8), it can be concluded that soil gas radon and radon potential (GEORP) in Northamptonshire is related more closely to rock and soil permeability and possibly to the uranium concentration in underlying rocks than to radium (eU) concentrations in the superficial soils.

Table 3-9. Pearson correlation matrix for Northamptonshire site investigation results (n = 15)

	GEORP (Map)	*GEORP (Soil Gas Rn)*	*Wet Class*	*Radon Bq/l*	*Thoron Bq/l*	*Lab Rn Eman Bq/kg.*	*K %*	*eU ppm*
GEORP (Soil Rn)	0.87							
Wet Class	-0.76	-0.74						
Radon	0.67	0.88	-0.68					
Thoron	0.81	0.92	-0.78	0.88				
Lab Rn Emanation	-0.06	-0.06	0.18	-0.15	-0.14			
K%	-0.49	-0.59	0.57	-0.54	-0.66	0.51		
eU ppm	0.03	-0.02	0.36	-0.22	-0.14	0.74	0.58	
eTh ppm	0.55	0.48	-0.54	0.42	0.63	-0.35	-0.49	-0.30

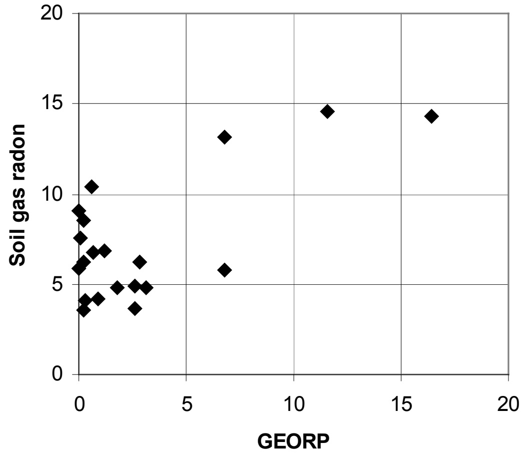


Figure 3-5. Plot of GEORP vs. soil gas radon (Bq/l), Northamptonshire

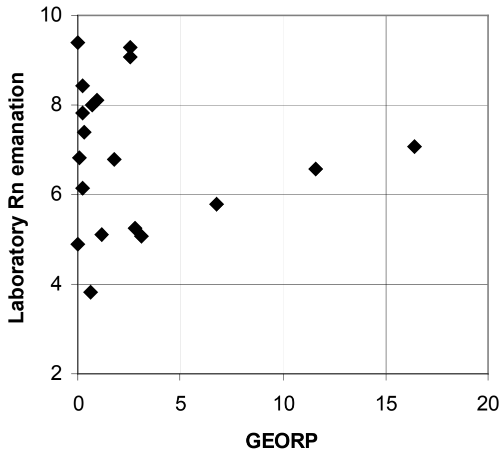


Figure 3-6. Plot of GEORP vs. Laboratory radon emanation (Bq/kg), Northamptonshire

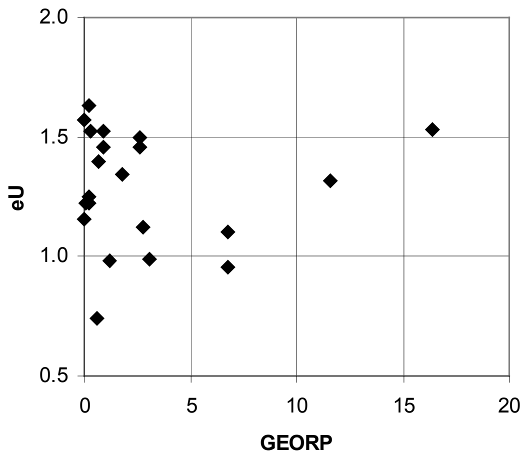


Figure 3-7. Plot of GEORP vs. eU (ppm), Northamptonshire

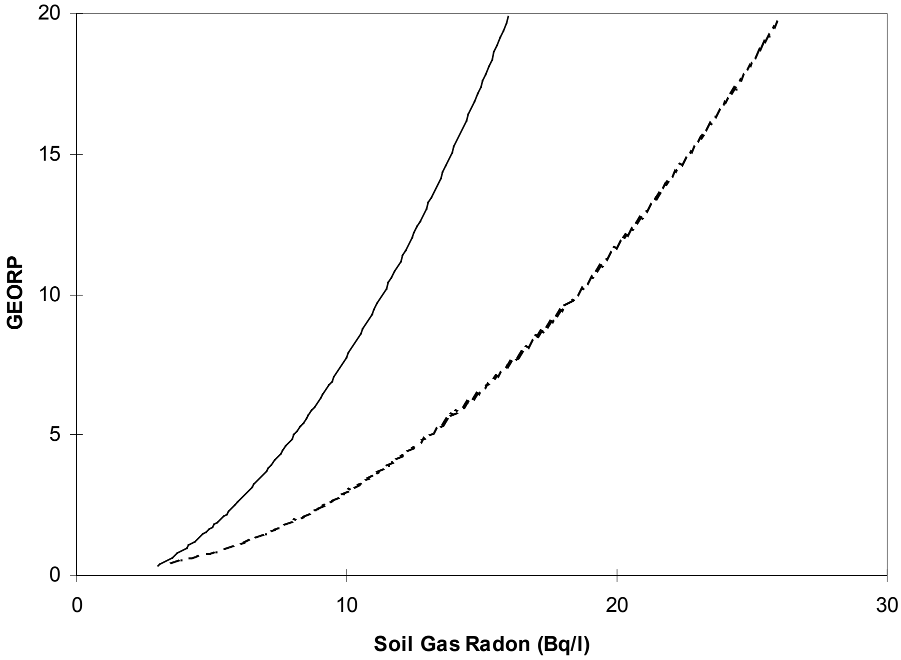


Figure 3-8. Provisional calibration plot for estimating geological radon potential (GEORP = estimated percentage of dwellings exceeding the UK Action Level of 200 Bq m³) from soil gas radon (Bq/l) and permeability (solid line = high permeability; broken line = moderate-low permeability). *The plot is derived from soil gas and indoor radon data for a series of geological units with a range of permeabilities. It illustrates the importance of using both soil gas radon concentration and permeability for the assessment of geological radon potential.*

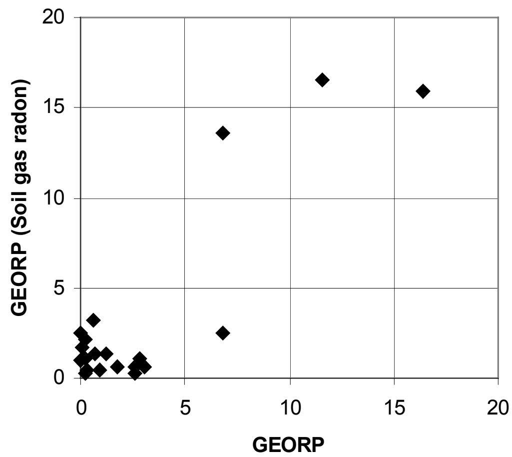


Figure 3-9. Plot of GEORP (Map) vs. GEORP (Soil gas radon), Northamptonshire

Evaluation of Site Investigation Procedures II: Derbyshire

Site characteristics

Geological Radon Potential (GEORP)

3.62. Geological units evaluated included the Crawshaw Sandstone of the Lower Coal Measures (Low - Moderate GEORP 0.4-2.1%>AL), the Monsal Dale (formerly known as Matlock) Limestones (High GEORP 14.5%>AL), the Longstone Mudstone Formation (High GEORP 20%>AL), Lower Coal Measures Shale (Low GEORP 0.5%>AL) and the Lower Magnesian Limestone (Low-Moderate GEORP 1.5%>AL). Adjoining sites covered by Boulder Clay were also sampled for each bedrock to assess the influence of drift.

3.63. Two GEORP values have been used in the course of this investigation. County GEORP is based on the analysis of all house data on the given geology within the county of Derbyshire. 5 km grid square GEORP is based on the house data for the given geology from the 5 km National Grid square in which the sample site is located.

3.64. For the site underlain by Boulder Clay on Crawshaw Sandstone, the grid square GEORP from an adjacent grid square has been used as no house data are available from the grid square containing the site. No house radon data are available for two combinations of drift and solid geology, which occur over relatively small areas of Derbyshire (Boulder Clay on Lower Magnesian Limestone and Monsal Dale Limestones).

Geology

3.65. *Low GEORP:* The *Lower Coal Measures Shales* form part of a sequence of marine shale and sandstone with a total thickness of about 600 m. A large number of coal seams and marine bands occur in this sequence. The boulder clay overlying this formation is a stiff, sometimes sandy clay containing rock fragments of both local and Lake District origin.

3.66. *Low to Moderate GEORP:* The *Crawshaw Sandstone* is a coarse-grained, cross bedded gritstone containing thin beds of mudstone and siltstone. It is typically 30-40 m thick. In the area of site D15 the Crawshaw Sandstone is covered by a sticky grey boulder clay which contains numerous blocks of locally-derived sandstone.

3.67. *Moderate GEORP:* The *Lower Magnesian Limestone* in the area investigated is about 12 m thick. It is a pink to yellow dolomitic limestone with some mudstone partings. The boulder clay on this formation is a red clay with sand and gravel bands.

3.68. *High GEORP:* The *Monsal Dale Limestones* are pale to medium grey, karstic limestones with interbedded lavas. In the vicinity of the sample sites it is approximately 65 m thick. The Winster Moor Lava is found between sites D9 and D7. The *Longstone Mudstone Formation* is approximately 17 m thick beneath the boulder clay at site D10 and approximately 20m thick in the vicinity of sites D11 and D12. It is a dark grey, sometimes calcareous mudstone of marine origin. Anomalously high uranium concentrations were observed over some of site D11 during the course of this investigation.

3.69. Boulder Clay covering parts of the high GEORP bedrock units is generally described as a stiff brown clay which contains erratics of both local and North West England origin.

Land Use

3.70. All of the sites tested, with the exception of those on the Lower Magnesian Limestone and one on Crawshaw Sandstone were on permanent pasture. Those on the Lower Magnesian Limestone were on arable land and site D15 (Crawshaw Sandstone) was on a broad roadside verge. However, because of the potential effect that differing land use regimes may have upon the behaviour of the radioelements, a detailed description of use at the time of sampling is presented in Appendix 2.

Soil

3.71. The main soil associations overlying the geological units studied are given in Appendix 4 (Soil Survey of England and Wales, 1984).

3.72. The Dale association, characterised by surface-water gley soils, occurs over the Lower Coal Measures Shales and the Longstone Mudstone. These are usually seasonally waterlogged soil of Wetness Class IV. Where the shales are overlain by glacial drift (boulder clay) they are characterised by the Dunkeswick association of stagnogley soils which tend to be waterlogged for long periods in the winter (Wetness Class IV).

3.73. Sandstones within the Lower Coal Measures sequence, such as the Crawshaw Sandstone, are characterised by soils of the Rivington 1 Association which are generally well drained coarse loamy soils. At site D15 the Crawshaw Sandstone is covered by a sticky grey boulder clay probably overlain by slowly permeable, fine loamy soils of the Brickfield 2 Association. These soils are seasonally waterlogged with slowly permeable subsurface horizons (Wetness Class IV).

3.74. Brown calcareous earths of the Aberford Association (Wetness Class I) overlie the Lower Magnesian Limestone. The glacial till (boulder clay) on this formation is a red clay with sand and gravel bands on which soils of the Salop association are developed. These are mainly stagnogley soils (Wetness Class IV) with slowly permeable subsoils in reddish drift derived mainly from Permo-Triassic rocks.

3.75. Brown earths of the Malham 2 association developed on silty aeolian drift overlie the Monsal Dale Limestones or Matlock Limestones. These are shallow or moderately deep fine silty soils with a characteristic brown unmottled soil over hard limestone. The soils are very porous (Wetness Class I). Boulder Clay covering parts of the Monsal Dale Limestones is generally a stiff brown clay upon which Dunkeswick association stagnogley soils have developed. These tend to be waterlogged for long periods in the winter (Wetness Class IV).

Results

3.76. A statistical summary of the results for the summer site investigations is presented in Table 3-10 and a comparison of summer and winter radon and thoron data in Table 3-11.

Table 3-10. Summary of summer site investigation results for Derbyshire

Site	50k Sheet	Bedrock Geology	Drift Geology	Wetness Class	GEORP Map	GEORP 5-km	GEORP* Soil Gas	SG Radon Bq/l	SG Thoron Bq/l	Lab. Radon Bq/kg	eK %	eU ppm	eTh ppm
D1	112	Magnesian Limestone	None	1	1.5	0.9	9.2	10.9	13.1	5.7	1.4	1.6	6.9
D2	125	LCM Crawshaw Sdst.	None	1.5	2.1	2.1	0.2	1.0	9.2	0.7	1.0	1.9	6.7
D3	125	LCM Shale	None	4	0.5	0.1	0.7	4.4	6.6	1.1	0.9	1.6	5.9
D4	125	LCM Shale	None	4	0.5	0.1	0.2	0.8	8.2	1.9	1.4	2.6	6.3
D5	125	LCM Shale	Boulder Clay	4	0.5		0.3	2.0	7.1	0.7	1.2	2.8	5.8
D6	125	LCM Crawshaw Sdst.	None	1.5	2.1	2.1	0.5	3.6	7.3	10.1	0.7	2.6	4.2
D7	111	Monsal Dale Limestones	Boulder Clay	4			0.8	5.0	10.9	6.2	0.7	2.3	4.6
D8	111	Monsal Dale Limestones	None	1	14.5	15.7	8.3	10.3	16.1	28.1	0.7	4.2	5.4
D9	111	Monsal Dale Limestones	None	1	14.5	15.7	15.3	14.0	17.8	22.0	0.6	4.3	4.4
D10	111	Longstone Mudstone	Boulder Clay	4	22.9	21.9	2.8	9.6	9.3	32.4	0.4	4.2	3.4
D11	111	Longstone Mudstone	None	4	20.0	10.3	3.2	10.5	10.6	48.8	0.5	4.9	4.7
D12	111	Longstone Mudstone	None	4	20.0	10.3	13.6	21.6	7.9	46.1	0.4	5.4	4.3
D13	112	Magnesian Limestone	None	1	1.5	0.9	0.5	3.2	12.3	8.7	1.2	1.8	6.4
D14	112	Magnesian Limestone	Boulder Clay	4			0.3	1.8	9.7	2.8	0.5	3.9	2.0
D15	112	LCM Crawshaw Sdst.	Boulder Clay	4	0.4		0.5	3.6	5.2	13.4	0.3	4.9	2.1

LCM = Lower Coal Measures; * = derived from calibration plot Figure 3-8

Table 3-11. Comparison of summer and winter Site Investigation data (medians)

Site No	Date	50K Sheet	Grid Square	Bedrock geology	Drift	Radon Bq/l	Thoron Bq/l
D4	Jun-1996	125	436 349	LCM shale	None	0.8	8.2
DW4	Dec-1996	125	436 349	LCM shale	None	8.9	4.6
D6	Jun-1996	125	438 350	LCM Crawshaw Sandstone	None	3.6	7.3
DW6	Dec-1996	125	438 350	LCM Crawshaw Sandstone	None	5.3	2.9
D8	Jun-1996	111	425 358	Monsal Dale Limestones	None	10.3	16.1
DW8	Dec-1996	111	425 358	Monsal Dale Limestones	None	38.7	9.1
D11	Jun-1996	111	421 370	Longstone Mudstone	None	10.5	10.6
DW11	Dec-1996	111	421 370	Longstone Mudstone	None	65.2	11.4
D13	Oct-1996	112	450 361	Magnesian Limestone	None	3.2	12.3
DW13	Dec-1996	112	450 361	Magnesian Limestone	None	35.6	5.3

Seasonal variation

3.77. Although the soil was considerably wetter under winter conditions it was possible to obtain a full suite of soil gas samples at three of the five sites. At the other two sites, eight gas samples were obtained at site D6 (Crawshaw Sandstone) and nine at site D13 (Lower Magnesian Limestone) This is in direct contrast to the site investigations in Northamptonshire where it was not possible to obtain adequate soil gas samples for analysis at many of the sites.

3.78. All the geological units investigated in Derbyshire are characterised by a higher median concentration of soil gas radon in winter than in summer (Figure 3-10). The ratio between winter and summer median concentrations ranges from about 1.5 on the Crawshaw Sandstone to about 11 on the Lower Magnesian Limestone and the Lower Coal Measures Shale. All except the Longstone Mudstone Formation yielded lower median concentrations of soil gas thoron in winter than in summer.

3.79. The general rise in soil gas radon and fall in soil gas thoron levels in winter is probably caused by sealing of the upper layer of the profile by soil moisture. When gas samples are taken below the moisture saturated upper layer, the collected soil gas has aged slightly with a consequential ingrowth of radon and decay of short lived thoron. The general increase in soil moisture may also retard the migration of thoron due to its short half life.

3.80. The main conclusion drawn from the comparison of winter and summer site investigation in Northamptonshire was that soil gas radon measurement during the winter period is not practicable over many geological units. The work in Derbyshire has shown that meaningful soil gas data can be collected in favourable geological settings. However there are differences between summer and winter soil gas radon levels so separate Soil Gas Radon vs. GEORP calibration graphs would be needed to assess site investigation data collected under different seasonal conditions. More detailed investigations are required to assess whether measurement of soil permeability would permit corrections to be made for seasonal variations.

3.81. Owing to the problems of using soil gas radon site investigation (SI) data collected during the winter period in all geological settings, the following evaluation of soil gas radon, laboratory radon emanation and gamma spectrometry site investigation procedures is based largely on the data collected during the drier summer period.

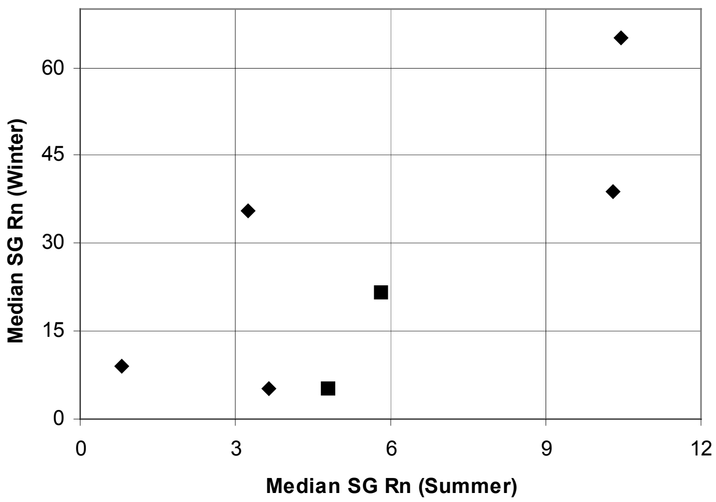


Figure 3-10. Relationship between median soil gas radon concentrations (Bq/l) measured at the same sites in summer and winter (◆ = Derbyshire data; ■ = Northamptonshire data).

Soil gas radon

3.82. During summer conditions, soil gas samples were obtained from all of the sites. For the Lower Coal Measures Shale and Crawshaw Sandstone, radon in soil gas concentrations were low with medians of 3.4 (site median range 0.8-4.4) and 2.1 (1.0-3.6) Bq/l respectively. A median of 2.0 Bq/l was recorded where the Lower Coal Measures Shale is covered by boulder clay and 3.6 Bq/l where boulder clay rests on Crawshaw Sandstone.

3.83. Similar or slightly higher median concentrations were observed at drift free sites over the Lower Magnesian Limestone (3.2 and 10.9 Bq/l; overall median 5.7 Bq/l) whereas a median value of only 1.8 Bq/l was recorded where the limestone is covered by boulder clay. It is possible that recent ploughing at site D13 may explain why soil gas radon is low compared with site D1 even though both have comparable Laboratory radon emanation and eU values (Table 3-10).

3.84. Over the Monsal Dale Limestones median radon concentrations of 10.3 and 14.0 Bq/l (overall median 12.6 Bq/l) were recorded with a median concentration of 5.0 Bq/l where the limestone is covered with Boulder Clay. No house data is available for boulder clay covered Monsal Dale Limestone but the moderately high soil gas radon and high permeability of the drift free limestone combine to indicate a high GEORP.

3.85. The highest median soil gas radon concentrations occur over the Longstone Mudstone Formation with 17.3 Bq/l (site median range 10.5-21.6 Bq/l) for the drift free sites and 9.6 Bq/l where boulder clay is present.

3.86. Statistical analysis of the data from drift free sites shows there to be significant differences between median soil gas radon between sites on the same geology in all cases except the Monsal Dale Limestones. In the case of the Monsal Dale Limestones there is a 98.7% probability that the median concentrations are statistically the same.

Soil gas thoron

3.87. With the exception of the Longstone Mudstone Formation, thoron concentrations are particularly high in summer conditions compared to winter (Table 3-11) and generally are also higher in permeable soils than in relatively impermeable soils (Tables 3-10 and 3-11). Thoron concentrations in soil gas have been used to give a rough estimate of relative permeability for areas that have a similar concentration of thorium.

K, eU and eTh

3.88. eU is generally low with the highest median values found over the Longstone Mudstone Formation (5.1 ppm) and boulder clay covered Crawshaw Sandstone (4.9 ppm) (Table 3-10). Boulder clay cover on the Monsal Dale Limestones and Longstone Mudstone Formation leads to a reduction in eU whereas on all other geological units investigated, boulder clay cover leads to an enhanced eU signal. eTh values are all considerably less than the average value in terrestrial rock of 9.6 ppm. Median eTh values for boulder clay covered sites are consistently lower than drift free sites on the same bedrock unit.

3.89. Anomalously high eU concentrations (> 0.1%) were measured at three locations at sample site D11 during the winter. These values exceed the upper calibration limit for the field gamma spectrometer and should only be regarded as approximate. Such high eU concentrations will also render the Th and K values for these locations unreliable. Despite this the radon concentrations at these locations (179.6, 83.0, 60.2 Bq/L cf. a site median of 65.2 Bq/L, Table 3-11) are not especially high. A number of reasons can account for such an observation. The U anomaly could be restricted to a horizon that does not contribute to the radon migration pathway; U mineralization could be in a form that doesn't readily release radon; or the U anomaly could be inhomogeneously distributed. Without very detailed investigation of the anomaly it would not be possible to identify which of these or other possibilities account for this case.

3.90. Median K values for the different geological units investigated in Derbyshire (Table 3-10) are all markedly lower than those found during the Northamptonshire investigations. This may relate to differences in bedrock chemistry or, at least in part, to differences in farming practices in the two areas. In the Northamptonshire report it was noted that most of the potassium is likely to occur in clay minerals so that the potassium value could be used to give an estimate of the relative clay content and hence permeability. By contrast in Derbyshire there appears to be no relationship between K and wetness class (hence permeability) (Table 3-10).

3.91. The eTh/eU ratio may be used to give a rough estimate of the amount of uranium located in the thorium bearing minerals. If the eTh/eU ratio is greater than four then it can reasonably be assumed that much of the uranium is contained in a thorium mineral. In only one case does the median eTh/eU ratio exceed four (D1) (Table 3-10). At all other sites the maximum eTh/eU ratio is 3.6 and the ratio is frequently below 2. It is concluded that significant amounts of uranium are not contained in thorium rich minerals.

3.92. A detailed interpretation of the relationship between aeroradiometric data, soil gas radon and geological radon potential is being carried out as part of the BGS Natural Environmental Radioactivity Survey. The results will be published in due course.

<u>Radon emanation from soil samples (laboratory data)</u>

3.93. The values for Lab. radon in Table 3-10 are laboratory determined and indicate the maximum available labile radon. This is the maximum radon that could be obtained from the mineral fraction of the soil that is available to pass into the gas phase if the soil was completely dry or into the water phase if the soil was completely water-logged.

<u>Soil gas radon, laboratory radon emanation and eU as indicators of radon potential</u>

3.94. GEORP for the county of Derbyshire and the 5 km grid square in which the sample site is located are compared with the selected site investigation radon potential indicators (soil gas radon, laboratory radon emanation and eU) in Table 3-10. The relationship between the indicators is illustrated in the correlation matrix (Table 3-12) and in Figures 3-11 to 3-13.

3.95. Soil gas Rn, Lab Rn and eU correlate significantly (99.5% level) with GEORP (county) whereas Laboratory Rn and soil gas radon correlate less significantly with GEORP (5-km grid). It is likely that the County GEORP is a more stable indicator of GEORP than the 5 km grid square GEORP because a larger number of house radon measurements have been used to estimate the County GEORP (see Appendix 3). As in Northamptonshire, there is a strong negative correlation between soil gas thoron and wetness class (Table 3-12) reflecting the impact of permeability on thoron concentrations in soil.

3.96. Figure 3-14 and Table 3-12 show that values of GEORP (soil) derived from a provisional soil gas radon - GEORP calibration (Figure 3-8) correlate less well with GEORP (county) and GEORP (5-km grid) than soil gas radon. It appears that the calibration graph (Figure 3-8) is not particularly appropriate for the geological settings encountered in the Derbyshire study area where it can be concluded that soil gas radon measurements can be used to predict GEORP directly . This is in contrast to the Northamptonshire study area, where consideration of soil and rock permeability improves the accuracy of the prediction.

Table 3-12. Pearson correlation matrix for Derbyshire site investigation results (n = 15)

	GEORP (Map)	*GEORP (5-km grid)*	*GEORP (Soil Rn)*	*Soil Wetness Class*	*Radon Bq/l*	*Thoron Bq/l*	*Lab Rn. Eman Bq/kg.*	*K %*	*eU ppm*
GEORP (5-km grid)	0.90								
GEORP (Soil Rn)	0.57	0.49							
Soil Wetness Class	0.16	0.12	-0.35						
Radon	0.77	0.59	0.91	-0.09					
Thoron	0.35	0.43	0.61	-0.67	0.39				
Lab Rn. Eman.	0.92	0.72	0.57	0.12	0.80	0.21			
K%	-0.63	-0.75	-0.21	-0.31	-0.39	0.09	-0.59		
eU ppm	0.75	0.79	0.46	0.31	0.59	0.06	0.80	-0.79	
eTh ppm	-0.41	-0.75	0.03	-0.44	-0.09	0.22	-0.28	0.85	-0.69

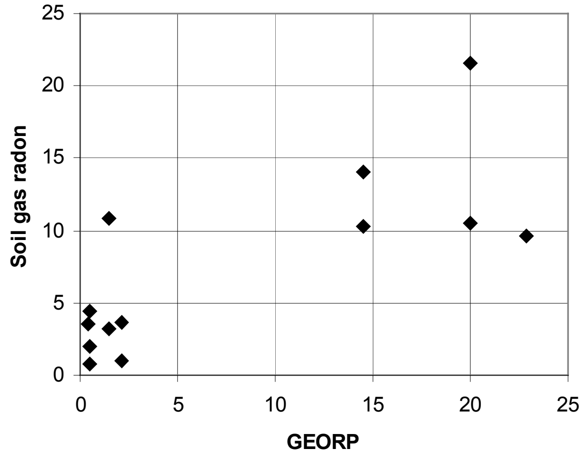


Figure 3-11. Plot of GEORP vs. soil gas radon (Bq/l), Derbyshire

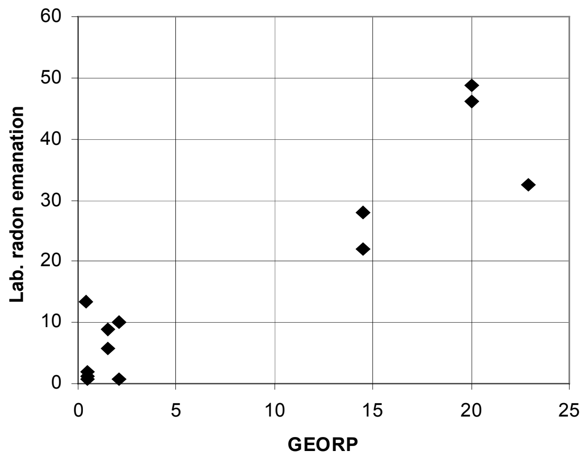


Figure 3-12. Plot of GEORP vs. Laboratory radon emanation (Bq/kg), Derbyshire

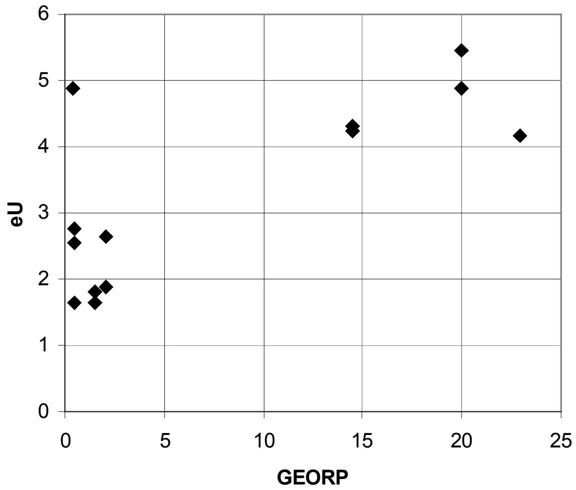


Figure 3-13. Plot of GEORP vs. eU (ppm), Derbyshire

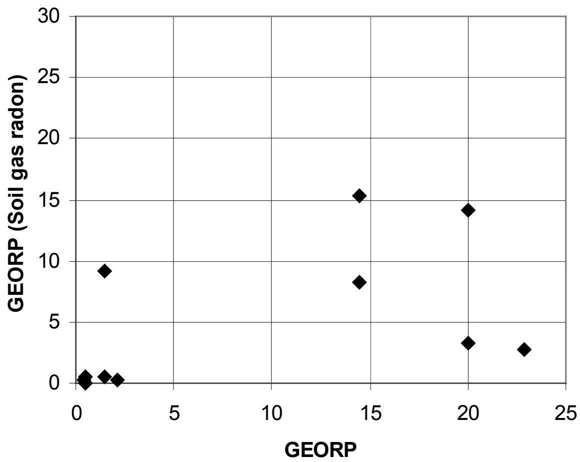


Figure 3-14. Plot of GEORP vs. GEORP (Soil gas radon, Bq/l), Derbyshire

Evaluation of Site Investigation Procedures III: Historical data

Introduction

3.97. Insufficient new field data (340 soil gas radon measurements at 34 sites) were obtained during the investigations in Northamptonshire and Derbyshire to permit the adequate determination of within and between site variability required to evaluate the reliability of the site investigation methods. The scope of the work programme was extended to include a statistical evaluation of historical soil gas radon measurements from Northamptonshire (Sharman, 1995[11]) together with historical BGS data from Derbyshire, Mansfield and the Okehampton are of Devon. The aim of the study was to obtain a better indication of the variations possible within and between sites and of the effectiveness of soil gas radon measurements as an indicator of radon potential for specific sites

3.98. As in the Northamptonshire and Derbyshire studies, radon site investigation procedures were evaluated by studying the relationship between the soil gas radon data with an independent estimate of the radon risk (geologic radon potential (GEORP)). 5-km grid radon potential (GRIDRP[12]) was used in the Okehampton study because 1:50,000 scale GEORP data are not yet available for this area.

Northamptonshire

3.99. Traverse identifiers were added to 1873 of the 3059 sites at which Sharman (1995) measured radon and thoron in soil gas. These comprise records for 86 individual traverses or grids with 5 or more sample points. The sample spacing was predominantly 20-50 m although a few grids and traverses were based on 5 m. spacing. The majority of the traverses are located above six geological units (Table 3-13) and are spread throughout Northamptonshire (Figure 3-15). Summary statistics for these traverses are presented in Table 3-14. The remainder of the radon measurement sites were spatially isolated and not directly relevant for the data evaluation reported here.

Table 3-13. GEORP values for geological units with >10 soil gas radon traverses (Sharman, 1995)

Geological Unit (Sharman Lithological Code)	Number of traverses	GEORP (range for three BGS 1: 50,000 scale geological maps)
Upper Lias Clay (5)	33	0.0 - 4.5
Northampton Sand Formation (6)	47	6.8 - 16.4
Grantham Formation (7) = Lower Estuarine Series	12	1.6 - 7.3
Rutland Formation (10) = Upper Estuarine Series	11	0.1 - 1.2
Blisworth Limestone (12) = Gt. Oolite Lst	11	0.3 - 1.8

[11] Sharman, G. 1995. *Radon: an environmental hazard: a geological case study of Northamptonshire.* Unpublished PhD thesis, University of Leicester.
[12] GRIDRP = radon potential (Est.%>AL) for a specific grid square

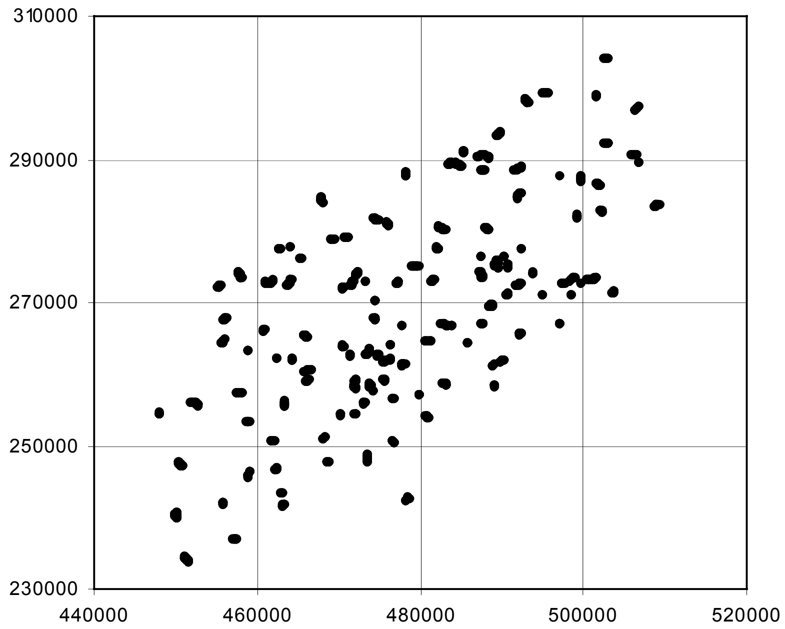


Figure 3-15. Location of 1873 radon in soil gas measurement sites used in this study (data from Sharman, 1995)

Table 3-14. Soil gas radon, SG-GEORP and 5 km GEORP summary statistics for traverses on geological units in Northamptonshire (April-October data from Sharman, 1995)

Litho code	Geological unit	No. Trav.	Mean SG Rn Bq/l	Median SG Rn Bq/l	Rn SD Bq/l	Min SG Rn Bq/l	Max. SG Rn Bq/l	SG-GEORP	No. 5 km sq.	Mean 5 km GEORP	Median 5 km GEORP	Min. 5 km GEORP	Max. 5 km GEORP
1	Lower Lias	3	21	19.4	4.6	17	26	5.5	2	0.4	0.4	0.0	0.8
2	Middle Lias	6	9.6	8.2	3.4	7	16	0.8	3	0.3	0.4	0.1	0.4
3	Marlstone Rock Bed	6	26.6	27.6	12.2	8	44	20.7	1	0.8			
5	Upper Lias Clay	30	9.7	9.4	4.7	2	21	0.8	28	1.1	0.5	0.0	5.2
6	Northampton Sand Fm.	41	15.8	13.8	9.4	2	38	7.3	28	12.1	9.2	0.0	29.5
7	Grantham Fm.	11	10.2	8.1	9.6	3	36	0.9	10	3.0	2.0	0.0	11.9
8	Lower Lincs. Lst.	7	4.2	2.8	4	0	12	0.6	2	0.3	0.3	0.0	0.7
9	Upper Linc. Lst.	2	9.4	9.4	2.5	8	11	2.6	1	18.1			
10	Rutland Fm.	8	8.5	5.1	8.9	3	29	0.6	16	0.8	0.2	0.0	4.5
11	Welllinboro' Lst. Member (Rutland Fm.)	6	4.9	6.3	2.8	1	8	0.8	4	6.4	5.4	0.0	14.5
12	Blisworth Lst.	9	7	6.7	4.1	1	14	1.5	14	1.1	0.9	0.0	5.3
14	Cornbrash	5	7	7	1.4	5	8	0.4	4	0.0	0.0	0.0	0.0
16	Kellaways Clay	3	7.7	6.1	4.6	4	13	0.5					
17	Oxford Clay	3	3.8	4.3	3.6	0	7	0.1	1	0.0			
18	River Terrace	5	5.4	4	4.8	0	13	0.2					
19	Alluvium	10	6.5	5.4	4.8	0	14	0.3					
22	BC on Middle Lias	1	4.9	4.9		5	5	0.1	1	0.1			
23	BC on Marlstone Rock Bed	1	10.5	10.5		11	11	1.0	3	0.2	0.2	0.1	0.2
26	BC on Northants. Sand Fm.	4	10.5	9.8	6.2	5	18	1.0	1	2.2			
28	BC on U. Lincs. Lst.	3	11.2	9.7	4	8	16	1.2	2	0.0	0.0	0.0	0.0
32	BC on Blisworth Lst.	4	11.7	10.8	5.1	7	18	1.3	5	0.1	0.1	0.0	0.3
33	BC on Blisworth Clay	2	9.5	9.5	5.2	6	13	0.8					
37	BC on Oxford Clay	5	4	5	4	0	9	0.1					
42	GSG on Middle Lias	1	29.5	29.5		30	30	12.9					
45	GSG on U. Lias Clay	5	17.5	17.8	8.6	6	26	3.5	2	0.0	0.0	0.0	0.0
46	GSG on Northants. Sand Fm.	1	4.2	4.2		4	4	0.6	4	3.7	3.5	0.1	7.6
52	GSG on Blisworth Lst.	4	9.9	10.5	3	6	13	2.9	1	0.6			
53	GSG on Blisworth Clay	2	15.6	15.6	8.5	10	22	2.6					

BC = Boulder Clay, GSG = Glacial Sand and Gravel.

3.100. The variability of the soil gas radon data is evaluated with respect to:

- median and mean concentrations
- sample spacing
- number of measurements
- variation within and between sites on the same geology and between geologies.

3.101. It is clear from Figures 3-16 and 3-17 that, as might be expected, the Standard Deviation increases whereas the Coefficient of Variation decreases with median soil gas radon concentration, when subdivided on the basis of lithological units. These relationships also hold for traverses from single lithological units (e.g. Northampton Sand Formation).

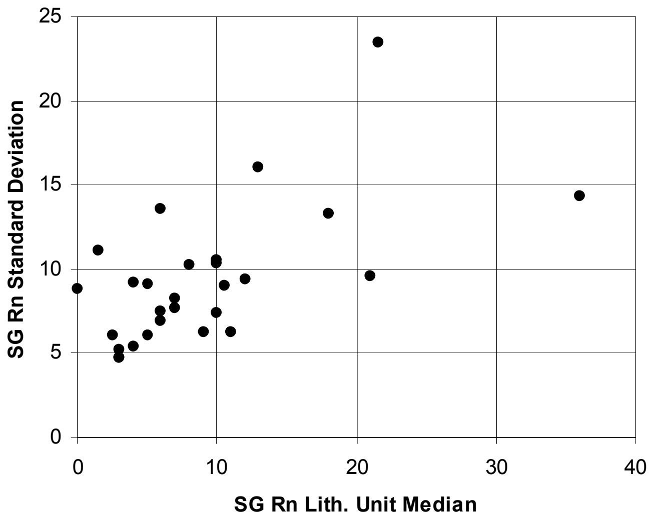


Figure 3-16. Relationship between standard deviation and median soil gas radon (SG Rn Bq/l) for all lithological units (data from Table 3-14)

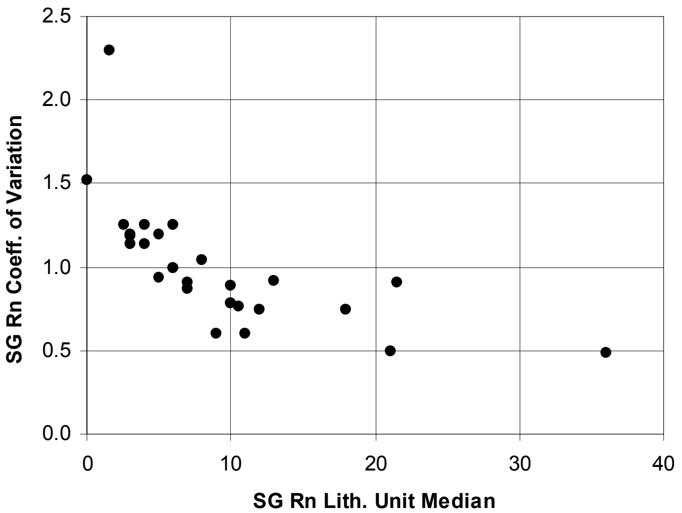


Figure 3-17. Relationship between coefficient of variation and median soil gas radon (SG Rn Bq/l) for all lithological units (data from Table 3-14)

3.102. There is a very close correspondence between mean and median soil gas radon both for lithological units (Figure 3-18) and for traverses on individual lithological units (Figure 3-19). For homogeneous sites, both the mean and median will provide a good estimate of the soil gas radon concentration on the site. For particularly inhomogeneous sites, the median may provide an underestimate for the site if more than 50% of the measurements are on the low radon sector. Use of mean radon for a site may provide a better indication of the radon concentration for such sites.

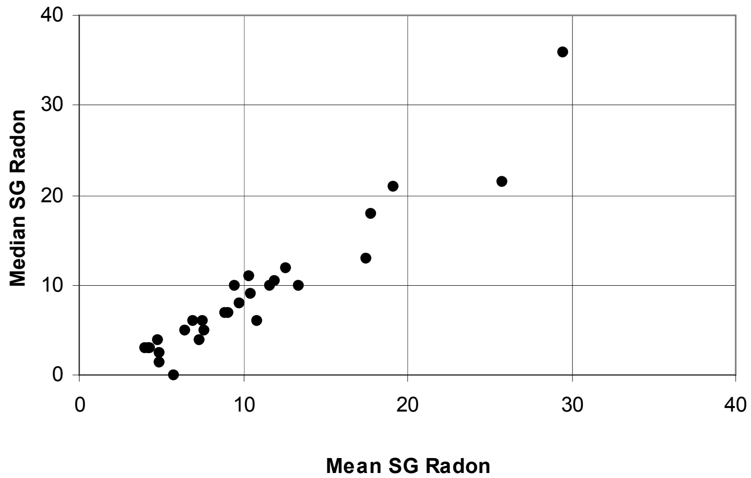


Figure 3-18. Relationship between mean and median soil gas (SG) radon (Bq/l) for all lithological units (data in Table 3-14)

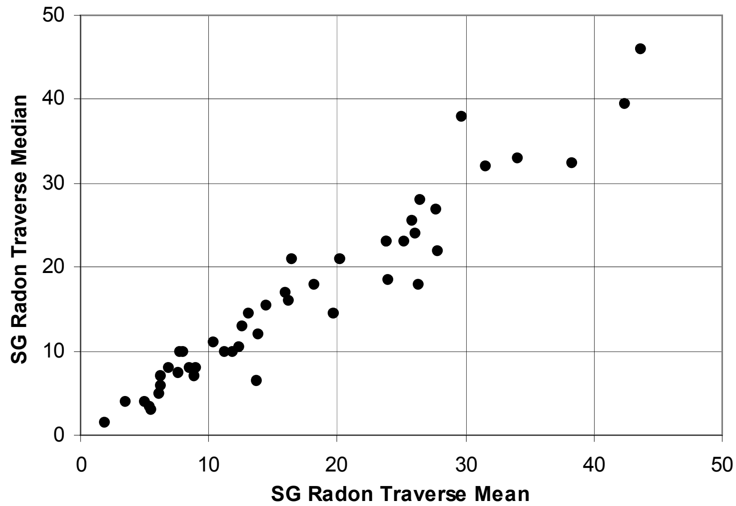


Figure 3-19. Relationship between mean and median soil gas (SG) radon (Bq/l) for traverses on the Northampton Sand Formation (Sharman, 1995)

3.103. Considering summer (April to October) measurements on the Northampton Sand Formation (NSF) alone, the coefficient of variation appears to be greatest at the widest sample spacing (50 m) (Figure 3-20). Greater variations in radon, reflecting gross variations in geology and soil characteristics might be expected when a wider sample spacing is used. However, such a wide sample interval would not be appropriate for most site investigations. The standard deviation shows no significant variation with sample spacing.

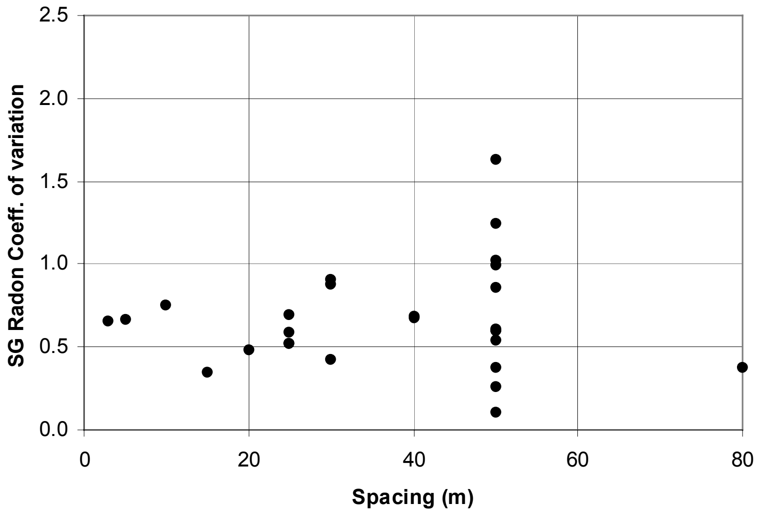


Figure 3-20. Relationship between sample spacing (m) and coefficient of variation of soil gas (SG) radon (Bq/l) for traverses on the Northampton Sand Formation (data for April-October; Sharman, 1995)

3.104. The range of the coefficients of variation appears to decrease with the number of measurements on a traverse or grid (Figure 3-21).

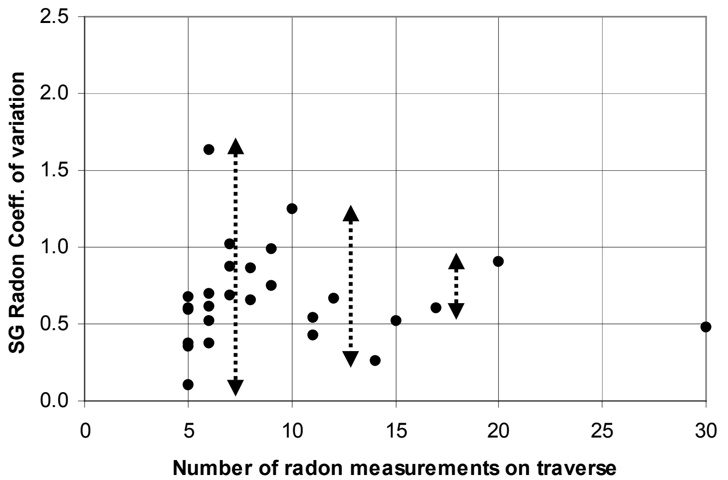


Figure 3-21. Relationship between number of measurements on traverse/grid and range of coefficients of variation (indicated by arrows) of soil gas (SG) radon for traverses on the Northampton Sand Formation (data for April-October; Sharman, 1995)

3.105. These observations tend to support the standard BGS site investigation protocol in which 10 measurements are taken on a 20 m spacing. However, a rigorously planned field programme would be required to establish the optimum sample number and spacing (Badr et al., 1996). In view of lateral variation in geology and soil characteristics together with economic constraints, it would be very difficult to arrive at an optimum sampling protocol for all conditions. The combination of 10 measurements with a 20 m spacing is probably an adequate and practical compromise.

3.106. Analysis of variance (ANOVA) confirms that there are significant variations in mean radon concentrations between traverses for individual geological units (Tables 3-15 and 3-16).

Table 3-15. ANOVA for Northampton Sand Formation (classical experimental approach; dependent variable is soil gas radon; April-October data from Sharman, 1995)

Due To	Sum of Squares	DoF	Mean Square	F-Stat	Signif
Main Effects	30775.317	40	769.383	6.233	0.0000
Traverse	30775.317	40	769.383	6.233	0.0000
Explained	30775.317	40	769.383	6.233	0.0000
Error	42216.427	342	123.440		
Total	72991.744	382	191.078		

Table 3-16. ANOVA for Upper Lias Clay (classical experimental approach; dependent variable is soil gas radon; April-October data from Sharman, 1995)

Due To	Sum of Squares	DoF	Mean Square	F-Stat	Signif
Main Effects	5030.323	29	173.459	2.172	0.0008
Trav	5030.323	29	173.459	2.172	0.0008
Explained	5030.323	29	173.459	2.172	0.0008
Error	19242.865	241	79.846		
Total	24273.188	270	89.901		

3.107. Within and between traverse variability was assessed for the two geological units with the greatest number of traverses: the Northampton Sand Formation (NSF) and the Upper Lias Clay (ULC). Box and whisker plots for the NSF (Figure 3-22) and the ULC (Figure 3-23) confirm the differences in means and ranges of radon concentrations recorded over different parts of the NSF and ULC within Northamptonshire. A third of traverses over the NSF have mean soil gas radon concentrations >20 Bq/l whereas only one traverse over the ULC exceeds this level, reflecting differences in the GEORP of these two geological units.

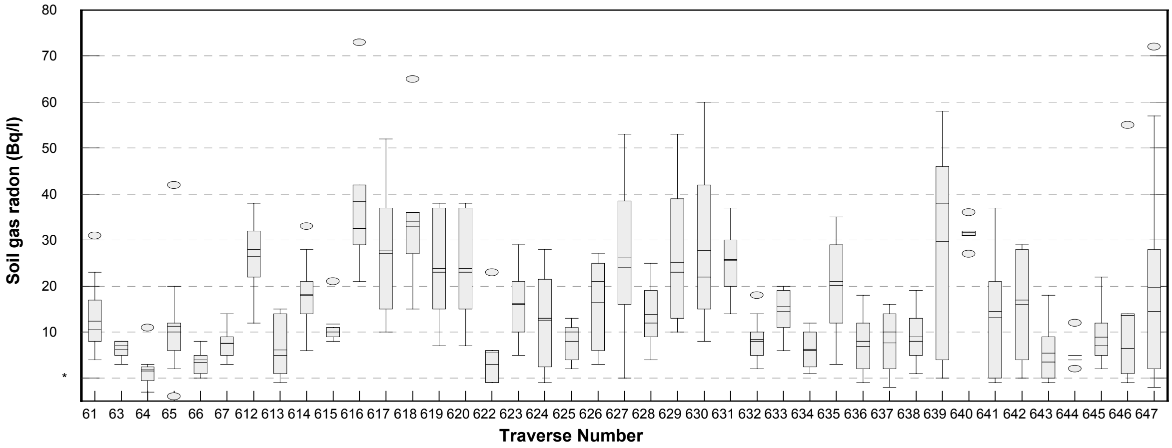


Figure 3-22. Soil gas radon (Bq/l) for traverses and grids over the Northampton Sand Formation (April-October data; traverse numbers along x axis; Lower & Upper quartiles: bottom & top lines of box; Median: middle line of box; Lower & Upper whiskers: max. of (i) lower or upper quartiles minus 1.5 times the inter-quartile range and (ii) the minimum or maximum observation; any values above or below this are outliers and are plotted individually)

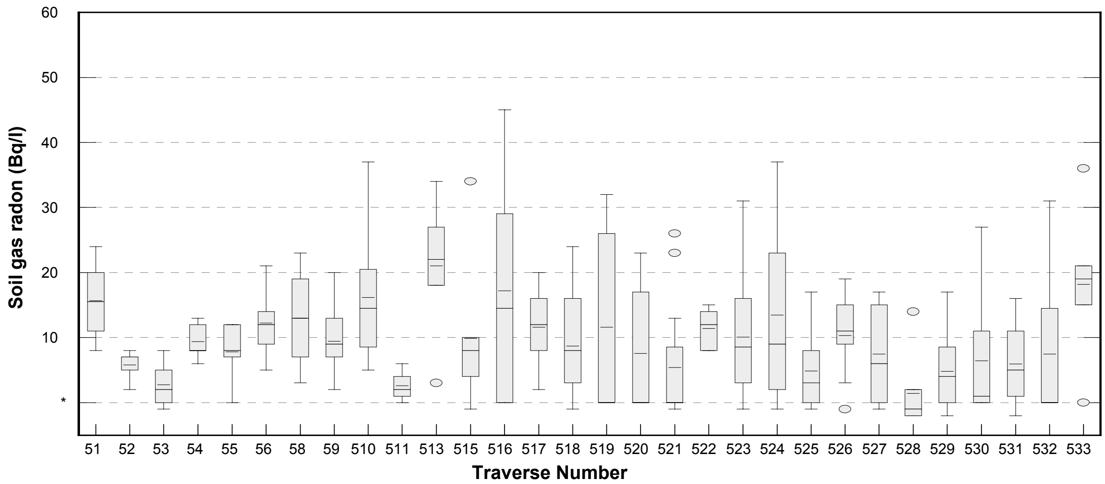


Figure 3-23. Soil gas radon (Bq/l) for traverses and grids over Upper Lias Clay (April-October data; traverse numbers along x axis; see Figure 3-22 for explanation of box and whisker information)

3.108. The range of mean soil gas radon concentrations for bedrock geological units with >5 traverses/grids is illustrated in Figure 3-24. This confirms earlier results that indicated a considerable overlap between the radon ranges for lithological units with significantly different geological radon potentials (GEORPs). It has been suggested previously that soil gas radon concentrations alone cannot be used to define the radon potential of a site and that it is necessary to take soil and rock permeability into account when using soil gas radon measurements to predict GEORP. It is clear from Figures 3-24 and 3-25 and Table 3-14 that taking soil/rock permeability into account permits better discrimination between low and high GEORP sites in Northamptonshire.

3.109. For lithological units with >8 soil gas radon traverses and 5 km grid square GEORP data (Litho codes 5, 6, 7, 10 and 12) there is a consistent relative relationship between the SG-GEORP (estimated from soil gas radon concentrations and permeability using the calibration plot in Figure 3-8) and the 5 km grid GEORP. The calibration plot (Figure 3-8) helped to deal with the influence of rock/soil permeability on soil gas radon concentrations when estimating radon potential for the Northamptonshire sites investigated in 1996. However, it is clear that use of this calibration plot with Sharman's data produces SG-GEORP values that are consistently higher than 5 km grid GEORP values for the same geological unit. For example, many SG-GEORP estimates for the Northampton Sand Formation (Litho Code 6) exceed 40% and range up to 115% (Figure 3-25), which is clearly inconsistent with the 5 km grid GEORP values estimated from house radon data. This discrepancy is discussed in a later section of this report (para. 3-115 and Figure 3-31).

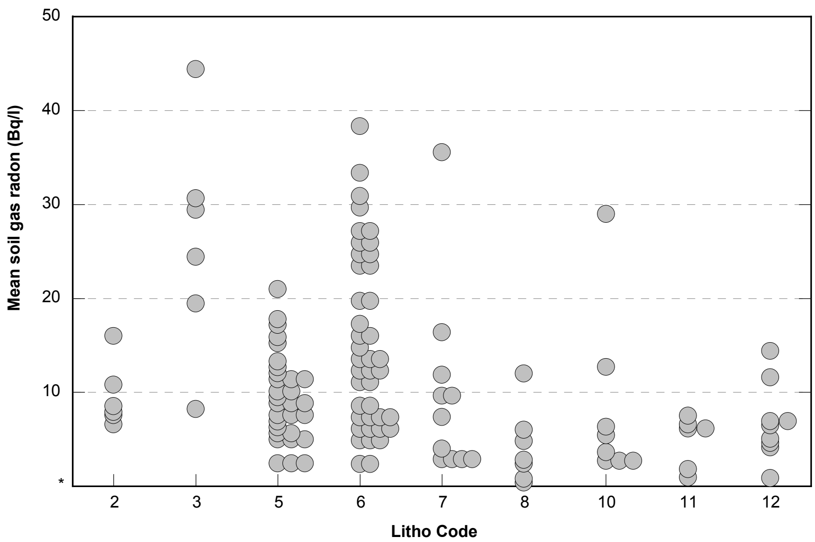


Figure 3-24. Range of mean soil gas radon (Bq/l) for traverses and grids over bedrock geological units with >5 traverses/grids (Lith Code : 2 = Middle Lias, 3 = Marlstone Rock Bed, 5 = Upper Lias Clay, 6= Northampton Sand Formation, 7 = Grantham Fm., 8 = Lower Lincs. Lst., 10 = Rutland Fm., 11 = Wellingborough Lst. Member (Rutland Fm.), 12 = Blisworth Lst.; data from Sharman, 1995)

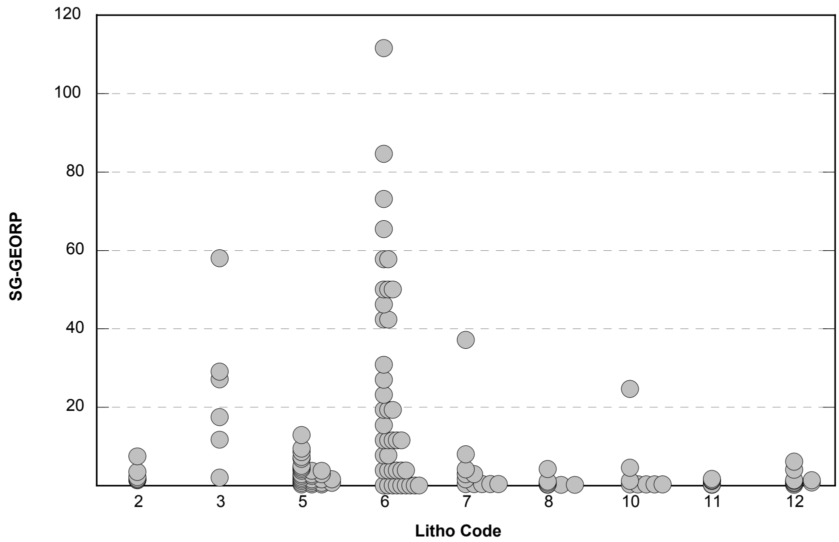


Figure 3-25. Range of SG-GEORP (estimated from mean soil gas radon and permeability using Fig 3-8) for traverses and grids over bedrock geological units with >5 traverses/grids (Lith Code : 2 = Middle Lias, 3 = Marlstone Rock Bed, 5 = Upper Lias Clay, 6= Northampton Sand Formation, 7 = Grantham Fm., 8 = Lower Lincs. Lst., 10 = Rutland Fm., 11 = Wellingborough Lst. Member (Rutland Fm.), 12 = Blisworth Lst.; data from Sharman, 1995)

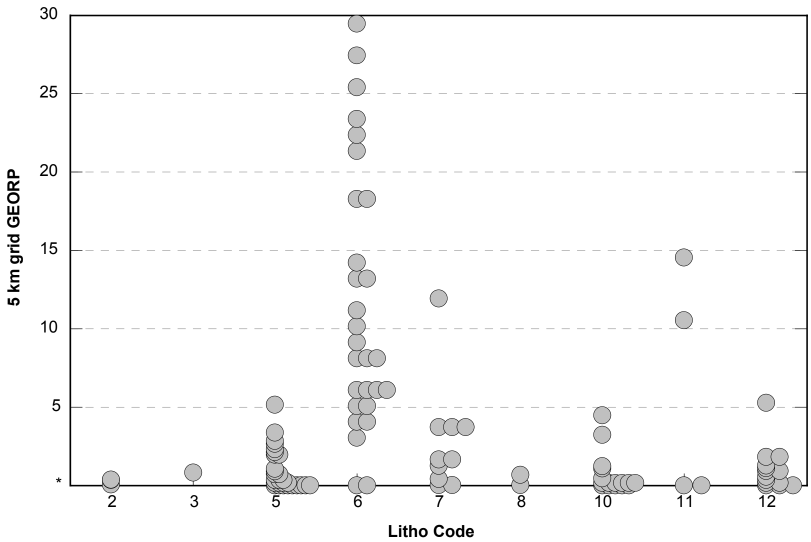


Figure 3-26. Range of 5 km GEORP (estimated from house data) for traverses and grids over bedrock geological units with >5 traverses/grids (Lith Code : 2 = Middle Lias, 3 = Marlstone Rock Bed, 5 = Upper Lias Clay, 6= Northampton Sand Formation, 7 = Grantham Fm., 8 = Lower Lincs. Lst., 10 = Rutland Fm., 11 = Wellingborough Lst. Member (Rutland Fm.), 12 = Blisworth Lst.; data from Sharman, 1995)

3.110. If radon site investigations are to predict the radon potential of a specific site then the regional variation in soil gas radon should correlate with the regional variation in the GEORP (as expressed by the Estimated % dwellings > Action Level for a specific geological unit in a 5 km grid square). Adequate 5 km grid GEORP and soil gas radon data are available only for the Northampton Sand Formation (NSF). For the other geological units, the range of GEORP is small or there are not enough corresponding soil gas radon and 5 km grid GEORP data for a relationship to be assessed. Soil gas radon traverses over the Northampton Sand Formation were included in the assessment only if the sample spacing was >20 m (ranging up to 50 m) as it was considered that traverses and grids with a smaller spacing (3-5 m) would not cover an adequate area for the soil gas radon data to be representative of the 5 km grid square. Ideally for this type of analysis, the distribution of soil gas radon data should closely correspond to the distribution of house radon data - unfortunately it was not possible to achieve this with the data available.

3.111. Table 3-17 summarises the data used to evaluate the relationship between 1:50,000 scale geological map sheet GEORP, 5 km grid GEORP, mean and median soil gas radon for the Northampton Sand Formation. Although there is a faintly discernible positive correlation between median soil gas radon and the 1:50,000 scale geological map sheet GEORP (Figure 3-27), this correlation becomes highly significant (at the 99.95% level) when the 5 km GEORP data are used (Figure 3-28). Thus soil gas radon site investigation data can be considered to provide a relatively reliable indication of the radon potential for a specific site underlain by the Northampton Sand Formation.

Table 3-17. Summary data for soil gas radon traverses on the Northampton Sand Formation (April-October data from Sharman, 1995)

Traverse or Grid Number	No. of Rn measurements	Spacing (m)	OS Easting Mean	OS Northing Mean	1:50,000 map sheet GEORP	5 km grid GEORP	SG Rn Mean (Bq/l)	SG Rn Median (Bq/l)
61	30	*25*	488631	269526	16.4	11.8	12	11
64	8	25	471289	262649	6.8	4.5	2	2
66	17	25	475882	261900	6.8	4.3	3	4
67	18	20	477836	261327	6.8	4.3	8	8
69	10	20	477277	272897	6.8	22.6	42	40
610	5	25	477837	266723	6.8	5.6	10	11
611	12	25	492281	274834	16.4	22.2	44	46
612	5	80	470480	272045	6.8	14.0	26	28
613	7	50	470497	263876	6.8	4.5	6	5
614	11	30	473723	263183	6.8	4.5	18	18
623	6	25	481193	264643	6.8	9.4	16	16
628	5	50	481453	272968	6.8	6.2	14	12
629	15	25	483302	266859	16.4	8.6	25	23
630	17	50	482863	267043	6.8	8.6	28	22
632	11	50	474440	267665	6.8	10.3	8	8
640	5	50	489070	275356	16.4	18.7	32	32

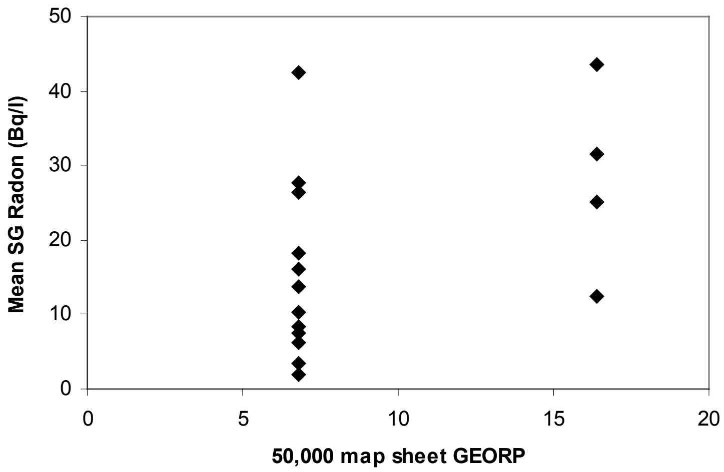


Figure 3-27. Relationship between mean soil gas radon concentration (Bq/l) and 1:50,000 scale geological map sheet GEORP for the Northampton Sand Formation (April-October data, sample spacing 20-50 m; data from Sharman, 1995)

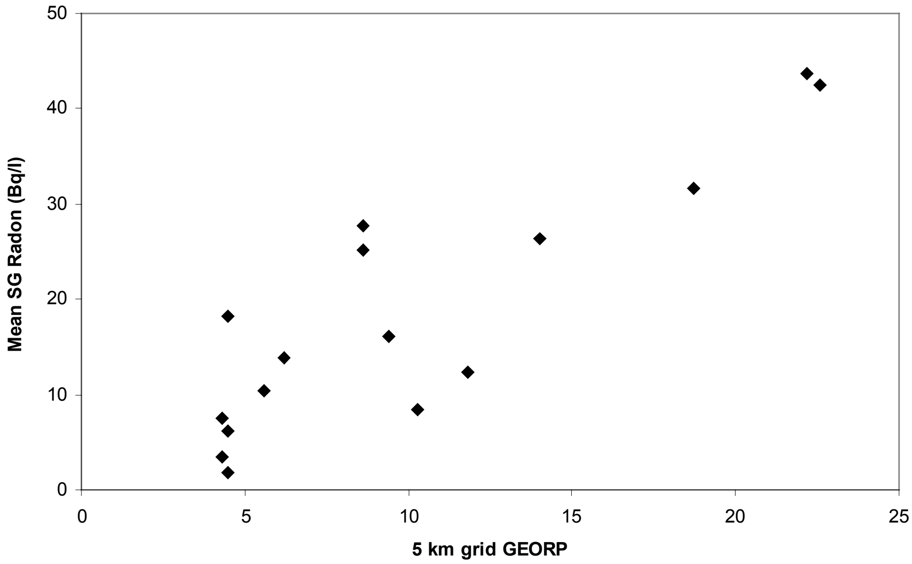


Figure 3-28. Relationship between mean soil gas radon concentration (Bq/l) and 5 km grid GEORP for the Northampton Sand Formation (April-October data, sample spacing 20-50 m; data from Sharman, 1995)

Derbyshire (BGS 1993 data)

3.112. The broad relationship between soil gas radon concentrations and GEORP was evaluated by comparing mean radon concentrations for the major geological units in Derbyshire with county GEORP data (Table 3-18 and Figure 3-29). Regression lines for limestone and shale units confirm the influence of soil/rock permeability on radon concentrations (Figure 3-29) and the importance of taking permeability into account when estimating radon potential (SG-GEORP) from soil gas radon data.

Table 3-18. Soil gas radon (SG Rn, Bq/l) and county GEORP data for major lithological units in Derbyshire (*unpublished BGS data from 1993 EEC project*)

Lithological Unit	N.	Mean SG Rn Bq/l	Median SG Rn Bq/l	SG Rn SD Bq/l	Min SG Rn Bq/l	Max. SG Rn Bq/l	County GEORP
Ashover Grit	15	11	9	6	2	22	2.0
Bee Low Lst.	33	15	12	15	0	82	20.2
Eyam Lst.	23	44	13	59	-1	227	27.1
L. Coal Measures	77	13	11	10	0	47	0.5
L. Magnesian Limestone	144	21	19	13	1	69	1.5
Longstone Mudstone	19	64	49	70	15	334	20.0
Middle Coal Measures	182	15	12	14	-1	76	0.2
Matlock Lst.	13	29	18	23	4	80	14.5
Monsal Dale Lst.	37	44	34	33	7	156	28.4
L. Coal Measures Sdst.	48	15	11	11	1	49	2.1
Woo Dale Lst.	20	13	11	9	0	35	4.4
Widmerpool Fm.	16	31	25	23	1	85	2.8

N. = number of radon measurements, SD = standard deviation.

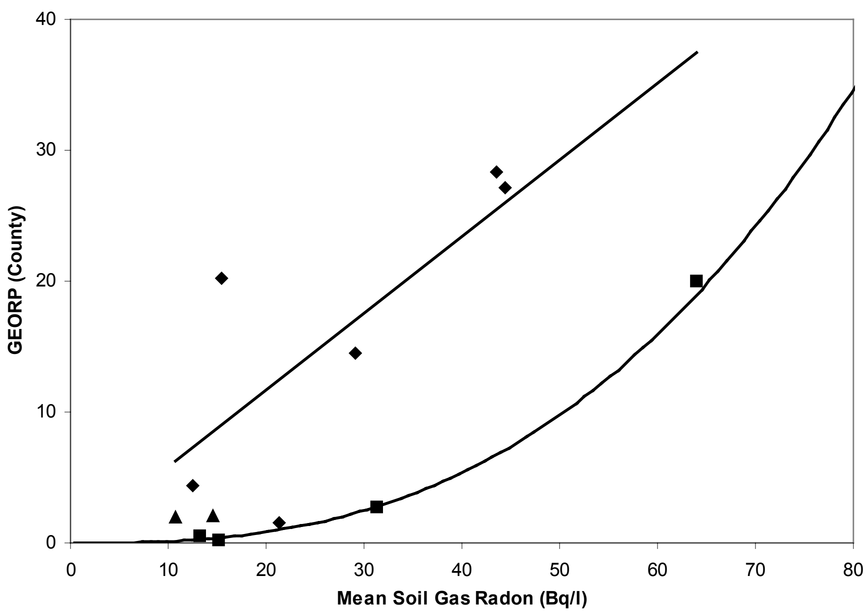


Figure 3-29. Relationship between median soil gas radon (Bq/l) and county GEORP for limestones (◆), shales (■) and sandstones (▲) in Derbyshire (*unpublished BGS data from 1993 EEC project;* Regression lines: upper = high permeability limestones; lower = low permeability shales).

3.113. A more site specific analysis was attempted by assessing the relationship between (i) mean soil gas radon values for sections of traverses pertaining to one geological unit and (ii) the 5 km grid square GEORP for that geological unit (Table 3-19 and Figure 3-30). Only traverses with 10 or more radon measurements and appropriate 5 km grid GEORP data are included in the analysis. There appears to be a broad correlation between soil gas radon and geological radon potential (Figure 3-30). Whereas one cannot expect the average of 10 soil gas radon measurements taken 25 to 50 m apart in one sector of a 25 km^2 area to correlate perfectly with the GEORP for a geological unit within such a large area, the closeness of the correlation suggests that soil gas radon may be used to indicate radon potential on a site specific as well as a regional scale.

Table 3-19. Summary soil gas radon (SG Rn Bq/l) and GEORP data for traverses in Derbyshire (*unpublished BGS data from 1993 EEC project*).

LithTrav	No.	Mean SG Rn Bq/l	Median SG Rn Bq/l	SD SG Rn Bq/l	Min. SG Rn Bq/l	Max. SG Rn Bq/l	5 km grid GEORP	County GEORP
AsG5x	14	11	10	6	2	22	4.5	2.0
BC21x	20	14	12	10	-1	34	1.8	2.0
BLL_D10x	10	22	21	16	1	58	6.5	20.2
BLL15x	11	27	24	20	12	82	20.7	20.2
BLL9x	13	8	9	5	2	18	2.1	20.2
cn19x	14	21	16	15	4	53	1.9	4.3
DST21x	14	12	11	7	1	24	0.1	0.0
DST22x	11	20	16	12	0	41	0.1	0.0
EcL13x	26	20	19	13	5	66	23.1	27.1
EyL6x	19	46	13	62	-1	227	29.4	27.1
KM39x	17	10	10	8	0	33	0.0	0.0
LCM32x	18	19	20	12	4	47	0.2	0.5
LCM49x	24	12	13	8	0	29	3.0	0.5
LCM52x	15	15	15	9	1	33	0.4	0.5
LML43x	32	21	18	12	3	46	0.8	1.5
LML44b	12	17	18	7	1	28	0.8	1.5
LML47x	17	13	11	5	8	24	0.8	1.5
LsM3x	10	45	40	22	22	87	10.0	20.0
MCM25x	22	11	11	5	-1	22	0.1	0.2
MCM26x	23	17	13	14	1	51	0.1	0.2
MCM33x	11	12	12	7	4	26	0.1	0.2
MCM36b	14	8	6	7	-1	23	0.2	0.2
MCM36x	13	5	2	5	0	14	0.2	0.2
MCM37x	14	18	17	10	3	37	0.2	0.2
MCM42x	22	13	11	10	1	43	0.1	0.2
MCM45x	13	12	10	12	0	39	0.1	0.2
MCM52x	17	19	18	11	5	50	1.2	0.2
MMG20x	10	15	14	7	3	28	0.1	0.0
Mo4b	10	34	29	21	11	69	31.2	28.6
Mo8x	13	56	41	44	14	156	42.1	28.6
S49x	14	17	15	8	3	34	2.0	2.1
SSG18x	11	15	14	8	4	29	0.7	0.3
SSG19x	13	7	7	3	4	16	0.0	0.3
WdF17x	12	32	22	23	11	85	9.0	2.8
WDL9x	20	13	11	9	0	35	4.7	4.4

LithTrav = letters are abbreviated geological code, digit is traverse number; No. = number of radon measurements, SG Rn = soil gas radon (Bq/l), SD = standard deviation

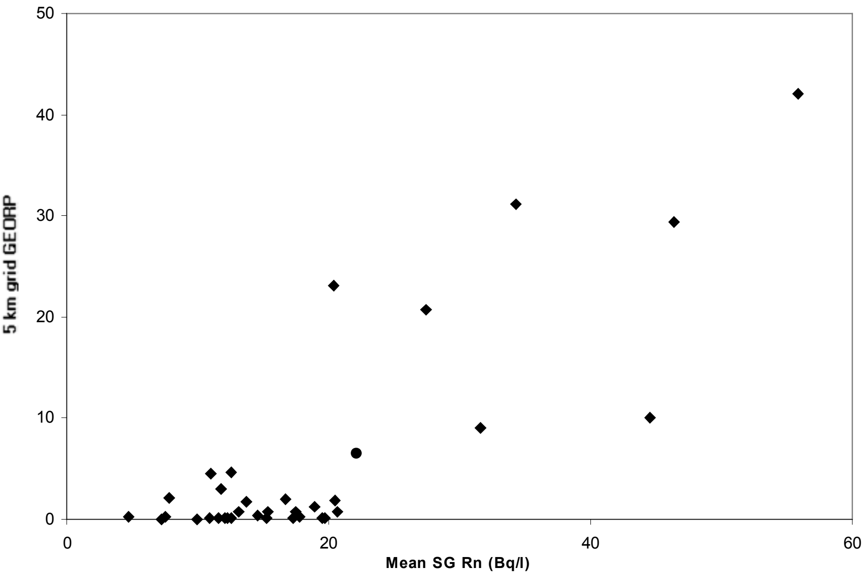


Figure 3-30. Relationship between mean soil gas radon (Bq/l) and 5 km grid square GEORP for selected traverses in Derbyshire (*unpublished BGS data from 1993 EEC project*)

3.114. Gamma spectrometry data were collected at a small proportion of sites during the 1993 soil gas radon survey. Summary statistics for these traverses are presented in Table 3-20 together with data for equivalent geological units collected in 1996. The site investigation studies carried out in Derbyshire in 1996 as part of this project demonstrated that both soil gas radon and eU, determined by gamma spectrometry in the field, are reliable indicators of GEORP in the Derbyshire area. Pearson correlation coefficients (Table 3-21) for radon, thoron and gamma spectrometry data for the 11 traverses from the 1993 survey for which gamma spectrometry data are available (summarised in Table 3-20) confirm the conclusions of the 1996 site investigation study.

3.115. Mean soil gas radon for the 1996 sites (Table 3-10) is significantly lower than for the majority of the 1993 sites, especially at low GEORP levels (Figure 3-31). It is not certain whether the higher radon levels recorded during the 1993 survey reflect an instrumental calibration problem or whether climatic conditions had caused a build up of radon in the soil profile. Whereas site investigation studies in Northamptonshire and Derbyshire reported earlier clearly demonstrated that soil gas radon concentrations in winter tended to be much higher than in summer due to the sealing effect of soil moisture in the winter (Figure 3-10), most of the data for the 1993 survey were collected during the drier summer months from April to September.

Table 3-20. Summary soil gas radon (Rn), thoron (Tn), gamma spectrometry (eK, eU, eTh) and county GEORP data for 11 traverses in Derbyshire from the 1993 radon potential survey (unpublished BGS data from 1993 EEC project) and 10 traverses from the 1996 (DETR) site investigation survey.

Geological unit	No.	Rn Mean Bq/l	Rn Med Bq/l.	Tn Mean Bq/l	Tn Med Bq/l.	eK Mean ppm	eK Med. ppm	eU Mean ppm	eU Med. ppm	eTh Mean ppm	eTh Med ppm.	County GEORP
BGS 1993												
Longstone Mudstone	6	42.8	35.6	12.6	12.6	0.8	0.7	3.2	2.9	6.3	6.0	20.0
Widmerpool Fm.	6	43.9	40.9	9.2	9.3	0.9	0.9	2.7	2.3	7.1	7.2	9.1
Ashover Grit	7	11.7	11.6	6.5	7.0	0.7	0.6	1.8	1.7	6.1	6.2	2.0
Lower Coal measures	7	10.5	11.4	6.0	5.6	1.1	1.1	1.7	1.7	8.2	7.9	0.5
Matlock Lst.	7	17.8	13.0	6.2	5.4	0.9	1.0	2.9	2.8	7.1	7.8	14.5
LCM Sdst.	7	14.2	14.1	6.3	6.2	1.0	1.0	1.6	1.6	7.6	8.0	0.1
Woo Dale Limestone	7	12.8	13.8	6.6	5.6	0.9	0.9	2.2	2.1	8.4	8.1	4.4
Middle Coal Measures	12	10.9	10.3	4.5	4.3	1.2	1.2	1.6	1.6	8.4	8.4	0.2
Monsal Dale Limestone	16	45.5	27.3	9.3	9.1	0.8	0.8	3.5	3.7	7.0	7.3	28.6
Denstone Fm.	17	14.6	14.2	5.9	5.9	1.8	1.8	1.6	1.5	8.2	7.5	0.0
Namurian	21	33.2	22.6	8.2	7.7	0.8	0.8	3.1	2.8	6.8	6.9	4.3
BGS 1996												
Magnesian Limestone	10	11.5	10.9	13.8	13.1	1.4	1.4	2	1.6	7.0	6.9	1.5
LCM Crawshaw Sst	10	0.6	1.0	10	9.2	1.0	1.0	2	1.9	6.6	6.7	2.1
LCM Shale	10	4.4	4.4	7.2	6.6	0.9	0.9	1.7	1.6	6.2	5.9	0.5
LCM Shale	10	1.7	0.8	8.1	8.2	1.4	1.4	2.5	2.6	6.4	6.3	0.5
LCM Crawshaw Sst	10	4.0	3.6	7.8	7.3	0.7	0.7	2.7	2.6	4.3	4.2	2.1
Matlock Limestone	10	15.5	10.3	14.6	16.1	0.7	0.7	5.1	4.2	5.8	5.4	14.5
Matlock Limestone	10	15.5	14.0	18.5	17.8	0.6	0.6	4.2	4.3	4.8	4.4	14.5
Longstone Mudstone	10	20.2	10.5	10.4	10.6	14.2	0.5	308.2	4.9	32.1	4.7	20.0
Longstone Mudstone	10	27.7	21.6	8.6	7.9	0.4	0.4	5.6	5.4	4.3	4.3	20.0
Magnesian Limestone	10	3.7	3.2	13.9	12.3	1.2	1.2	1.8	1.8	6.0	6.4	1.5

No. = number of radon measurements; Med. = median

Table 3-21. Pearson correlation matrix for Derbyshire 1993 radon and gamma spectrometry survey (data for 11 traverses in Table 3-20; *unpublished BGS data from 1993 EEC project*).

	Rn Mean Bq/l	*Rn Median Bq/l*	*Tn Mean Bq/l*	*Tn Median Bq/l*	*eK Mean ppm*	*eK Median ppm*	*eU Mean ppm*	*eU Median ppm*	*eTh Mean ppm*	*eTh Median ppm*
Rn Mean	1.00									
Rn Median	0.94	1.00								
Tn Mean	0.88	0.87	1.00							
Tn Median	0.86	0.88	0.99	1.00						
eK Mean	-0.40	-0.33	-0.47	-0.45	1.00					
eK Median	-0.41	-0.36	-0.51	-0.51	0.99	1.00				
eU Mean	0.85	0.69	0.76	0.69	-0.54	-0.51	1.00			
eU Median	0.79	0.57	0.67	0.61	-0.53	-0.50	0.97	1.00		
eTh Mean	-0.54	-0.48	-0.64	-0.69	0.69	0.71	-0.55	-0.50	1.00	
eTh Median	-0.54	-0.54	-0.73	-0.80	0.44	0.53	-0.45	-0.36	0.88	1.00
GEORP	0.77	0.60	0.71	0.67	-0.46	-0.43	0.87	0.92	-0.49	-0.38
Significance levels: n = 11										
95%	0.549									
99%	0.715									
99.50%	0.765									
99.95%	0.872									

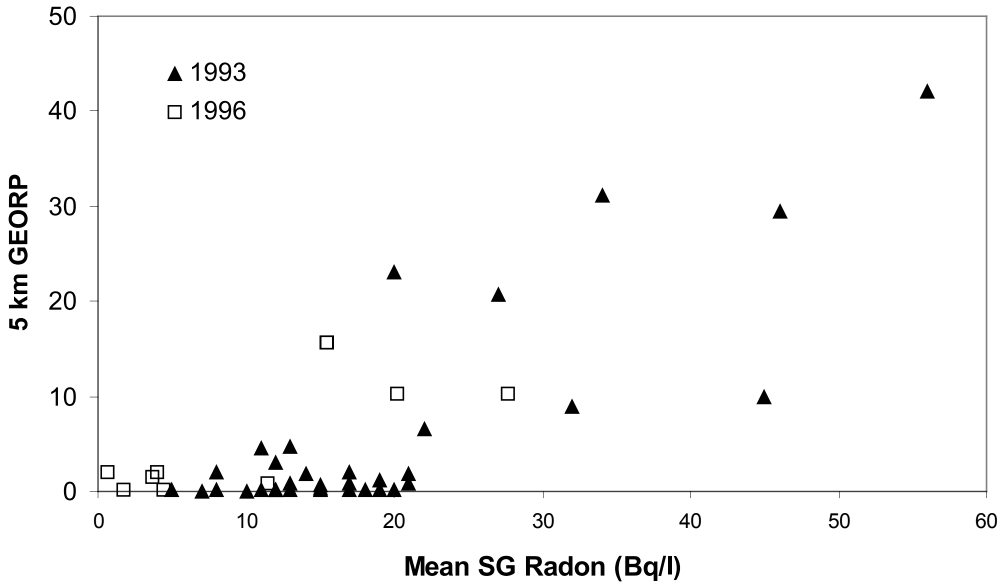


Figure 3-31. Relationship between mean soil gas (SG) radon (Bq/l) and 5 km GEORP for the 1993 EEC survey (▲ Table 3-19, *unpublished BGS data*) and the 1996 DETR site investigations (□, Table 3-10).

Mansfield

3.116. Soil gas radon measurements were made in the Mansfield and Ashfield area using a partial 500 m grid as part of the BGS GBASE programme. More than thirty measurements were made on only two geological units. Comparison of soil gas radon with GEORP (estimated from house radon data for Nottinghamshire) confirms that soil gas radon measurements may be used to estimate the radon potential for different lithological units (Table 3-22). The results for the Magnesian Limestone are similar to those for one of the sites sampled in 1996 (D1) whereas the other site (D13) has much lower radon (Table 3-22). Although the sample spacing used for BGS GBASE radon survey (500 m) was much wider than the spacing recommended for surveying a building site (20 m), these results, taken together with the data collected during the detailed site investigations in Derbyshire (see Table 3-10 above) indicate that soil gas radon measurements may be used to estimate the radon potential for geological units covering relatively large areas but not necessarily for small development sites (Table 3-22).

Table 3-22. Mansfield and Ashfield area: soil gas (SG) radon (Bq/l) compared with GEORP (estimated from house data) (*D1 and D13 from Table 3-10 above)*

Geological Unit	n	Mean SG radon (Bq/l)	Median SG radon (Bq/l)	Notts. GEORP (Estimated)
Regional GBASE data				
Nottingham Castle Sandstone Formation*	31	3.4	3.0	0.1
L. Magnesian Lst.	30	14.4	10.7	3.6
BGS 1996 data				
L. Magnesian Lst. (D1)	10	11.5	10.9	3.6
L. Magnesian Lst. (D13)	10	3.7	3.2	3.6

n = number of radon measurements. * formerly Bunter Pebble Beds

Okehampton, Devon

3.117. The Okehampton area is partly underlain by the Hercynian Dartmoor Granite, which is intruded into Carboniferous cherts with limestones and black shales (the Meldon Formation) and a very thick sequence of grey shales and sandstones (Crackington and Bude Formations). Permo-Triassic breccia conglomerates, mudstones and igneous rocks also occur in the Okehampton area. Uranium values are high in the granite, cherts within the metamorphic aureole and in some of the Carboniferous black shales. The sedimentary rocks have been intensely folded and there are major faults trending NW-SE. The area is situated south of the limit of the main Pleistocene glaciation, but periglacial weathering occurred and local ice features are seen on the higher ground. Patches of deep Tertiary weathering are preserved. 1089 radon in soil gas measurements were made along traverses in the Okehampton area (Figure 3-32) with a sample spacing of 25 or 50 m.

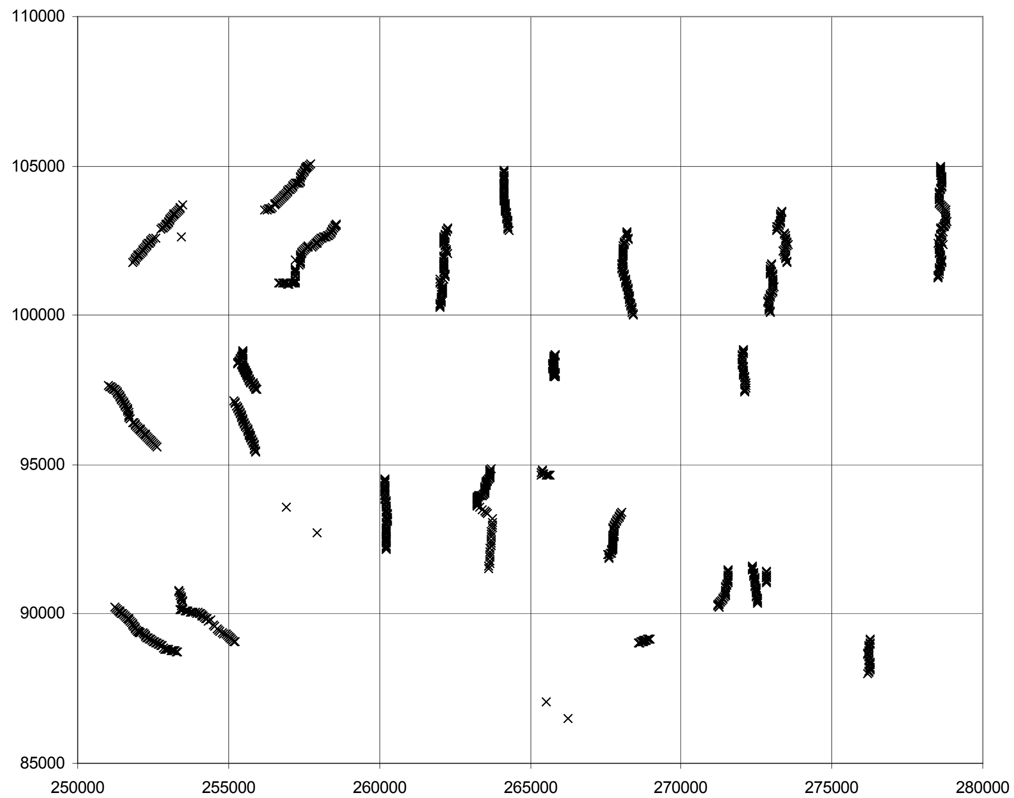


Figure 3-32. Location of soil gas radon sampling points, Okehampton area (BGS, 1993 data)

3.118. Consistent and statistically significant differences exist between the soil gas values associated with different rock types (Table 3-23; ANOVA F-statistic and significance level are 6.28 and 0.0000, respectively). The highest values occur over the granite and the Meldon Formation. These lithologies are characterised by over 30% of the houses being above the Action Level compared to 10-30% of the houses on the other rock types being affected.

Table 3-23. Means and standard deviations for radon (Bq/l) in soil gas over major lithologies in the Okehampton area (Ball et al., 1992).

Lithology	Number of measurements	Mean radon (Bq/l)	Standard deviation
Permian	139	22	6.1
Carboniferous			
Bude Fm.	124	22	3.4
Crackington Fm.	394	43	6.8
Meldon Fm.	18	150	38.1
Granite aureole	199	67	22.4
Dartmoor Granite	104	121	23.0

3.119. The relationship between soil gas radon and GEORP was evaluated by calculating median and mean soil gas radon concentrations for all sampling points which lie within each 5 km grid square for which the NRPB have estimated GRIDRP (Figure 3-33 and Table 3-24). Although not equally distributed throughout the grid squares, the sampling traverses were designed to intersect the main geological units. This combined with the relatively wide sample spacing (25 to 50 m) and the large number of sampling points results in mean and median radon in soil gas concentrations which should be reasonably representative of the individual 5 km grid squares. Figure 3-33 demonstrates that soil gas radon measurements can be used to identify variations in radon potential, as indicated by GRIDRP, in the Okehampton area. Whereas this conclusion applies on a regional rather than site specific scale, it is likely that radon in soil gas measurements should be equally effective in determining the radon potential of a new development site in the Okehampton area.

Table 3-24. GRIDRP and soil gas radon (SG-Rn, Bq/l)) for 5 km grid squares in the Okehampton area (BGS unpublished data; Geology: U = uranium mineralised zone, G= Granite, D4 = Crackington Formation, D5 = Bude Formation, E = Permian).

East	North	Geology	GRIDRP	GRID GM Rn	Median SG-Rn Bq/l	Mean SG-Rn, Bq/l
250	85	U-D4	22.7	104	28	39
250	90	U-D4	8.2	39	27	78
250	95	D4	3.9	38	25	25
250	100	D4	1.8	29	21	24
255	85	G	21.5	95	nd	nd
255	90	U-D4	30.2	119	nd	nd
255	95	D4	18.9	81	27	28
255	100	D4-D5	6.2	47	6	14
260	85	G	59.5	245	nd	nd
260	90	U-D4	37.1	143	36	60
260	95	D4	7.8	54	nd	nd
260	100	E-D5	1.3	41	18	20
265	85	G	84.6	399	67	73
265	90	G-U-D4	54.5	219	92	130
265	95	D4	15.6	77	1	6
265	100	E	1	46	23	27
270	85	G	75.8	311	nd	nd
270	90	G	53.6	213	41	66
270	95	D4	0.8	21	23	23
270	100	E-D5	1.7	34	20	24
275	85	G	76.1	317	103	157
275	90	U-D4	6.4	50	nd	nd
275	95	D4	0.6	31	nd	nd
275	100	E-D5	2.3	37	21	23

GM = geometric mean, Rn = radon

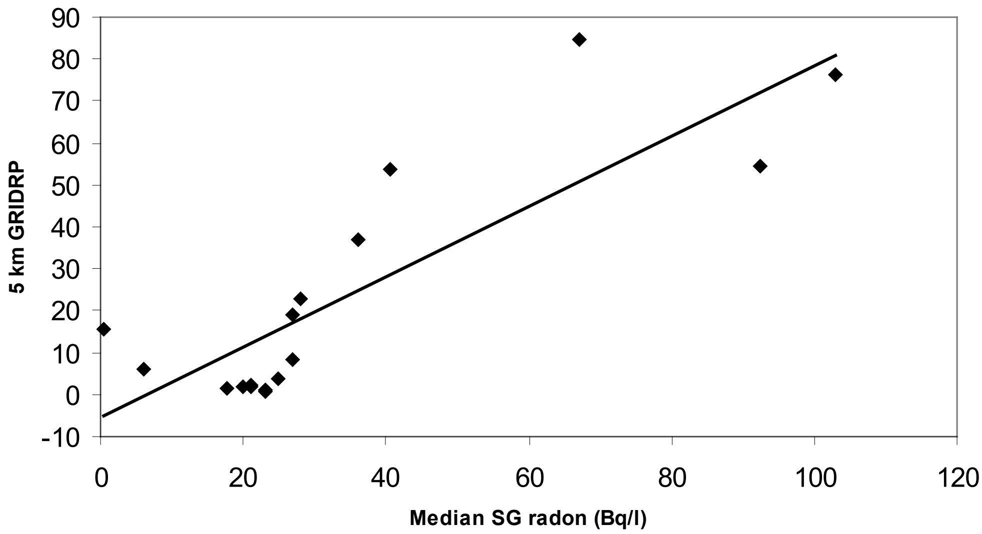


Figure 3-33. Relationship between median soil gas radon concentration (Bq/l) and 5 km grid GRIDRP for the Okehampton area (BGS, unpublished data)

Discussion and conclusions

3.120. Median soil gas radon concentrations are generally significantly higher in winter than in summer. This relationship has also been reported from the Claremorris area, County Mayo, Ireland (Cliff and Mills, 1997). In Northamptonshire it was demonstrated that site investigations using soil gas radon cannot be carried out reliably in the winter because (a) soil gas cannot be obtained from water logged soils and (b) soil gas radon concentrations may be abnormally enhanced in some soils due to the sealing effect of soil moisture. In contrast, studies in Derbyshire showed that it is possible to carry out site investigations using soil gas radon in the winter over some permeable geological units.

3.121. Soil gas radon, soil radon emanation and field gamma spectrometric U determination all provide reasonably good geochemical indicators of radon potential in Derbyshire but only soil gas radon correlates significantly with GEORP (determined from house radon measurements) in Northamptonshire. Radon in soil gas discriminates more effectively between sites with different radon potential in Northamptonshire if soil permeability is also taken into account. In general, measurement of soil gas radon in the field provides the most universally applicable geochemical indicator of radon potential.

3.122. If soil gas radon concentrations cannot be determined because of climatic factors, for example when the soil profile is waterlogged, measurement of radon emanation in the laboratory or gamma spectrometric measurement of eU can be used as radon potential indicators in some geological environments. This applies particularly in areas where the soil composition rather than the composition and permeability of the underlying rock or superficial deposits are the dominant controls of radon potential. ^{226}Ra determined by gamma spectrometry in the laboratory has also been demonstrated to be a broad indicator of house radon levels in dwellings in Ireland (McAulay & Marsh 1992).

3.123. In Northamptonshire soil/rock permeability appears to be the major factor controlling soil gas radon concentrations whereas in Derbyshire both soil eU (as confirmed by the preliminary results of the BGS HIRES airborne gamma spectrometry survey) and permeability are important. This possibly reflects the differing recent Quaternary history of the two areas. In some cases no method will provide a reliable indicator of radon potential under unfavourable climatic conditions.

3.124. An evaluation of the variability of soil gas radon measurements in relation to sample spacing and number of measurements tends to support the standard BGS site investigation protocol in which 10 measurements are taken on a 20 m spacing. However, a rigorously planned field programme would be required to establish the optimum sample number and spacing. In view of lateral variation in geology and soil characteristics together with economic constraints, it would be difficult to arrive at an optimum sampling protocol for all conditions. The combination of 10 measurements with a 20 m spacing is probably an adequate and practical compromise.

3.125. Evaluation of Sharman's soil gas radon data for Northamptonshire confirms that there is considerable overlap between the radon ranges for lithological units with significantly different radon potentials (GEORPs). In general there is a consistent relative relationship between the SG-GEORP (estimated from soil gas radon concentrations and permeability using the calibration plot in Figure 3-8) and the 5 km grid GEORP. Whereas the calibration plot helped to deal with the influence of rock/soil permeability on soil gas radon concentrations when estimating radon potential for the Northamptonshire sites investigated in 1996, it is clear that use of this calibration plot with Sharman's data produces SG-GEORP values that are consistently higher than 5 km grid GEORP values. For example, many SG-GEORP estimates for the Northampton Sand Formation exceed 40% and range up to 115%, which is clearly incorrect and inconsistent with the 5 km grid GEORP values estimated from house radon data. This discrepancy indicates that the calibration plot needs to be refined further.

3.126. The significant positive correlation between median soil gas radon and 5 km grid square GEORP for the Northampton Sand Formation in the Northamptonshire area implies that soil gas radon site investigation data could be used to provide a relatively reliable indication of the radon potential for an area.

3.127. Evaluation of the Derbyshire 1993 radon data confirmed the influence of soil/rock permeability on radon concentrations and the importance of taking permeability into account when estimating radon potential (SG-GEORP) from soil gas radon data. Whereas one cannot expect the average of 10 soil gas radon measurements taken 25 to 50 m apart in one sector of a 5 km grid square or geological map sheet to correlate perfectly with the 5 km grid or map GEORP, the closeness of the correlation suggests that soil gas radon may be used to indicate radon potential on a site specific as well as a regional scale.

3.128. Mean soil gas radon for the 1996 Derbyshire sites is significantly lower than for the majority of the 1993 sites, especially at low GEORP levels. It is not certain whether the higher radon levels recorded during the 1993 survey reflect an instrumental calibration problem or whether climatic conditions had caused a build up of radon in the soil profile.

3.129. Soil gas radon data for the Mansfield area of Nottinghamshire confirm that soil gas radon measurements may be used to estimate the radon potential for geological units covering a relatively large area but not necessarily for a small development site. Results indicate considerable variation in radon potential between sites on the same geological unit, which would be expected.

3.130. Soil gas radon measurements identify variations in radon potential indicated by 5 km GRIDRP, in the Okehampton area of Devon. Whereas this conclusion applies on a regional rather than site specific scale, it is not known whether radon in soil gas measurements could be equally effective in determining the radon potential of a new development site in the Okehampton area.

3.131. Whereas laboratory radon emanation data is a reliable indicator of GEORP in Derbyshire but not in Northamptonshire, no data are available for other areas. Therefore the universal use of laboratory radon emanation data must be considered untested until additional studies are carried out.

3.132. Studies by the BGS in Great Britain have demonstrated that, whereas there is sometimes a reasonable correlation between radon in dwellings and eU determined in the field by gamma spectrometry, the relationship is not consistent and the method does not appear to work effectively in Northamptonshire (Talbot et al., 1998). Insufficient data are available for other areas of the UK so the universal use of eU as an indicator of GEORP has not been fully tested.

3.133. Whereas soil gas radon is accepted as being the best method for determining GEORP on both a regional and site specific scale, seasonal and temporal variation in soil gas radon concentrations are difficult to deal with. Alternative site investigation protocols might be to (1) carry out measurements on 2 or three well documented calibration sites prior to carrying out each new survey so that seasonal effects related to soil moisture could be taken into account or (2) measure permeability and soil moisture and use calibration plots to estimate GEORP from soil gas radon data.

3.134. It may be necessary to devise a system of calibration plots not only for different soil/rock permeabilities but also for different soil moisture levels. Additional research would have to be carried out to investigate this and also to investigate the practicality of making permeability measurements as part of a radon site investigation protocol used prior to the construction of new dwellings. It may be necessary also to measure permeability and moisture content both close to the surface and at the sampling depth of 70 cm.

3.135. The incorporation of field permeability measurements into a site investigation protocol was not tested during the current research programme. Problems with the determination of permeability and its incorporation into a radon site investigation procedure have been encountered in the Czech Republic (Neznal et al., 1996) where the current practice of determining permeability is based on *in situ* measurements or particle size analysis. Neznal et al (1996) observe that the quality of the permeability classification obtained at a site is very reliant on the personal experience of the technical staff carrying out the site investigation.

3.136. With regard to the practical application and effectiveness of soil gas radon site investigation methods as part of a Building Control system it has not yet been proven that soil gas radon data can be used to discriminate reliably between, for example, 1.0% and 3.0% GEORP taking into account the problems of seasonal and temporal variation in soil gas radon. Soil gas radon site investigation methods are probably precise enough to define the GEORP for a new building site at around the 10% GEORP level as long as soil/rock permeability is taken into consideration.

3.137. A more rigorous test of the effectiveness of radon site investigation methods would be to carry out soil gas radon surveys in the immediate vicinity of a representative number of dwellings constructed on a range of geological units with different radon potentials. Approximately 100 sites on each geological unit would be required and radon measurements would need to be made in each dwelling under carefully monitored conditions. Selection of dwellings with similar construction characteristics would reduce the number of confounding factors in the data analysis. Such an evaluation was beyond the scope and financial constraints of the present research project. Previous attempts to assess the relationship between radon in dwellings and soil gas radon measured in the immediate vicinity of the dwelling have produced divergent results (e.g. Nason & Cohen, 1987; Cliff & Miles, 1997) perhaps because they were based on a relatively small number of dwellings and because of the influence of a building on soil gas radon levels in the ground immediately surrounding the dwellings.

4. REVISED GUIDANCE ON PROTECTIVE MEASURES (BR211, 1999)

Introduction

4.1. The publication of revised guidance and details of new measures to protect new homes from radon gas in affected areas of England and Wales was announced on 11 November 1999. *Radon: Guidance on Protective Measures for New Dwellings*[13] updates previously published guidance and details measures that must be incorporated in new buildings and defines the geographical areas where radon protection is necessary. The Approved Document to Part C of the Building Regulations 1991 refers to the BRE document as a source of advice on where radon protection may be needed and what measures are appropriate. In addition to Cornwall and Devon and parts of Somerset, Northamptonshire and Derbyshire - which were covered in previous guidance - the new guidance identifies new areas where radon protection will be needed. These are parts of the Yorkshire Dales; parts of Wales and the Welsh Border; North Oxfordshire; parts of the Midlands adjacent to the currently delineated areas in Derbyshire; Northamptonshire; parts of Gloucestershire, the Lake District and Northumberland. There are also a few scattered areas in south-east England where these measures need to be applied.

4.2. As well as maps based on NRPB data, BR 211 (1999) contains a second set of maps based on the assessment of geological radon potential which has been prepared by the British Geological Survey. These maps show grid squares that are underlain, completely or in part, by geological units that require either basic or full protection. The guidance explains how the two sets of maps should be used to determine the level of protection needed.

4.3. The new guidance brings together the best practice for protecting new homes against radon. It provides a comprehensive source of information on the measures that should be incorporated in new dwellings, and of the areas of England and Wales in which this will be necessary. The companion Departmental Circular, also issued on 11 November 1999, indicated that these measures were necessary from 14 February 2000.

4.4. Amendments to the guidance document (BR211) have evolved over two years following a DETR consultation exercise[14]. The principal changes in BR211 reflect greater knowledge of radon-prone areas and the advances made in developing practical cost-effective protective measures. In addition, the development of protective measures and the monitoring of their effectiveness indicated that the general approach to radon protection should be reconsidered and embody the findings of recent research.

4.5. In the Approved Document to Part C of the Building Regulations, it indicates that the precise areas where radon protective measures should be taken are reviewed by the DETR in the light of advice from the NRPB. The NRPB *Radon Atlas of England* (Lomas et al., 1996) and the *Radon Atlas of Wales* (Lomas et al., 1998) indicated that radon protection was required in more areas than those listed in BR211 (as revised 1992). The 1999 edition of BR211 was published on 11 November 1999 to reflect this change and also the results of the current research project.

---

[13] The new guidance, *BR 211: Radon: guidance on protective measures for new dwellings* (1999 edition, ISBN 1 86081 3283, price £26) is published by CRC Ltd. Copies are available from CRC Ltd., 151 Rosebery Avenue, London, EC1R 4GB (Tel. 0171 505 6622; Fax. 0171 505 6606). The Departmental Circular *The Building Act 1984: The Building Regulations 1991: BR 211: Radon: guidance on protective measures for new dwellings, 1999 edition* (DETR Circular 8/99) is published by TSO. Copies are available from: TSO Publications Centre, PO Box 276, London, SW8 5DT and through booksellers.

[14] DoE Consultation Paper, March 1997: *Proposed amendments to the Approved Document to Part C of the Building Regulations and to Guidance Document BR211 - Radon: guidance on protective measures for new dwellings*

Determining the level of radon protection

4.6. The DETR Building Regulations Division devised a system for determining the level of protection needed based on two sets of maps that show, as 5km grid squares of the Ordnance Survey National Grid, where protective measures from radon will or may be needed. The areas shown on the maps will need to be revised as more information becomes available and the maps will be amended accordingly. The 5 km grid squares can be easily cross referenced to local area Ordnance Survey maps at scales that are used for building control and for planning purposes (e.g. 1:50 000, 1:25 000 or 1:10 000).

4.7. The two map sets are quite different due to the way they have been prepared. The NRPB maps (Annex A, BR211 (1999)) are based on a statistical analysis of radon measurements in existing houses and show 5 km grid squares for which the estimated percentages of homes above the radon Action Level (AL; 200 Bq m^{-3}) exceed the threshold percentages designated for either basic (3% >AL) or full (10%>AL) radon protection (Figures 4-1 and 4-2). The BGS maps (Annex B, BR211 (1999)) are also based on a statistical analysis of radon measurements in existing houses but indicate those grid squares which are underlain, completely or in part, by geological units for which the estimated percentages of homes above the Action Level exceed the thresholds for either basic or full radon protection. The shading on the BGS maps (Figures 4-3 and 4-4) shows the highest geological radon potential found somewhere within the grid square rather than the average for the grid square (shown on the NRPB maps). As a result there are many more shaded grid squares shown on the BGS maps (Annex B, BR211) than on the NRPB maps (Annex A, BR211).

4.8. There is a flow chart in the 1999 Edition of BR 211 (Figure 4-5) that sets out a two-stage procedure to be followed when using the maps in the guidance. It indicates when full protection should be installed, and when no protection is necessary at all. When the NRPB maps indicate no radon protection or the installation of basic protection, the BGS maps should be consulted to establish if underprotection might be possible. Developers or their advisors can use Table 4-1[15] in combination with the maps in Annexes A and B of BR211 (1999) to work out what radon protective measures are indicated for a site, and whether a geological assessment might allow them to install a lower level of protection[16].

4.9. If a site falls within one of the squares shaded on the Annex B (BGS) maps, it does not necessarily mean that it must have radon protection. This is because some of the grid squares contain bed rocks and unconsolidated (drift) deposits with lower radon potential than the maximum levels shown on the map. In many cases the geological radon potential varies considerably within a grid square. In other cases, only a very small area (sometimes only a few hundred square metres) with a radon potential exceeding the thresholds for basic or full protection occurs within the grid square but, as the squares are coded according to the highest radon potential, the whole square has been shaded. The level of protection that might be required is thus site specific, and can be determined by reference to the relevant maps in Annexes A and B followed, if appropriate, by a geological assessment of the site. In BR211 (1999) the two types of map are complementary, and neither should be used in isolation.

4.10. A geological assessment involves checking whether a site is on or close to a geological unit for which either basic or full radon protection is required. Radon Protective Measures (RPM) site reports[17] are

---

[15] adapted from Miles J, *Interpreting BR211* published in NRPB Environmental Radon Newsletter, Issue 23, Summer 2000.

[16] Developers may choose to install the higher level of radon protection indicated by the maps in Annex B of BR211 (1999) should they not wish to obtain a geological assessment.

[17] RPM site reports are available from: National Geological Records Centre, British Geological Survey, Keyworth, Nottingham NG12 5GG (Telephone: 0115 936 3109, Fax: 0115 936 3276 e-mail: ngrc@bgs.ac.uk). Further information and an order form are available on the BGS web site http://www.bgs.ac.uk/radon and will also be available in the near future on http://www.british-geological-survey.co.uk/

generated by the Radon Protective Measures Geographical Information System (RPM-GIS), which was developed by the BGS using its own resources, to provide Stage 2 Geological Assessments (RPM Site Reports). Assessments are derived from a geologically based interpretation of radon measurements in dwellings which were provided to the BGS by the NRPB without prejudicing confidentiality undertakings to householders and the Department of the Environment, Transport and the Regions (DETR).

4.11. The search area (circle or rectangle) for a development site is increased by a buffer zone of 50 m in areas with 1:50,000 scale data and 500m in areas with 1:250,000 scale data. This is to allow for potential inaccuracies in the position of the geological boundaries. In many cases a number of combinations of bed rock and drift with differing geological radon potentials will occur within the total search area. Following the precautionary principle, the requirement for protective measures is derived from the highest geological radon potential encountered within the total search area. Consideration must be given to installing basic or full radon protection if the geological assessment shows that this is required.

4.12. The RPM GIS currently comprises 1:250,000 scale data with more detailed 1:50,000 scale data covering the most radon-prone parts of Derbyshire, Northamptonshire, Nottinghamshire, Leicestershire, Lincolnshire, Oxfordshire, Shropshire, Somerset and Yorkshire. The reliability of a geological radon potential assessment is approximately proportional to the number of radon measurements available and the scale of the geological data. The RPM-GIS is being upgraded to 1:50,000 scale over the next 12 months as new digital map data become available through the BGS *DigMapGB* programme.

4.13. For most parts of the UK, a higher resolution geological assessment of radon protective measures requirements can be provided by BGS. This will comprise: (i) Assessment by a qualified geologist of the relevant 10,000, 1:10,560 or 1:50,000 scale geological map(s) from BGS archives covering the total search area; (ii) Precise identification of the level of radon protective measures indicated for all geological units encountered within the site and the immediately surrounding area[18]. A higher resolution assessment may be cost-effective for a multi-dwelling development where the developer wishes to avoid the expense of installing basic or full radon protective measures. For example, there are likely to be situations where the site itself is underlain by a geological unit that does not require protective measures whilst a unit requiring full measures is located within the buffer zone. In the example illustrated in Figure 4-6, the RPM-GIS assessment of the requirement for radon protective measures is based on a geological assessment of the Total Search Area. The site area itself (inner circle) requires no protective measures but, as the buffer intersects a geological unit for which full measures are indicated (dark shading), the RPM-GIS site report indicates full measures. A follow-up report based on detailed geological maps (such as 1:10,000 scale) would be likely to indicate that the development site was actually located on a unit for which no measures are indicated (pale shading in Figure 4-6).

---

[18] The basic charge for a Radon Follow-up Report is £80+VAT. Reports for very large or geologically complex sites may, however, have to be supplemented with additional £40+VAT increments to allow for each extra half-hour of time taken – in such cases, enquiry staff will confirm with the client before proceeding. The Radon follow-up reports can be ordered from:- Geological Enquiries, British Geological Survey, Keyworth, Nottingham NG12 5GG; Tel: 0115-936-3192; Fax: 0115-936-3192; e-mail: geohelp@bgs.ac.uk. An on-line ordering facility will be available in the near future from Services on the BGS web site *http://www.bgs.ac.uk*.

4.14. A different approach has been taken in Scotland where NRPB 5 km grid maps are used to identify areas where Stage 1 and Stage 2 protective measures should be incorporated[19]. Stage 1 and Stage 2 protective measures are equivalent, respectively, to *basic* and *full radon protection* in England and Wales. Stage 1 protective measures are required in 5 km grid squares for which the estimated percentages of homes above the radon Action Level (200 Bq m^{-3}) is between 1 and 10%. No account is taken of geological radon potential.

---

[19] BR376 *Radon: guidance on protective measures for new dwellings in Scotland* (BRE, 1999b)

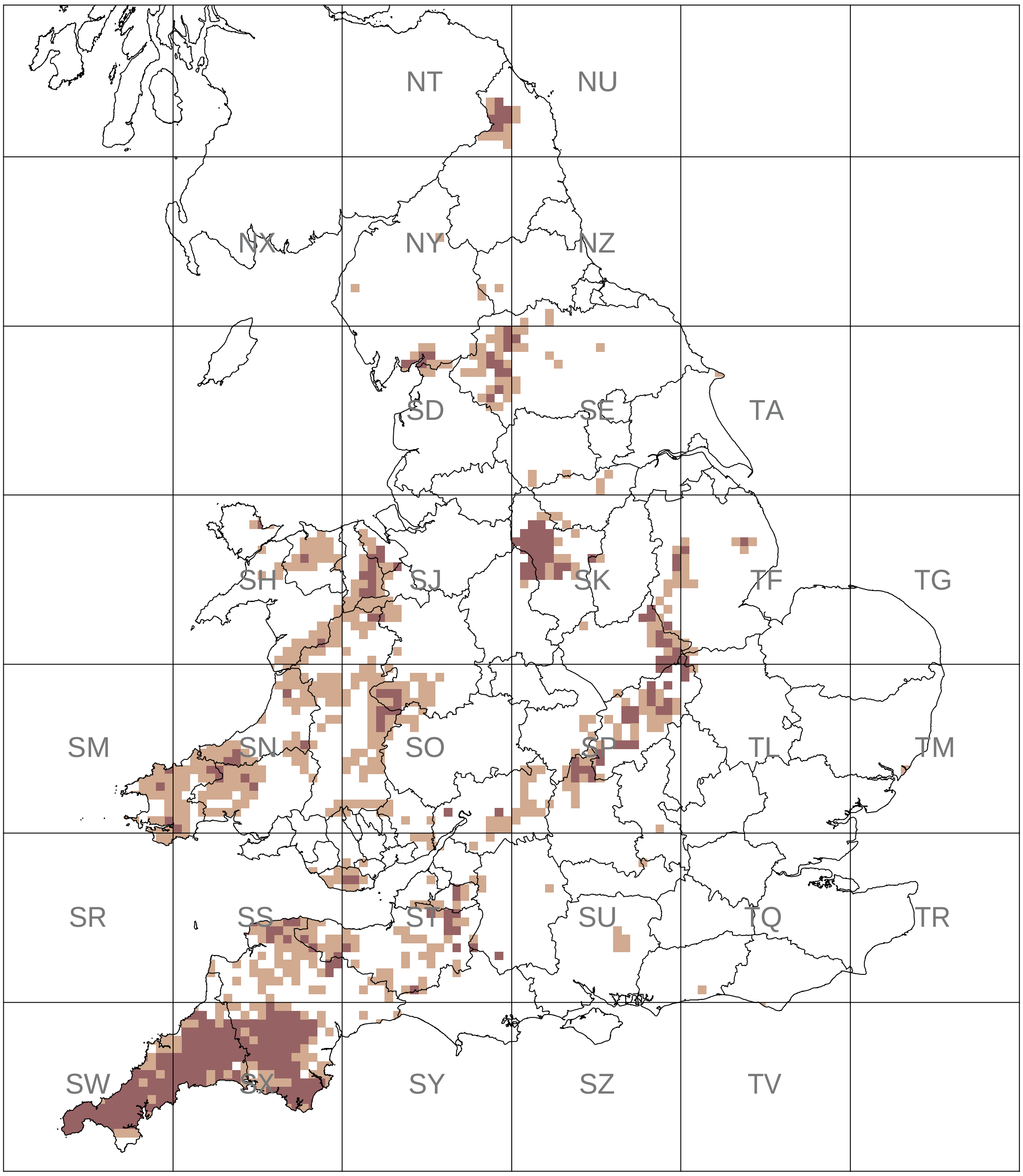


Figure 4-1. Map 1 (BR211, 1999) showing 5 km grid squares in England and Wales where basic (light brown) and full (dark brown) radon protection should be provided in new dwellings. *(The administrative boundaries shown on this map are based upon the OS map by the DETR with the permission of Ordnance Survey on behalf of The Controller of Her Majesty's Stationery Office. Unauthorised reproduction infringes Crown Copyright and may lead to prosecution or civil proceedings. Licence Number: GD272671) (cartography by BGS on behalf of the DETR; reproduced from BR211 (1999) with permission from The Copyright Unit, HMSO).*

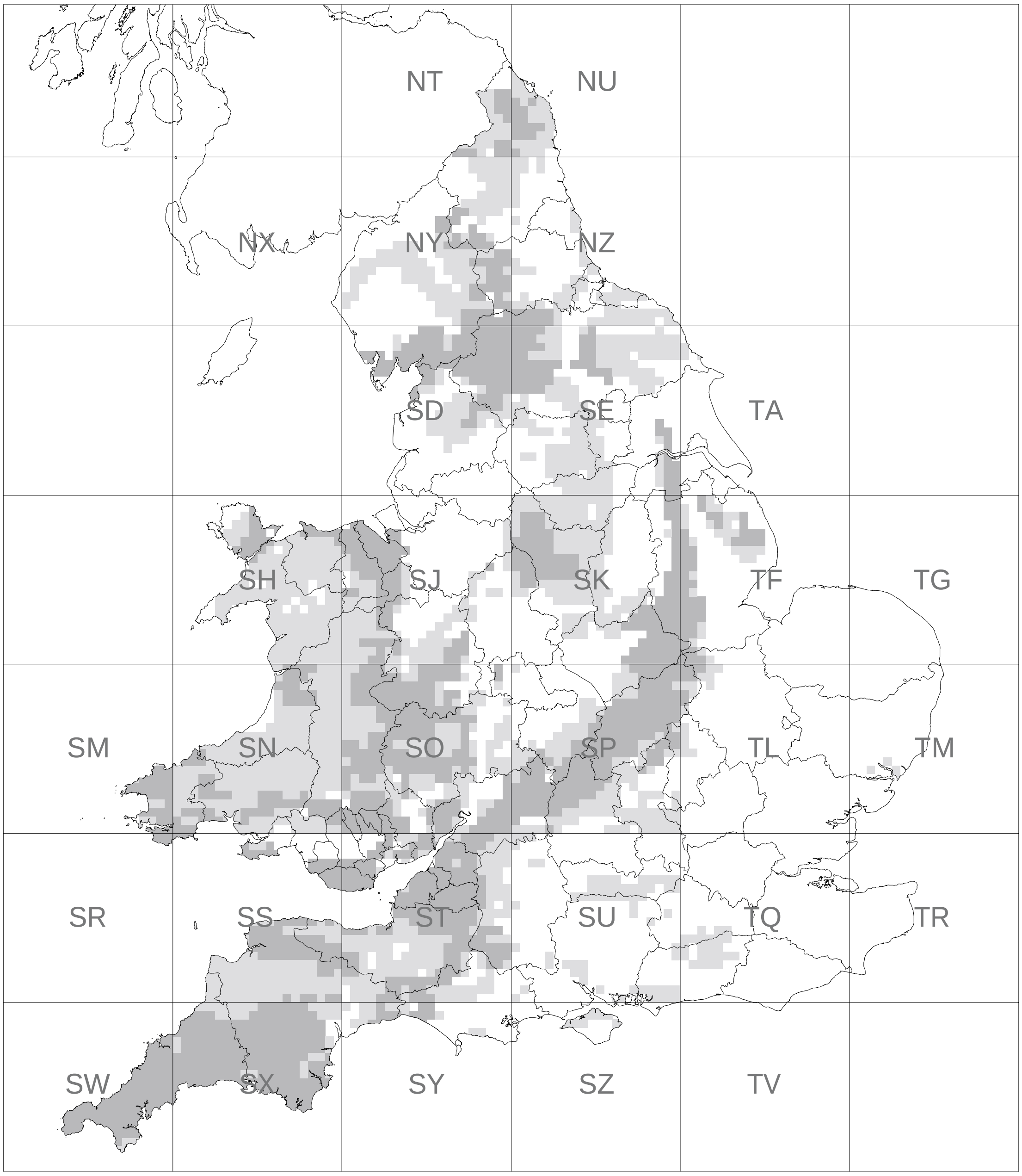


Figure 4-2. Map 2 (BR211, 1999) showing 5 km grid squares in England and Wales where a geological assessment should be carried out. Shaded squares underlain, completely or in part, by geological units which require basic (light shaded) or full (dark shaded) radon protection to be provided in new dwellings. *(The administrative boundaries shown on this map are based upon the OS map by the DETR with the permission of Ordnance Survey on behalf of The Controller of Her Majesty's Stationery Office. Unauthorised reproduction infringes Crown Copyright and may lead to prosecution or civil proceedings. Licence Number: GD272671) (mapping and cartography by BGS on behalf of the DETR; reproduced from BR211 (1999) with permission from The Copyright Unit, HMSO).*

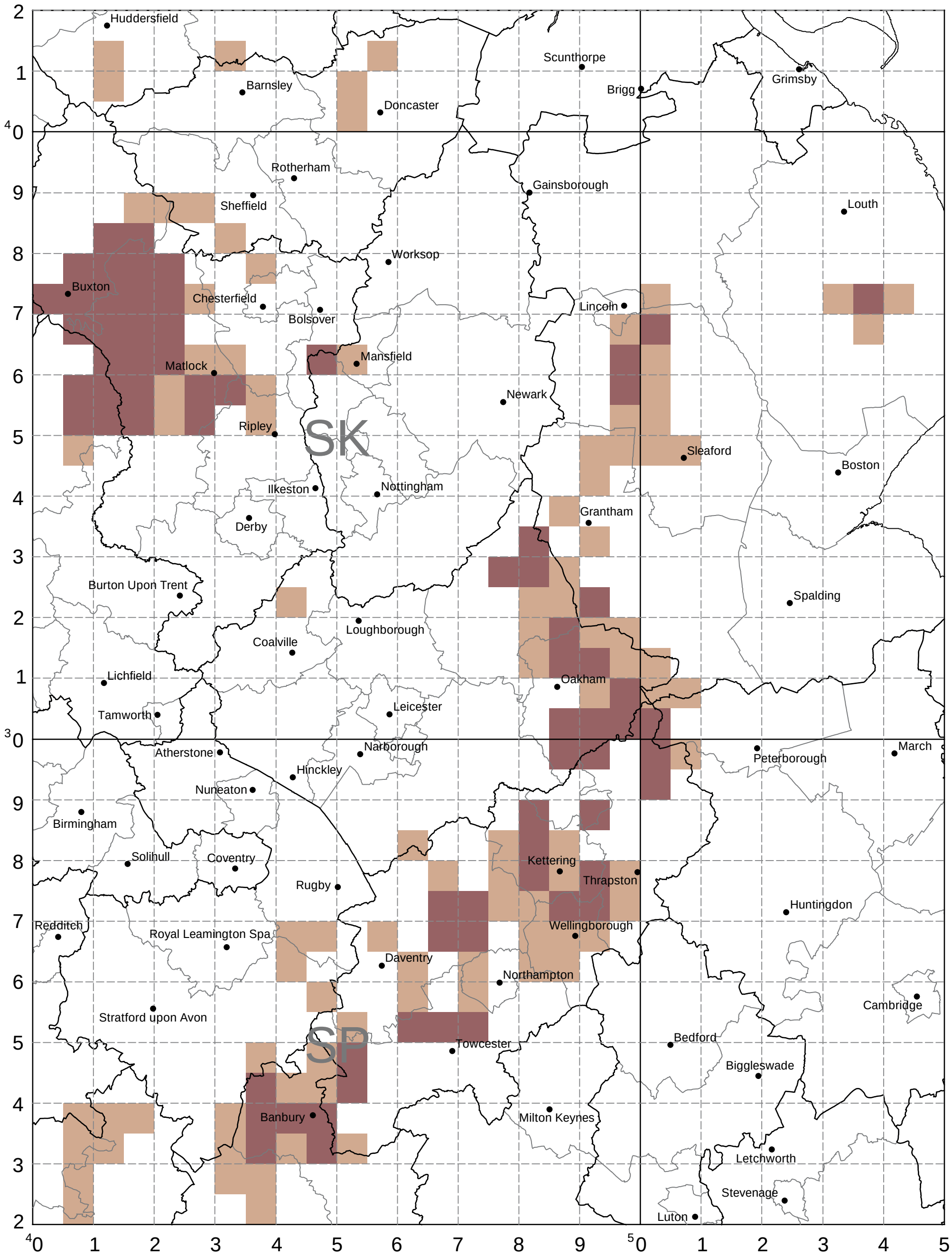


Figure 4-3. Plate 7 (BR211, 1999) showing 5 km grid squares in the East Midlands where basic (light brown) and full (dark brown) radon protection should be provided in new dwellings. *(The administrative boundaries shown on this map are based upon the OS map by the DETR with the permission of Ordnance Survey on behalf of The Controller of Her Majesty's Stationery Office. Unauthorised reproduction infringes Crown Copyright and may lead to prosecution or civil proceedings. Licence Number: GD272671) (cartography by BGS on behalf of the DETR; reproduced from BR211 (1999) with permission from The Copyright Unit, HMSO).*

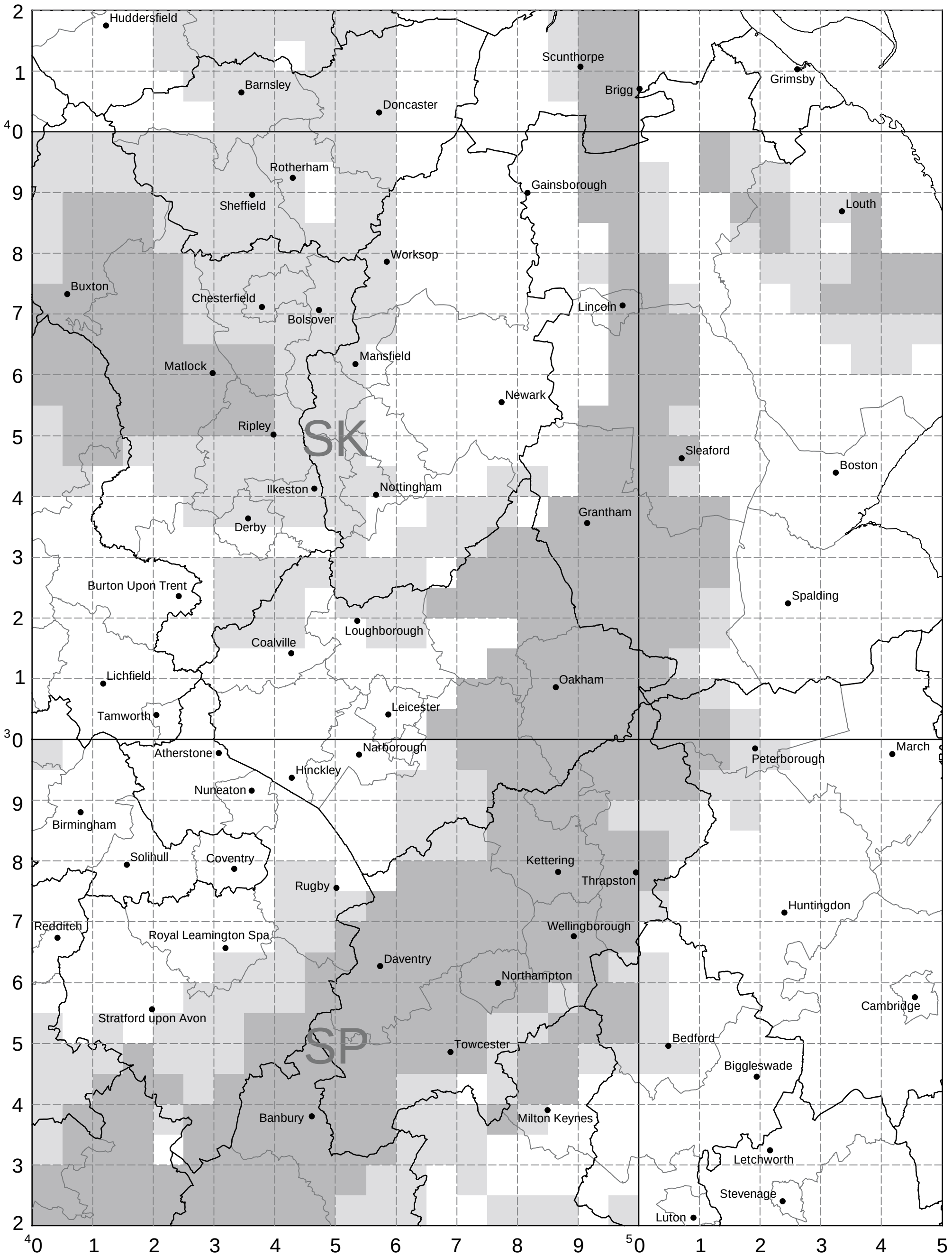


Figure 4-4. Plate 18 (BR211, 1999) showing 5 km grid squares in the East Midlands where a geological assessment should be carried out. Shaded squares underlain, completely or in part, by geological units which require basic (light shaded) or full (dark shaded) radon protection to be provided in new dwellings. *(The administrative boundaries shown on this map are based upon the OS map by the DETR with the permission of Ordnance Survey on behalf of The Controller of Her Majesty's Stationery Office. Unauthorised reproduction infringes Crown Copyright and may lead to prosecution or civil proceedings. Licence Number: GD272671) (mapping and cartography by BGS on behalf of the DETR; reproduced from BR211 (1999) with permission from The Copyright Unit, HMSO).*

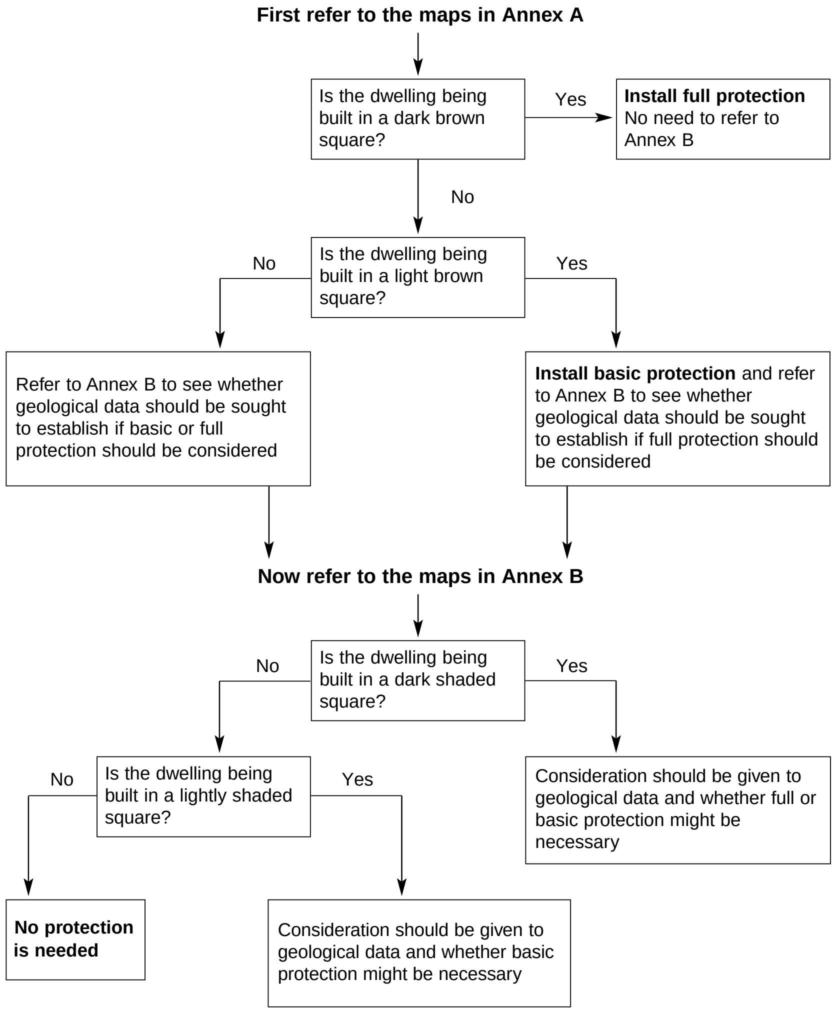


Figure 4-5. Flow chart indicating how to use the maps in Annexes A and B (BR211) to decide what level of protection is necessary in a new dwelling (reproduced from BR211 (1999) with permission from The Copyright Unit, HMSO).

Table 4-1. Radon protective measures which should be provided in new dwellings, depending on the shading found in grid squares on maps in Annexes A and B of BR211 (1999)[20].

		Shading of maps in Annex A		
		White	**Light brown**	**Dark brown**
Shading of maps in Annex B	**White**	None	Basic	Full
	Light grey	Basic, unless geological report[21] indicates None	Basic	Full
	Dark grey	Full, unless geological report indicates Basic or None	Full, unless geological report indicates Basic	Full

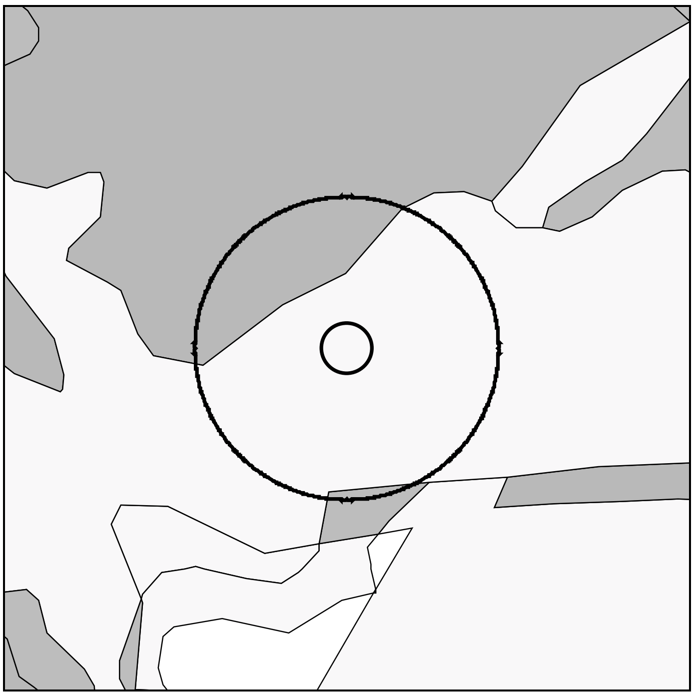


Figure 4-6. Example of a situation where a follow-up geological assessment might permit the developer to elect not to install protective measures when the RPM-GIS report indicated full measures. (dark shading = full measures, light shading = no measures, white = no data available; inner circle defines site area (centre point and radius provided by developer); outer circle defines total search area comprising the site area and the automatically generated buffer zone; 1:250,000 data; 500 m wide buffer zone; see text for further explanation).

[20] adapted from Environmental Radon Newsletter, Issue 23, p.1
[21] see footnote [17]

Annex B maps (BR211, 1999 edition)

Introduction

4.15. Recommendations for the production of a radon potential map for use by building control and planning systems evolved from the evaluation of mapping options[22,23]. This demonstrated that the maps in the 1992 version of BR211 and also in the DETR Consultation paper[24] had limitations which in many situations would result in radon protection not being installed where required and vice versa. It was concluded that geological radon potential mapping in general provides the best spatial detail and accuracy as this method relates radon risk to geology - identified as the most important overall control on the concentration of radon in dwellings. An exception to this applies in those parts of Cornwall and Devon characterised by cross-cutting uranium mineralisation where the 3% threshold cannot be defined on the basis of readily mappable lithological boundaries. In this situation, 1 km GRIDRP mapping appears to be the most effective method for defining the need for protective measures.

4.16. As part of this research programme, the BGS, working in collaboration with the NRPB, produced a 5-km grid map indicating those grid squares that contain one or more geological units with a GEORP that exceeds the thresholds for basic or full protective measures. The principal objective of these 5-km grid maps was to avoid cases of underprotection that might occur had the BR211 guidance depended solely on the average radon level in the 5 km grid square indicated by the NRPB maps. The 5-km grid maps were produced by carrying out a geological radon potential evaluation of England and Wales using the new BGS 1:250,000 scale lithostratigraphic (bed rock) and the 1:625,000 scale drift digital maps which became available in November 1998.

Methodology

4.17. Using *Bentley Geographics* running as an addition to *Bentley Microstation 95*, a point topology was built using the dwelling geographical co-ordinates. Area topologies were built using BGS 1:250,000 scale solid and 1:625,000 drift geological polygons. The point-in-polygon overlay process was used to add solid and drift geological codes to each dwelling location point and the co-ordinates, geological codes, 100 km grid square identifier, 1:250,000 and 1:50,000 scale geological map sheet numbers were loaded back to an *Access* database. NRPB added temperature-normalised house radon data and removed location co-ordinates from the file to preserve confidentiality. Lognormal modelling was then carried out by BGS on the house radon data using *dBase* and *Excel* macros. Optimisation of the estimation method is described in section 5.2.2. of Miles & Appleton (2000). This process produced an estimate of the percentage of homes with radon exceeding the Action Level for each combination of solid and drift within each 100 km grid square, 1:250,000 and 1:50,000 map sheets.

4.18. The geological radon potential for any solid-drift combination may vary both within the 100 km grid square and between adjacent 100 km grid squares. This may be caused by lateral variations in the physical and chemical characteristics of the bed rocks and unconsolidated deposits, as well as variations in housing characteristics.

4.19. The following GEORP assignment procedure was adopted. When the number of radon measurements for a solid-drift combination is equal to or greater than 30, the GEORP estimate based on calculated GM and GSD is used to assign the combination to a GEORP class (<3%, 3-

[22] BGS Confidential Report to the DOE: *Definition of areas where radon protection measures should be installed in new dwellings*, January 1997.

[23] BGS-NRPB Confidential Report to the DOE: *Geological evaluation of radon potential in south-west England.* October 1997.

[24] DoE Consultation Paper, March 1997: *Proposed amendments to the Approved Document to Part C of the Building Regulations and to Guidance Document BR211 - Radon: guidance on protective measures for new dwellings*

10%, >10%). In cases where the number of radon measurements is between 5 and 29, the following information was taken into account in addition to the estimate based on GM and GSD: (i) estimate based on GM and the average GSD for all solid-drift geological combinations in England and Wales (i.e. 2.34), (ii) estimate based on GM and the NRPB's average GSD for the UK (i.e. 2.5), (iii) the estimate for the same or similar combinations in adjacent 100 km grid squares and/or 1:250,000 scale map sheets. No assignment was made for a number of the geological combinations that have no postcodes (e.g. dwellings are rarely constructed on peat covered areas). For solid-drift combinations with less than 5 house measurements, assignments were made in some cases by taking into account estimates for the same or similar combinations in adjacent 100 km grid squares and/or 1:250,000 map sheets. The assignment procedure used for areas with 1:50,000 scale data is outlined in Section 5.2.3 of Miles and Appleton (2000). Following the precautionary principle, a small number of the assignments for combinations with 30 or more measurements were adjusted after comparisons were made with adjoining map sheets. The numbers of postcodes covered by the three assignment procedures is given in Table 4-2.

4.20. Combinations of bed-rock and drift (unconsolidated deposits) with geological radon potentials in the 3-10% and >10% classes were mapped and converted into a 5 km grid map for publication in the revised version of BR211.

4.21. The new radon potential thematic map was developed by the BGS in collaboration with the NRPB for inclusion in BR211 (see Figures 4-2 and 4-3). Each 5 km grid square of the map is shaded according to the highest radon potential for a bed rock - drift combination located within the grid square. This information is derived from a statistical analysis of radon measurements made in existing dwellings. Grid squares shaded pale grey in Figures 4-2 and 4-4 contain at least one area (polygon) of a bed rock - drift combination whose geological radon potential is equal or greater than 3%. Dark grey squares contain an area with a geological radon potential equal or greater than 10%. These areas will need to be revised as more information becomes available and the maps will be amended accordingly.

Table 4-2. Number of postcodes covered by the three assignment procedures.

No. of house measurements per solid-drift combination	Procedure used to assign solid-drift combinations to radon potential classes	No. of postcodes covered by assignment method	% of total no. of postcodes covered by assignment method
30 and >	GM+GSD	1046663	76
5-29	average of GM+GSD and GM+ 2.34 GSD; comparison with similar combinations in adjacent 100 km grid squares and/or 1:250,000 and 1:50,000 scale map sheets	257255	18
<5	comparison with similar combinations in adjacent 100 km grid squares and/or 1:250,000 and 1:50,000 scale map sheets	79090	6

Discrepancies between Annex A and Annex B maps (BR211, 1999 edition)

4.22. DETR Building Regulations Division included the Annex A maps in the BR211 procedure because a few 5-km grid squares with GRIDRP's exceeding basic or full thresholds were not identified on the Annex B maps. This occurred because GEORP's estimated for 100 km OS tiles were used to generate the Annex B maps. Lateral variation in GEORP (discussed in section 2.91 above and in Miles & Appleton, 2000) inevitably results in a few 5-km grid squares having GEORPs that exceed basic or full thresholds when the 100 km tile GEORP is below the threshold. These discrepancies were investigated in collaboration with the NRPB and it was concluded that there are eight 5-km grid squares in which there are sufficient house radon measurements to be sure that the 5-km GRIDRP is significantly higher than the GEORP value (Table 4-3) and a further seven where insufficient indoor radon data are available.

Table 4-3. Discrepancies between Annex A and Annex B maps

10K Map	5 Km grid	GRIDRP (Est. %>AL)	Annex A Map	Annex B Map	No. indoor radon measurements	GEORP explanation	Comments
SE10NW	410405	5.9	3-10%	<3%	16	Sheet 86 Millstone Grit n=102, 3.2%>AL	Small scale GEORP variation identified by 50K sheet GEORP
SO26SW	320260	25.5	>10%	3-10%	48	Sheet 180 Ludlow Rocks 13.5%>AL	Small scale GEORP variation identified by 5-km GEORP and 50K sheet GEORP
TM33NW	630235	4.7	3-10%	<3%	42	Sheet 225, Crag >3%>AL	Small scale GEORP variation identified by 5-km GEORP and 50K sheet GEORP
SS44NE	245145	12.1	>10%	3-10%	88	Sheet 276 Morte Slates 9.7%>AL; Sheet 277 Morte Slates 11.8%>AL	Small scale GEORP variation identified by 5-km GEORP and 50K sheet GEORP
ST03SW	300130	20.9	>10%	3-10%	17	No GEORP explanation apparent	?
SU26NW	420165	2.1	3-10%	<3%	5	No GEORP explanation apparent	Insufficient indoor radon data
SU78SE	475180	3.2	3-10%	<3%	7	No GEORP explanation apparent	Insufficient indoor radon data
SU64SW	460140	7.5	3-10%	<3%	8	Sheet 300, Upper Chalk 2.9%>AL (max. radon 1153 Bq/m3)	Insufficient indoor radon data but similar to SU63SW
SU63SE	465130	5.3	3-10%	<3%	6	Sheet 300, Upper Chalk 2.9%>AL (max. radon 1153 Bq/m3)	Insufficient indoor radon data but similar to SU63SW
SU63NE	465135	7.5	3-10%	<3%	7	Sheet 300, Upper Chalk 2.9%>AL (max. radon 1153 Bq/m3)	Insufficient indoor radon data but similar to SU63SW
SU63SW	460130	3.0	3-10%	<3%	229	Sheet 300, Upper Chalk 2.9%>AL (max. radon 1153 Bq/m3)	Small scale GEORP variation identified by 5-km GEORP and 50K sheet GEORP
SU63NW	460135	3.5	3-10%	<3%	5	Sheet 300, Upper Chalk 2.9%>AL (max. radon 1153 Bq/m3)	Insufficient indoor radon data but similar to SU63SW
TQ10NW	510105	14.0	3-10%	<3%	12	No GEORP explanation apparent	Small scale GEORP variation identified by 50K sheet GEORP
TV49NE	545095	15.2	3-10%	<3%	7	No GEORP explanation apparent	Small scale GEORP variation identified by 50K sheet GEORP
SX98SW	290080	5.5	3-10%	<3%	40	Sheet 339, Exeter Group Breccia 1.4%>AL (N=2173, max. 757 Bq/m3)	Small scale GEORP variation identified by 5-km GEORP

4.23. As an example, the four SU63 5-km grid squares for which basic radon protective measures are required in new dwellings are highlighted in Figure 4-7. The average GEORP for the Upper Chalk in the SU 100 km tile is only 1.6%>AL based on 863 radon measurements (maximum radon = 1153 Bq m^{-3}). However, the SU63 5-km grid squares lie within geological map sheet 300 for which the actual proportion of dwellings that exceed the action level is 3.5% and the estimate based on GSD is 2.9%. Therefore, basic measures should be recommended for new dwellings constructed on the Upper Chalk in the area covered by BGS geological map sheet 30.

4.24. The RPM-GIS is being upgraded to 1:50,000 scale over the next 12 months as new digital map data become available through the BGS *DigMapGB* programme. This will permit smaller scale intra-geological map sheet and intra-5-km grid square variations in GEORP to be mapped where sufficient indoor radon measurements are available. The Annex B maps will be amended accordingly, as indicated on page 5 of BR211 (1999). Amended maps will be posted on the BGS web site (www.bgs.ac.uk/radon). Once this re-appraisal of the indoor radon data has been completed, there will, in theory, be no need for the Annex A maps in the BR211 process.

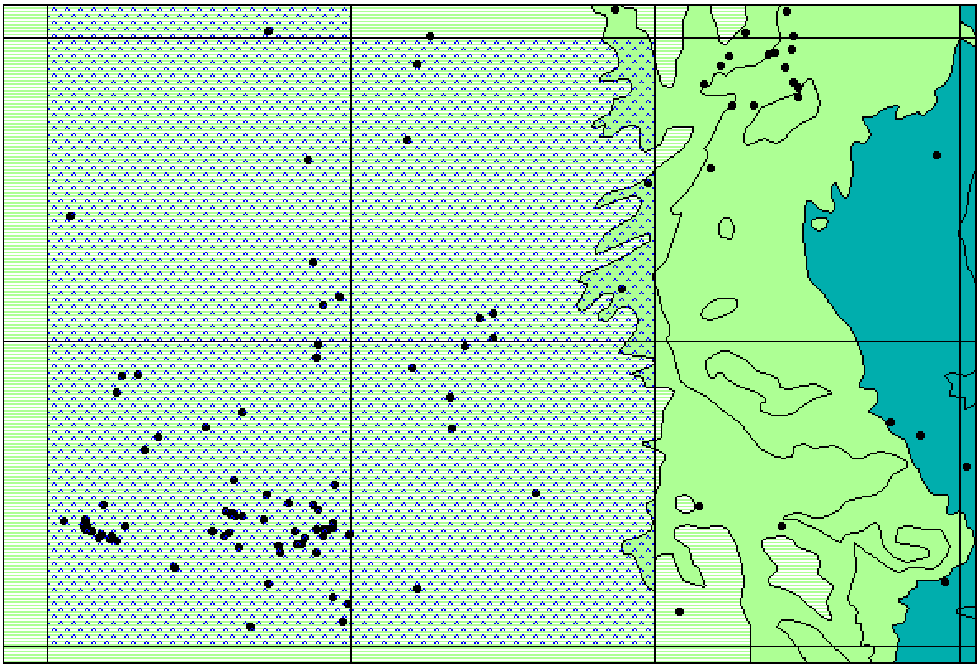


Figure 4-7. SU63 5-km grid squares (blue overlay shading), south of Basingstoke, Hampshire in which new dwellings require Basic radon protective measures. [Geological units from BGS 1:250,000 geological map: pale green = Upper Chalk; medium green = Middle and Lower Chalk; dark green = Upper Greensand; dots = approximate locations of dwellings with radon measurements].

Over-protection indicated by Annex A maps (BR211, 1999 edition)

4.25. The BR211 (1999) process indicates that full protective measures should be provided if a new dwelling is located in one of the dark brown shaded grid squares on the maps in Annex A. Because of the variation of GEORP within individual 5 km grid squares (see section 2 of this report for further details), there will be many situations in which a developer will be required to provide full radon protection when this would not be required on the basis of the geological radon potential.

4.26. Figure 4-8 illustrates the situation for grid square TL09SW. in Northamptonshire where Full measures are indicated for the whole of the 5-km grid square (red brick ornamentation) even the geological radon potential indicates a requirement for full measures (pink) in less than 10% of the grid square and basic measures in about 20%. The explanation for this situation is quite clear from the data presented in Table 4-4. New dwellings on the Blisworth Limestone Formation and Upper Estuarine Series clearly do not require even basic protective measures.

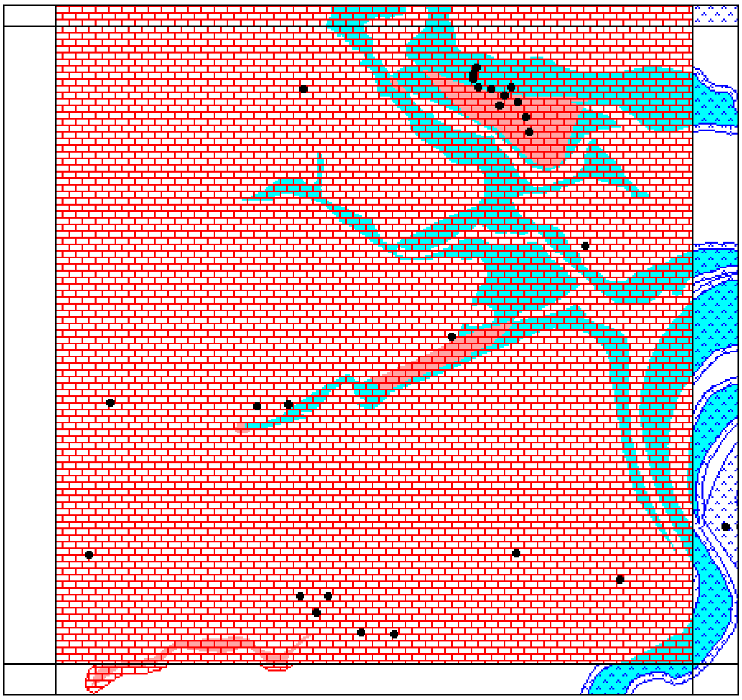


Figure 4-8. Radon protective measures required in the TL09SW 5-km grid square (red brick overlay indicates requirement for full radon protection, based on BR211 Annex A; pink shading = GEORP indicates full protection required; blue shading = GEORP indicates basic protection required; white = GEORP indicates no protection required; black dots indicate approximate locations of indoor radon measurements).

Table 4-4. Geological radon potential for TL09SW 5-km grid square.

Bedrock	Drift	No. of indoor radon measurements	GEORP (Est.%>AL based on GM & GSD)
Blisworth Limestone Formation	No drift	59	1
Lower Lincolnshire Limestone	No drift	24	4
Northampton Sand Formation	No drift	47	41
Upper Estuarine Series	Alluvium	10	1
Upper Estuarine Series	No drift	12	<0.1

4.27. A similar situation pertains in a number of other 5-km grid including ST64SW (Shepton Mallet) for which full protection is required according to the Annex A map. However, GEORP data indicate full protection for about 40% of the grid square, basic for 40% and no measures for 20% (Figure 4-8 and Table 4-5). Mercia Mudstone Group underlies the area indicated as requiring no measures. Whereas no indoor radon measurements are available for the Mercia Mudstone Group within the ST64SW grid square, the GEORP for Mercia Mudstone in Sheet 280 is 1.1%>AL.

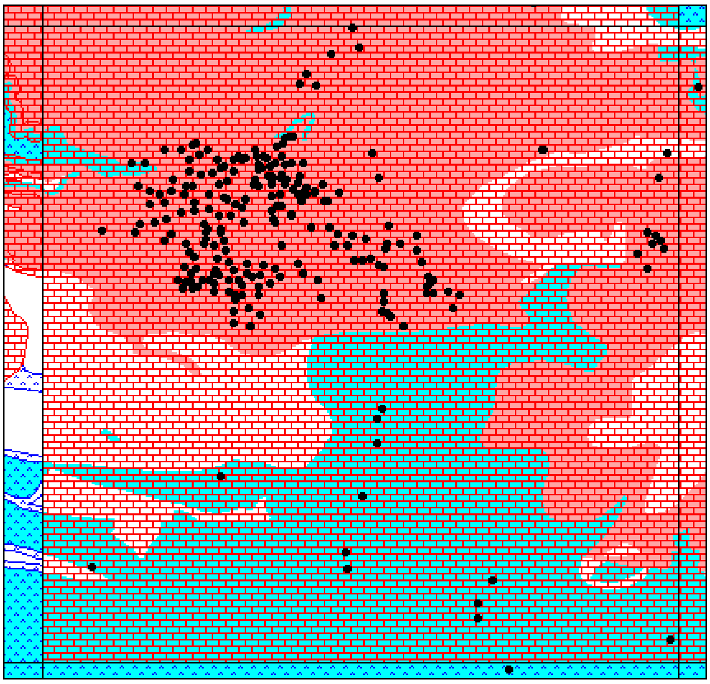


Figure 4-8. Radon protective measures required in the ST64SW (Shepton Mallet) 5-km grid square (red brick overlay indicates requirement for full radon protection, based on BR211 Annex A; pink shading = GEORP indicates full protection required; blue shading = GEORP indicates basic protection required; white = GEORP indicates no protection required; black dots indicate approximate locations of indoor radon measurements).

Table 4-5. Geological radon potential for ST64SW 5-km grid square.

Bedrock	Drift	No. of indoor radon measurements	GEORP (Est.%>AL based on GM & GSD)
Inferior Oolite Group	No drift	37	30.19
Lower Lias (Littoral Facies)	No drift	723	25.93
Lower Lias (Marginal facies)	No drift	294	18.46
Lower Lias	No drift	53	4.40

5. MAPPING AND SITE INVESTIGATION COSTS

Estimated cost of geological radon potential mapping using indoor radon data

5.1. For radon potential mapping it is necessary to assign national grid geographical co-ordinates to each postal address at which a radon measurement has been made. There are currently three sources of address-linked geographical co-ordinates: Royal Mail's PAF® (Postcode Address File, a registered trademark of Royal Mail), Ordnance Survey (OS) Address-Point™ and OS Data-Point® (now marketed as Code-Point®).

5.2. Royal Mail's PAF® *Postzon* file gives geographical co-ordinates for Postcodes in the UK. The co-ordinate resolution is 100 m (information from http://www.royalmail.com/paf/).

5.3. OS Data-Point® provides a precise geographical location for each 'postcode unit' in Great Britain. A postcode unit is a group of, on average, fifteen adjoining addresses. It may be a whole street, part of a street, a block of flats or one large individual customer. Each OS Data-Point® record has a postcode and National Grid reference. The OS Data-Point® is derived from the mean of the most accurate address locations in OS Address-Point™ product, for each postcode unit. To ensure that the OS Data-Point® centroid stays within the extent of the postcode unit, it is given the co-ordinates of the nearest reliable address to the mean position. Each postcode unit has a unique grid reference and the same grid reference is rarely shared by more than one unit postcode. The co-ordinate resolution varies with the number of addresses in the unit postcode (information from http://www.ordsvy.gov.uk/).

5.4. Address-Point™ is an OS data product that provides a national grid co-ordinate and a unique reference code for every postal address in England, Scotland and Wales. Address-Point™ was created from OS digital map data and the approximately 25 million addresses in Royal Mail's PAF®. The co-ordinate resolution is quoted as 0.1m.

5.5. The cost of obtaining national grid co-ordinates for the approximately 400,000 addresses at which radon measurements have been made would be approximately £80,000 using OS Address-Point™ (assuming 20p per address through DETR 'call-out' contract with OS). The annual licence fee for OS Code-Point® for the Great Britain is £2,000 for Year 1 and £500 for subsequent years. The cost of the Royal Mail *Postzon* data is about £950.

5.6. Assuming that 50 radon measurements per geological unit will provide an acceptable estimate of GEORP, the average cost for each 1:50,000 scale map sheet would be approximately £51,000. This is based on an average of 34 bedrock-drift combinations in each map sheet and 50 indoor radon measurements per combination - each measurement costing £30 (Miles & Appleton, 2000). The number of radon measurements used to evaluate a geological unit could be varied in proportion to the surface area underlain by the unit and/or the housing density (number of postcodes). If this approach was adopted, it is estimated that the average cost per map sheet could be reduced to about £42,000 (Table 5.1). Mapping costs could be further reduced if a significant discount could be obtained for the bulk provision of radon measurements. Mapping the whole of England and Wales following this procedure would require approximately 420,000 indoor radon measurements. Coincidentally, this is approximately the number of measurements currently available, although the measurements are not systematically distributed and are concentrated in the most affected areas.

5.7. The cost of statistically evaluating and processing this indoor radon data into a GIS-compatible 1:50,000 scale digital geological radon potential theme would be £150,000 to £300,000 for England

and Wales. Data processing costs for 5-km and 1-km grid square radon potential mapping would be much less. This is because the data processing is almost totally automatic and does not involve the same amount of interpretation that is required for geological radon potential mapping, especially in areas where relatively few indoor radon data are available.

Table 5-1. Estimated radon data cost for geological radon potential mapping of 1:50,000 map sheets (number of radon measurements per geological combination increases with number of postcodes).

Number postcodes	Number geology combinations*	Number radon measurements /combination	Total number measurements	Cost indoor data**	Cost soil gas data***
5 to 10	312	30	9,360	£280,800	£187,200
10 to 30	138	30	4,140	£124,200	£82,800
30 to 1000	129	50	6,450	£193,500	£129,000
>100	106	75	7,950	£238,500	£159,000
Average per 50K map			1,395	£41,850	£27,900
Total for 300 50K maps***			418,500	£12,555,000	£8,370,000

* in 20 map sheets (data from Miles & Appleton, 2000)
* * Mapping cost using indoor radon data = No. of geology combinations x No. of radon measurements per combination x £30 per measurement (a discounted rate would apply for large numbers of radon measurements)
* ** Mapping cost using soil gas radon data = No. of geology combinations x No. of radon measurements per combination x £20 per measurement
* *** Complete coverage of England and Wales

Estimated cost of geological radon potential mapping using soil gas radon data

5.8. Badr et al (1996) recommended that soil gas radon measurements on a 250-500 m grid would be required to obtain local estimates of radon concentrations as part of large scale radon potential mapping. They observed that it would be costly to cover large areas of the UK using this procedure. Indeed, approximately 600,000 soil gas radon measurements, costing about £12,000,000 (based on £20 per radon measurement), would be required to cover the 150,000 km^2 of England and Wales. Badr et al. (1996) note that a substantial part of the variation in radon concentrations would still be unresolved, even at this sampling density, and this would result in significant errors in regional radon estimates. Where intensive sampling is not a practical option, because of cost or logistic reasons, then radon can best be estimated from the mean concentration for a given lithology. A similar conclusion was reached from an evaluation of soil gas radon data presented in Section 3 of this report. Badr et al. (1996) noted that as a result of the small scale variability in soil gas radon, estimating radon values by kriging would probably not improve estimates made using classical estimation methods (i.e. mean, median or geometric mean radon for a geological unit).

5.9. If the number of radon measurements used to evaluate the radon potential of a geological unit was varied in proportion to the surface area underlain by the geological unit and/or the housing density (indicated by the number of postcodes), it is estimated that the total cost of data collection for soil gas radon potential mapping the whole of England and Wales would be approximately £8.4 million (Table 5.1).

5.10. It is debatable whether the resultant soil gas radon potential maps would be as useful or accurate as those based on indoor radon data.

Estimated cost of radon site investigation prior to construction

5.11. In the Czech Republic it is mandatory to carry out a radon risk assessment at new building sites using soil gas radon measurements. Fifteen soil gas measurements have to be taken over the site for an individual dwelling with proportionally fewer radon measurements on multi-dwelling developments. Labour costs are relatively low in the Czech Republic so the average cost of the radon site investigation per dwelling site is £40-50.

5.12. Should an acceptable and reliable radon site investigation (SI) procedure be developed for use in the UK, it is estimated that the likely average cost to estimate the requirement for radon protective measures on a single dwelling site would be £250 plus VAT. In this case, it would probably be more cost-effective to install basic measures, at a cost of £100 per dwelling, rather than risk the possibility that both site investigation and installation costs will be incurred (Total £350). In addition, installation of a radon barrier would result in benefits to the development other than radon protection as it would provide enhanced protection against the entry of moisture and other types of gases (see 3.11 in Appleton et al., 2000).

5.13. A number of site investigation and protective measures installation costs are illustrated in Tables 5-2 to 5-3 and in Figures 5-1 to 5-2. It is assumed that the cost of taking the 15 soil gas radon measurements is 25% of the total cost of the site investigation - so site investigation costs increase by £62.50 for each additional dwelling on the site above the base cost of £250. It might be possible to reduce the number of soil gas radon measurements required for a large site if it was geologically and pedologically homogeneous.

5.14. For multi-dwelling sites there is little difference between the cost of installing basic measures and the cost/dwelling for radon investigation (Table 5-2 and Figure 5-1). There would, therefore, be little incentive to carry out a radon site investigation if the maximum possible requirement was basic radon measures (i.e. the site was situated within a pale grey coloured square on the relevant Annex B (BR211, 1999) map).

5.15. Where Annex B maps indicated that the maximum possible requirement was full protective measures, significant cost savings could be achieved if radon site investigation data showed that no radon protective measures were required.

5.16. Other potential, but difficult to quantify, costs that might need to be considered include the potential cost to the developer of providing documentary evidence to a buyer's solicitor explaining why radon protective measures had not been installed even though the site was located in a pale or dark grey coloured grid square on the relevant BR211 Annex B map.

Table 5-2. Estimated costs for radon site investigation (SI) and the installation of basic protective measures

No. dwellings	Total cost SI	Total cost Basic Measures	Total cost SI + Basic Measures	Cost/dwelling SI	Cost/dwelling Basic*	Cost/dwelling SI + Basic
1	250	100	350	250	100	350
2	313	200	513	156	100	256
3	375	300	675	125	100	225
4	438	400	838	109	100	209
5	500	500	1,000	100	100	200
10	813	1,000	1,813	81	100	181
15	1,125	1,500	2,625	75	100	175
20	1,438	2,000	3,438	72	100	172

* data provided by Chris Scivyer (BRE)

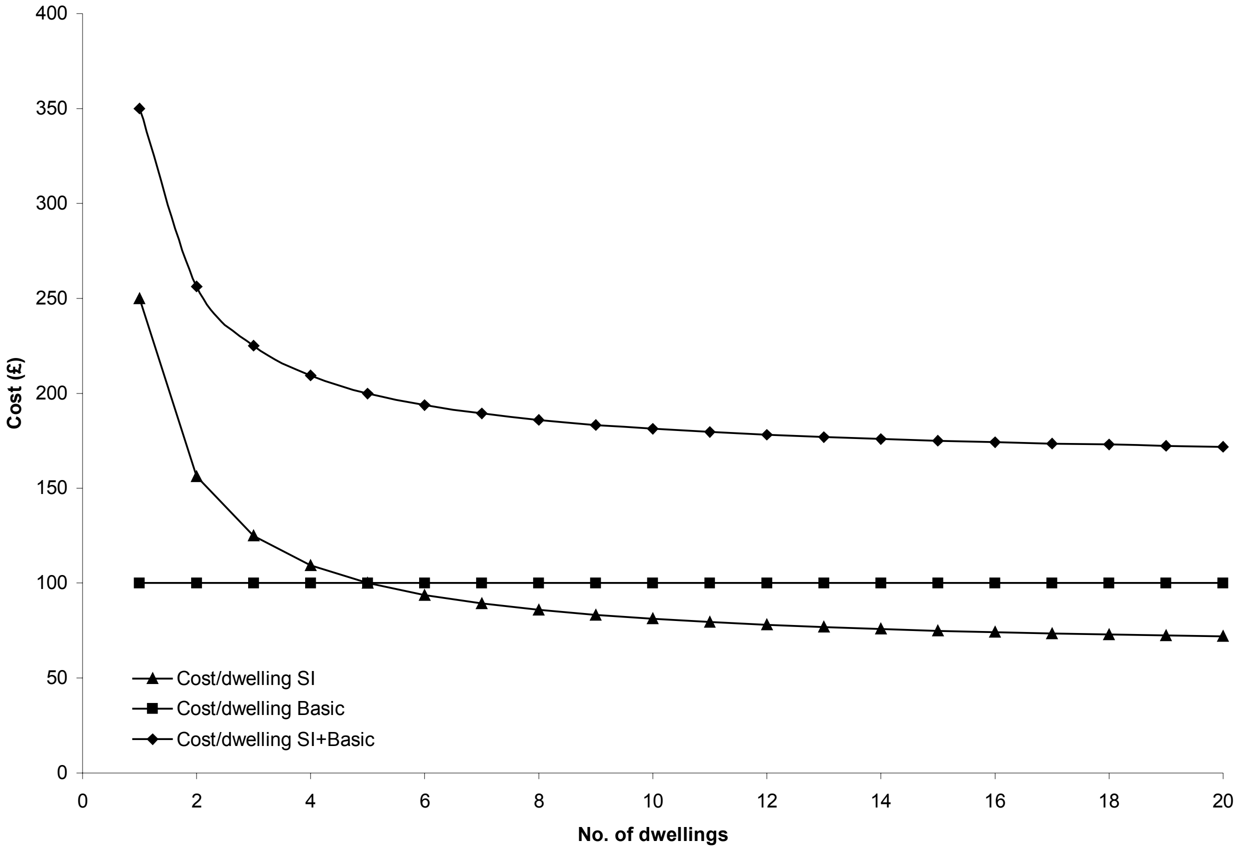


Figure 5-1. Estimated cost/dwelling for radon site investigation (SI) and installation of basic protective measures

Table 5-3. Estimated costs for radon site investigation (SI) and the installation of full protective measures

No. dwellings	Total cost SI	Total cost Full measures	Total cost SI + Full measures	Cost/dwelling SI	Cost/dwelling Full*	Cost/dwelling SI+Full
1	250	200	450	250	200	450
2	313	400	713	156	200	356
3	375	600	975	125	200	325
4	438	800	1,238	109	200	309
5	500	1,000	1,500	100	200	300
10	813	2,000	2,813	81	200	281
15	1,125	3,000	4,125	75	200	275
20	1,438	4,000	5,438	72	200	272

* data provided by Chris Scivyer (BRE)

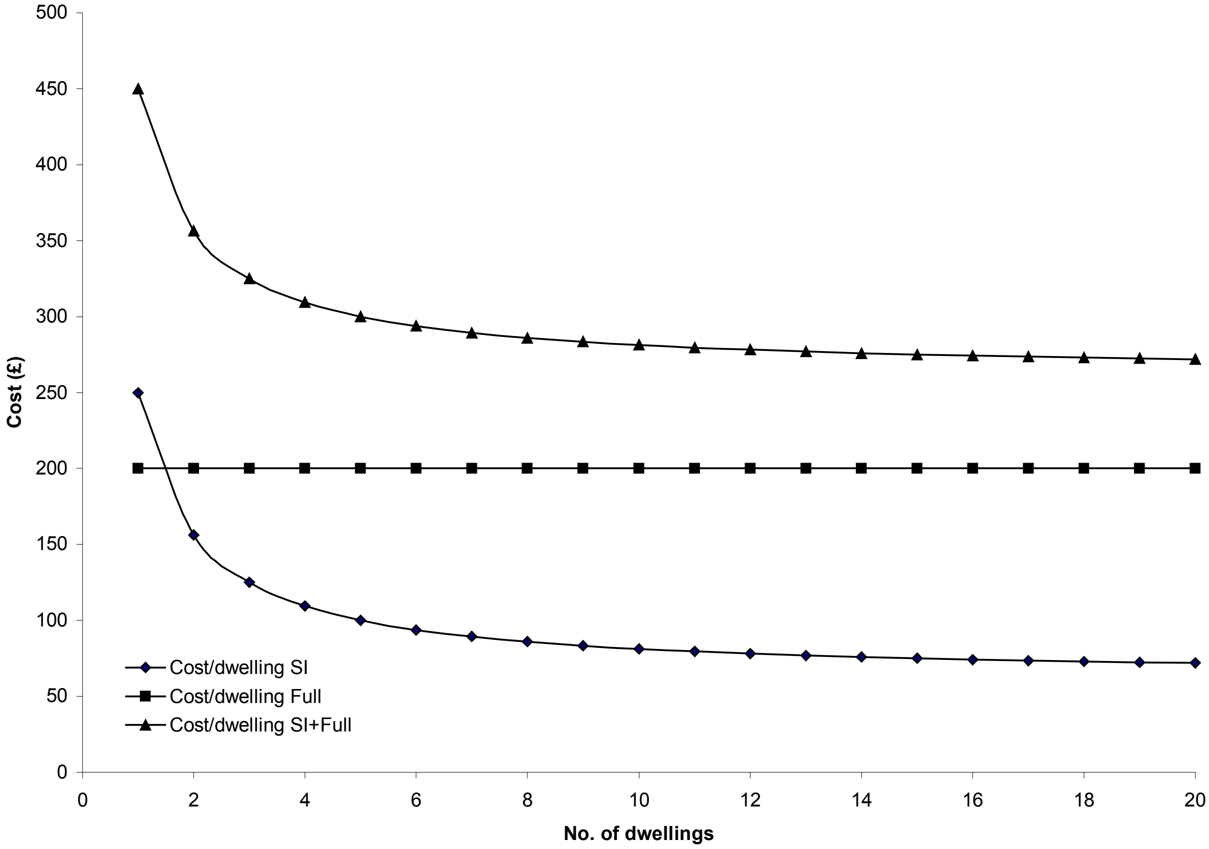


Figure 5-2 Estimated costs for radon site investigation (SI) and installation of full protective measures

6. CONCLUSIONS AND RECOMMENDATIONS

Mapping

6.1. Two main procedures have been used for mapping radon-prone areas in the UK. The first uses radon measurements in existing dwellings to map the variation of radon potential between administrative districts or grid squares. The 5 km grid square radon potential (GRIDRP) mapping procedure developed by the NRPB has, to date, provided the basis for identifying those areas where protective measures need to be installed in new homes and where monitoring of existing dwellings is recommended. The second procedure, geological radon potential mapping, is based on the interpretation of indoor radon within the framework of a geological map. Geological radon potential (GEORP) mapping requires greater development effort than GRIDRP mapping and it relies on the availability of digital geological maps at an appropriate scale. The BGS 1:50,000 scale digital geological data base for the UK will be completed in March 2001.

6.2. This research programme has demonstrated that there is scope for using indoor radon results, classified in terms of the underlying geology, in order to more clearly delineate radon-prone areas. In areas where many indoor radon measurements are available, it has been possible to demonstrate that each geological unit within a map sheet or smaller area, such as a 5 km grid square, has a characteristic geological radon potential (GEORP) which is frequently very different from the average radon potential for the grid square.

6.3. Using geological criteria, extrapolations can be made to other areas with similar rocks, and areas of potentially high or low radon levels, can therefore be predicted. However, this alone is insufficient for accurately determining radon potential in new areas and further survey work should be carried out where required.

6.4. Whereas geological radon potential is the preferred and most spatially precise method of defining the requirement for protective measures in the sedimentary geological environments that cover most of England and Wales, 1 km GRIDRP mapping appears to be the most effective method, based on the use of existing data, in areas where pervasive uranium mineralisation crosses mapped lithological boundaries. So far as has been determined, this applies only to the SW and SX 100 km grid squares of the Ordnance Survey National Grid.

6.5. Both geological radon potential mapping and 1 km grid square radon mapping can provide much more detailed maps than the 5 km grid square maps used prior to 1999, and so can allow radon protective measures in new development and radon measurement programmes to be targeted more efficiently.

6.6. The reliability and spatial precision of both mapping methods is, in general, proportional to the measurement density. It is, however, reassuring to note that even when the measurement density is as low as the minimum for 5 km grid square mapping, 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 map sheets with higher measurement densities.

6.7. Lithological variations within geological units can cause geological radon potential mapping in some parts of England to miss significant areas of higher radon potential which are identified by 1 km grid square mapping.

6.8. Geological and grid square mapping are likely to be most powerful when used in a complementary fashion, by comparing maps produced by the two methods, and by grouping results both by geological unit and by grid square. It is recommended that this line of investigation should be pursued (Miles and Appleton, 2000).

6.9. Finally, it is important to remember that however indoor radon data are grouped (whether by grid square or geological unit), a wide range of indoor radon levels are likely to be found. 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. Geological radon potential does not indicate whether a building constructed on a particular site will have a radon concentration that exceeds the Action Level. This can only be established through measuring radon in the building.

Radon potential maps for BR211

6.10. Revised guidance (BR211, 1999) defines the geographical areas where radon protection is necessary in new dwellings. It incorporates a system for determining the level of protection needed based on two sets of maps that show, as 5km grid squares of the Ordnance Survey National Grid, where protective measures from radon will or may be needed.

6.11. The Annex A maps are based on the average estimated percentages of homes above the radon Action Level (200 Bq m^{-3}) whilst the Annex B maps indicate those grid squares which are underlain, completely or in part, by geological units for which the estimated percentages of homes above the Action Level exceed the thresholds for either basic or full radon protection.

6.12. When the Annex A maps indicate that no radon protection or the installation of basic protection is required, the Annex B maps should be consulted to establish if underprotection might be possible and whether a geological assessment might allow developers to install a lower level of protection. A geological assessment involves using the BGS Radon Protective Measures GIS to check whether a site is on or close to a geological unit for which either basic or full radon protection is required.

6.13. The RPM GIS currently comprises 1:250,000 scale data with the more detailed 1:50,000 scale data covering some of the most radon-prone parts of England. The RPM-GIS is being upgraded to 1:50,000 scale over the next 12 months as new digital map data become available through the BGS *DigMapGB* programme. Smaller scale intra-geological map sheet and intra-5-km grid square variations in GEORP will be mapped where sufficient indoor radon measurements are available. The Annex B maps will be amended accordingly, as indicated on page 5 of BR211 (1999). Amended maps will be posted on the BGS web site (www.bgs.ac.uk/radon).

6.14. One disadvantage of the current BR211 system is that there are some situations in which a developer will be required by the Annex A maps to provide full or basic radon protection when this would not be required on the basis of geological radon potential . This is because there are frequently major variations in GEORP within individual 5 km grid squares. The Annex A maps were included in the BR211 procedure because it was discovered that approximately eight 5-km grid squares (in which there are sufficient house radon measurements) with GRIDRP's exceeding basic or full thresholds but which were not identified on the Annex B maps. This occurred because of local lateral variations in GEORP. These discrepancies will be resolved once the new 1:50,000 scale digital geological radon potential data and local GEORP information for 5-km and 1-km grid squares has been incorporated into the RPM-GIS. Once this has been done, the Annex A maps may become redundant.

Radon site investigation methods

6.15. In general, measurement of soil gas radon in the field provides the most universally applicable geochemical indicator of radon potential. However, 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 water logged soils or when soil gas radon concentrations are abnormally enhanced in some soils due to the sealing effect of soil moisture. These conditions are particularly common in winter. Soil and rock permeability exerts a significant influence on soil gas radon concentrations and permeability normally needs to be taken into account when estimating radon potential from soil gas radon data. However, inconsistent results were observed when the Soil Gas Radon - GEORP - Soil Permeability calibration plot was used to determine GEORP from soil gas radon data so calibration plots clearly need to be refined further.

6.16. It may be necessary to devise a series of calibration plots not only for different soil/rock permeabilities but also for different soil moisture levels. Additional research would have to be carried out to investigate this and also to investigate the practicality of making permeability measurements as part of a radon site investigation protocol used prior to the construction of new dwellings. It may be necessary also to measure permeability and moisture content both close to the surface and at the sampling depth of 70 cm. The incorporation of field permeability measurements into a site investigation protocol was not tested during the current research programme. Problems with the determination of permeability and its incorporation into a radon site investigation procedure have been encountered in the Czech Republic where the quality of the permeability classification obtained at a site is very reliant on the personal experience of the technical staff carrying out the site investigation.

6.17. Whereas soil gas radon is accepted as being a relatively reliable method for determining GEORP on both a regional and site specific scale, seasonal and temporal variation in soil gas radon concentrations are difficult to deal with. Alternative site investigation protocols might be to (1) carry out measurements on two or three well documented calibration sites prior to carrying out each new survey so that seasonal effects related to soil moisture could be taken into account or (2) measure permeability and soil moisture and use calibration plots to estimate GEORP from soil gas radon data.

6.18. Soil gas radon measurements may be used to estimate the radon potential for geological units covering a relatively large area but not necessarily for a small development site. Results indicate considerable variation in radon potential between sites on the same geological unit, which would be expected. In addition, there is often considerable overlap between the soil gas radon ranges for lithological units with significantly different radon potentials (GEORPs).

6.19. Whereas the average of 10 soil gas radon measurements taken 25 to 50 m apart in one sector of a 5 km grid square or geological map sheet cannot be expected to correlate perfectly with the 5 km grid or map GEORP, the closeness of the correlation suggests (but does not prove) that it might be possible to use soil gas radon data to indicate radon potential on a site specific as well as a regional scale.

6.20. An evaluation of the variability of soil gas radon measurements in relation to sample spacing and number of measurements tends to support the standard BGS site investigation protocol in which 10 measurements are taken on a 20 m spacing. However, a rigorously planned field programme would be required to establish the optimum sample number and spacing.

6.21. If soil gas radon concentrations cannot be determined because of climatic factors, for example when the soil profile is waterlogged, 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.

6.22. Different radon site investigation methods may be required dependent upon the specific factors controlling radon emanation from the ground. In some cases no method will be reliable under unfavourable climatic conditions.

6.23. With regard to the practical application and effectiveness of soil gas radon site investigation methods as part of a Building Control system, it has not yet been proven that soil gas radon data can be used to discriminate reliably between, for example, 1.0% and 3.0% GEORP taking into account the problems of seasonal and temporal variation in soil gas radon. Soil gas radon site investigation methods are probably precise enough to define the GEORP for a new building site at around the 10% GEORP level as long as soil/rock permeability is taken into consideration.

6.24. A more rigorous test of the effectiveness of radon site investigation methods might be to carry out soil gas radon surveys in the immediate vicinity of a representative number of dwellings constructed on a range of geological units with different radon potentials. Approximately 100 sites on each geological unit would be required and radon measurements would need to be made in each dwelling under carefully monitored conditions. Selection of dwellings with similar construction characteristics would reduce the number of confounding factors in the data analysis. Such an evaluation was beyond the scope and financial constraints of the present research project. It should be noted that previous attempts to assess the relationship between radon in dwellings and soil gas radon measured in the immediate vicinity of the dwelling have produced divergent results perhaps because they were based on a relatively small number of dwellings and because of the influence of a building on soil gas radon levels in the ground immediately surrounding the dwellings.

6.25. The results of this research programme indicate that in most cases it is impractical to assess the severity of a radon problem on a particular site accurately until the building has been constructed and occupied, therefore precautions should be taken in areas where high radon levels have been predicted by the mapping programme. Radon site investigation techniques are not yet reliable enough to be incorporated into guidance. Many of the problems associated with the development of rigorous and robust site investigation procedures for the determination of methane and carbon dioxide hazard also apply to radon. As with methane, it is likely that a great deal of detailed research will be required before a practical protocol can be devised which can be used to reliably determine radon potential of a development site. In the interim, it is recommended that radon potential mapping is used for delineating those areas where radon protective measures are required in new development.

7. REFERENCES

Åkerblom, G. 1987. Investigations and mapping of radon risk areas. 96-106 in *Proceedings of International Symposium on Geological Mapping, Trondheim, 1986: In the Service of Environmental Planning.* (Oslo: Norg. geol. Unders.)

Åkerblom, G. 1994. Ground radon - monitoring procedures in Sweden. *Geoscientist* 4(4): 21-27.

Åkerblom, G. 1995. The use of airborne radiometric and exploration survey data and techniques in radon risk mapping in Sweden. 159-180 in *Application of uranium exploration data and techniques in environmental studies. Proceedings of a Technical Committee meeting held in Vienna, 9-12 November 1993*. IAEA Report No. IAEA-TECDOC-827.

Åkerblom, G, Andersson, P, and Clavensjo, B. 1984. Soil gas radon - a source for indoor radon daughters. *Radiation Protection Dosimetry* 7: 49-54.

Anderson, C E, Søgaard-Hansen J, and Majborn, B. 1994. Soil gas and radon entry into a simple test structure: comparison of experimental and modelling results. *Radiation Protection Dosimetry* 56(1-4): 151-155.

Appleton, J D, and Ball, T K. 1995. Radon and background radioactivity from natural sources: characteristics, extent and the relevance to planning and development in Great Britain. *British Geological Survey Technical Report* WP/95/2.

Appleton, J D, and Ball, T K. 2001. Geological radon potential mapping. In: P Bobrowsky (ed.) *Geoenvironmental mapping: methods, theory and practice* (Rotterdam: Balkema)

Appleton J D, Miles J C H, Scivyer C R, and Smith, P H. 2000. Dealing with radon emissions in respect of new development: Summary report and recommended framework for planning guidance. *British Geological Survey Research Report* RR/00/07

Andjelkov, M , and Brajnik, D. 1996. Map of natural radioactivity and radon emanation in Slovenia. *Environment International* 22(Suppl. 1): 799-804.

Badr, I, Oliver, M A, and Durrani, S A. 1996. Statistical evidence of the geological control over soil gas concentrations and its implications for mapping radon potential. *Radiation Protection Dosimetry*, 63(4): 281-291.

Ball, T K, Cameron, D G, and Colman, T B. 1992. Aspects of radon potential mapping in Britain. *Radiation Protection Dosimetry* 45: 211-214.

Ball, T K , Cameron D G, Colman, T B, and Roberts, P D. 1991. Behaviour of radon in the geological environment. *Quarterly Journal Engineering Geology* 24: 169-182.

Ball, T K , Cameron, D G, Colman, T B, and Roberts, P D. 1995. The use of uranium exploration data for mapping radon potential in the UK - advantages and pitfalls. 139-149 in *Application of uranium exploration data and techniques in environmental studies. Proceedings of a Technical Committee meeting held in Vienna, 9-12 November 1993*. IAEA-TECDOC-827. (Vienna: International Atomic Energy Agency.)

Ball, T K , and Miles, J C H. 1993. Geological and geochemical factors affecting the radon concentration in homes in Cornwall and Devon, UK. *Environmental Geochemistry and Health* 15: 27-36.

Ball, T K, and Miles, J C H. (in press). The role of house surveys in geological radon potential mapping. In *Uranium exploration data and techniques applied to the preparation of radioelement maps. Proceedings of an IAEA Technical Committee meeting, Vienna 1996.*

Barnet, I. 1991. Radon risk mapping in the Czech Republic. Results. 13-19 in *Radon Investigations in Czechoslovakia II.* Barnet, I. (ed). (Prague: Geological Survey.)

Barnet, I. 1991. Radon Risk Classification for Building Purposes in the Czech Republic. 18-24 in *Radon Investigations in Czechoslovakia II*. Barnet, I, and Neznal, M. (eds). (Prague: Geological Survey.)

Barnet, I, Mikšova, J, Tomas, R, and Karenová, J. 2000. Radon risk mapping of the Czech Republic on a scale 1:50,000. 4-15 in *Radon Investigations in the Czech Republic VII and Fifth International Workshop on the Geological Aspects of Radon Risk Mapping*. Barnet, I, and Neznal, M.(editors). (Prague: Czech Geological Survey and Radon corp.)

Building Research Establishment (BRE). 1992. Radon: guidance on protective measures for new dwellings. *Building Research Establishment Report* BR 211.

Building Research Establishment (BRE). 1995. Radon in the workplace. *Building Research Establishment Report* BR 293.

Building Research Establishment (BRE). 1999. Radon: guidance on protective measures for new dwellings. *Building Research Establishment Report* BR 211 (1999).

Burian, I, Merta, J, et al. 1993. Estimation of the category of radon risk emission on individual building area questions and different approaches. 18-21 in *Radon Investigations in the Czech Republic IV*. Barnet, I (editor). (Prague: Czech Geological Survey.)

British Geological Survey (BGS) 1998. *Radon potential based on solid and drift geology (Sheet 53N 04W Liverpool Bay; 1:250,000 scale map: Natural Environmental Radioactivity Survey)*. Keyworth, UK: British Geological Survey.

Brown, C E, Mose, D G, Mushrush, G W, and Chrosniak, C E. 1992. Statistical analysis of the radon-222 potential of rocks in Virginia, U.S.A. *Environmental Geology and Water Science* 19(3): 193-203.

Clavensjö, B , and Åkerblom, G. 1994. *The Radon Book*. Stockholm: The Swedish Council for Building Research.

Cliff, K D, and Miles, J C H. (eds) 1997. *Radon Research in the European Union*. EUR 17628. (Chilton, UK: National Radiological Protection Board.)

Cohen, B L, Stone, C A, and Schilken, C A. 1994. Indoor radon maps of the United States. *Health Physics* 66: 201-205.

Colgan, P A , and Gutiérrez J. 1996. National approaches to controlling exposure to radon. *Environment International* 2(Suppl.1): 1083-1092.

Daly, L. 1994. (University College Dublin) Private communication.

Durrani, S A. 1999. Radon concentration values in the field: correlation with 8underlying geology. *Radiation Measurements* 31 (1-6): 271-276.

Durrani, S A, and Badr, I. 1995. Geostatistically controlled field-study of radon levels and the analysis of their spatial variation. *Radiation Measurements* 25: 565-572.

Durrani, S A, Khayrat, A H, Oliver, M A, and Badr I. 1997. Estimating soil radon concentrations by krigng in the Biggin area of Derbyshire (UK). *Radiation Measurements* 28 (1-6): 633-639, Sp. Iss. SI.

Duval, J S, and Otton, J K. 1990. Radium distribution and indoor radon in the Pacific Northwest. *Geophysics Research Letters* 17(6): 801-804.

Duval, JS, Otton, JK, and Jones, W J. 1989. *Estimation of radon potential in the Pacific Northwest using geological data.* USGS Report prepared for the US Department of Energy.

Ek, B-M. 1996. Effects of freezing and thawing on radon in soils. 117-123 in *Radon Investigations in the Czech Republic VI*. Barnet, I, and Neznal, M. (eds). (Prague: Czech Geological Survey and Radon corp.)

Ennemoser, O, Giacomuzzi, S M G, Brunner, P, Scheider, P, Stingl, V, Purtscheller, F, and Ambach, W. 1995. Radon measurements in soil to predict indoor radon concentrations in new buildings in an area with unusually high radon levels. *Science of the Total Environment*. 162: 209-213.

Findlay, D.C, Colbourne, G J N, Cope, D W, Harrod, T R, Hogan, D V, and Staines, S J. 1984 Soils and their use in south west England. *Bulletin Soil Survey England & Wales:* 14.

Friedmann, H, Zimprich, P, Atzmuller, C, Hofmann, W, Lettner, H, Steinhausler, F, Hamernik, E, Maringer, F J, Mossbauer, L, Kaineder, H, Nadschlager, E, Sperker, S, Karacson, P, Karg, V, Kralik, C, Pock, K, Schonhofer, F, Breitenhuber, L, Kindl, P, Oberlercher, G, Seiberl, W, Stadtmann, H, Steger, F, and Tschurlovits, M. 1996. The Austrian Radon Project. *Environment International* 22 (Suppl 1): 677-686.

Friedmann, H. 2000. Radon in Austria. 79-85 in *Radon Investigations in the Czech Republic VII and Fifth International Workshop on the Geological Aspects of* Radon Risk Mapping. Barnet, I, and Neznal, M.(editors). (Prague: Czech Geological Survey and Radon corp.)

Gates, A E, and Gundersen, L C S. 1989. Role of ductile shearing in the concentration of radon in the Brookmeal zone, Virginia. *Geology* 17: 391-394.

Gates, A E, and Gundersen, L C S (eds). 1992a. Geologic Controls on Radon. *Special Paper Geological Society America* 271.

Gates, A E, and Gundersen, L C S. 1992b. Sensitivity of soil radon to geology and the distribution of radon and uranium in the Hylas Zone area, Virginia. *In* Gates, A E, and Gundersen, L C S, (eds.), *Geologic Controls on Radon*. Special Paper Geological Society America 271: 17-28.

Gulabyan, L A, and Marenny, A M 1999. Identification of radon potential of the building sites in Moscow. 270 in *Book of Abstracts. Workshop on 'Radon in the Living Environment' April 1999, Athens, Greece.* (EU Directorate General for Science, Research and Development, Radiation Research Unit in collaboration with Nuclear Engineering Section, National Technical University of Athens, Greece).

Grasty, R L. 1997. Radon emanation and soil moisture effects on airborne gamma-ray measurements. *Geophysics.* 62 (5): 1379-1385.

Green, B.M.R, Lomas, P R, and O'Riordan, M C. 1992. Radon in dwellings in England. *National Radiological Protection Board. Chilton.* NRPB-R254.

Gregory R G, Durrance E M, and Mitchell, C R. 1986. Soil gas surveying at Whitchurch Down, near Tavistock, Devon: an integrated approach to vein and fracture mapping. *Proceedings of the Ussher Socity* Vol. 6, 389-397.

Gunby, J A, Darby, S C, Miles, J C H, Green, B M R, and Cox, D R. 1993. Factors affecting indoor radon concentrations in the United Kingdom. *Health Physics* 64: 2-12.

Gundersen, L C S, Reimer, M G, and Agard, S F. 1987. Geologic control of radon in Boyertown and Easton, Pa. *Southeast Section Geological Society America, Abstracts with Program*, 19(2).

Gundersen, L C S, Reimer, G M, Wiggs, C R, and Rice, C A. 1988. Map showing radon potential of rocks and soils in Montgomery County, Maryland. *US Geological Survey Misc. Field Studies Map MF-2043* (1:62,500 scale)

Gundersen, L C S, and Schumann, E R. 1996. Mapping the radon potential of the United States: examples from the Appalachians. *Environment International* 22(Suppl.1): S829-S844.

Gundersen, L C S, Schumann, E R, Otton, J K, Dubief, R F, Owen, D E, and Dickenson, K E. 1992. Geology of radon in the United States. *In* Gates, A E, and Gundersen, L C S. (eds.), *Geologic Controls on Radon* Geological Society America Special Paper 271: 1-16.

Hopke, P K. (ed.) 1996. The Natural Radiation Environment VI. Proceedings of the Sixth International Symposium on the Natural Radiation Environment (NRE-VI), Montreal, Canada, 5-9 June 1995. *Environment International* 22 (Suppl. 1).

Hubbard L M, and Hagberg, N. 1996. Time-variation of the soil gas radon concentration under and near a Swedish house. *Environment International,* 22 (Suppl. 1): S477-S482.

Hutter, A R. 1995. Spatial and temporal variations of soil gas 220-Rn and 222-Rn at two sites in New Jersey. *Proceedings of the AARST IV International Radon Symposium*, 4.1-4.23

Hutter, A R, and Knutson, EO. 1998. An international comparison of soil gas radon and radon exhalation measurements. H*ealth Physics* 74 (1): 108-114.

Jackson, S A. 1992. Estimating radon potential from an aerial radiometric survey. *Health Physics* 62(5): 450-452.

Janssens, A, Lowder, W, Olast, M, Sinnaeve, J, and Steinhauslet, F. (eds.) 1992. *The natural radiation environment*. Proceedings of the Fifth International Symposium on the Natural Radiation Environment, Salzburg, Austria, September 1991. *Radiation Protection Dosimetry* 45(1-4).

Kemski, J, Klingel, R, and Siehl, A. 1996. Classification and mapping of radon-affected areas in Germany. *Environment International* 22(Suppl. 1): 789-798.

Kemski, J, Lehmann, R, Siehl, A, and Stegmann, R. 2000. Radon mapping in Germany - state of investigations and future work. 86-91 in *Radon Investigations in the Czech Republic VII and Fifth International Workshop on the Geological Aspects of Radon Risk Mapping*. Barnet, I, and Neznal, M.(editors). (Prague: Czech Geological Survey and Radon corp.)

Kies, A, Fieder, M, Biell, A, and Rowlinson, L. 1996. Radon survey in the Grand-Duchy of Luxembourg - indoor measurements related to house features, soil, geology and environment. *Environment International* 22(Suppl. 1): 805-808.

Kimbell, S F, Cooper D C, and Scrivener, R. 2000. The digitisation and interpretation of data from the 1957/9 airborne radiometric survey of south-west England. *British Geological Survey Technical Report* WK/00/04.

King, C Y, and Minissale, A. 1994. Seasonal variability of soil gas radon concentration in central California. *Radiation Measurements* 23: 683-692.

Kline, S W, and Mose, D G. 1987. Predictive tools for indoor radon studies in Virginia. *Abstracts for Annual Meeting Geological Society of America (Phoenix, Arizona)*, 19(7).

Kunz, C, Schwenker, C, Green, J, and Kitto, M. 1994. *Identifying high risk areas in New York State: mapping indoor radon data.* Paper Presented at the International Radon Symposium of the American Association of Radon Scientists and Technologists, Atlantic City, September 1994.

Lomas, P R, Green, B M R, Miles, J C H, and Kendall, G M. 1996. Radon Atlas of England. *National Radiological Protection Board*, Chilton. NRPB-R290.

Lomas, P R, Green, B M R, and Miles, J C H. 1998. Radon in Dwellings in Wales: Atlas and 1998 Review. *National Radiological Protection Board*, Chilton. NRPB-R303.

Madden, J. (Radiological Protection Institute for Ireland) Private communication.

Markinowski, F, Lucas, R M, and Yeager, W M. 1994. National and regional distributions of airborne radon concentrations in US homes. *Health Physics* 66: 699-706.

Markkanen, M and Arvela, H. 1992. Radon Emanation from Soils. *Radiation Protection Dosimetry*, 45 (1-4): 269-272.

Matolín, M. 1996. Reference sites for measurement of radon volume activity in soil air in the Czech Republic. 72-77 in *Radon Investigations in the Czech Republic VI*. Barnet, I, and Neznal, M. (eds). (Prague: Czech Geological Survey and Radon corp.)

Matolín, M, Jáně Z, Neznal, M, and Neznal, M. 2000. Geometry of soil gas sampling, soil permeability and radon activity concentration. 27-29 in *Radon Investigations in the Czech Republic VII and Fifth International Workshop on the Geological Aspects of Radon Risk Mapping*. Barnet, I, and Neznal, M.(editors). (Prague: Czech Geological Survey and Radon corp.)

McAulay, I R, and Moran, D. 1988. Natural radioactivity in the soil of the Republic of Ireland. *Radiation Protection Dosimetry* 24(1-4): 47-49.

Miles, J C H. 1994. Mapping the proportion of the housing stock exceeding a radon reference level. *Radiation Protection Dosimetry* 56: 207-210.

Miles, J C H. 1998. Mapping radon-prone areas by log-normal modelling of house radon data. *Health Physics* 74(3): 370-378.

Miles, J C H. (in press). Development of maps of radon-prone areas using radon measurements in houses. *Proceedings of Risk 97. International Conference on Mapping Environmnetal Risks and Risk Comparison.*

Miles, J C H, 2000 Temporal variations of radon levels in houses and implications for radon measurement strategies. *Radiation Protection Dosimetry (submitted for publication)*

Miles J C H, and Appleton, JD. 2000. Identification of localised areas of England where radon concentrations are most likely to have >5% probability of being above the Action Level. *Department of the Environment, Transport and the Regions Report* DETR/RAS/00.001

Miles, J C H, and Ball, T K. 1996. Mapping radon-prone areas using house radon data and geological boundaries. *Environment International* 22(Suppl. 1): 779-782.

Miles, J C H, Green, B M R, Lomas, P R, and Cliff, K D. 1990. Radon affected areas: Cornwall and Devon. *Documents NRPB* 1(4): 37-43.

Miles, J C H, Green, B M R, and Lomas, P R. 1992. Radon affected areas: Derbyshire, Northamptonshire and Somerset. *Documents NRPB* 3(4): 19-28.

Miles, J C H, Green, B M R, and Lomas, P R.. 1996. Radon affected areas: England, Wales. *Documents NRPB* 7(2).

Mose, D G, Mushrush, G W, and Chrosniak, C E. 1992. Soil radon, permeability, and indoor radon prediction. *Environmental Geology & Water Science.* 19(2): 91-96.

Mose, D G, and Mushrush, G W. 1999a. Prediction of indoor radon based on soil radon and soil permeability. *J. Environmental Science & Health. Pt A - Toxic/Hazardous Substances & Environmental Engineering.* 34(6): 1253-1266.

Mose, D G, and Mushrush, G W. 1999b. Comparisons between soil radon and indoor radon. *Energy Sources.* 21(8): 723-731.

Nason, R, and Cohen, B L. 1987. Correlation between ^{226}Ra in soil, ^{222}Rn in soil gas and ^{222}Rn inside adjacent houses. *Health Physics* 52(1): 73-77.

Nazaroff, W W. 1988. Measurement Techniques. In *Radon and its Decay Products in Indoor Air*: 491-504. (New York: John Wiley & Sons.)

Nero, A V. 1993. Methodologies for identifying high-radon areas: A brief review. In: Jantunen, M, and Seppanen, O. Eds, *Indoor Air '93 (Proceedings of the 6th International Conference on Indoor Air Quality and Climate*) 4: 419-425.

Nero, A V, Leiden, S M, Nolan, D A, Price, P N, Rein, K L, Revzan, H R, Wollenberg, H R, and Gadgil, A J. 1994. Statistically based methodologies for mapping of radon "actual" concentrations: the case of Minnesota. *Radiation Protection Dosimetry* 56: 215-219.

New Jersey Department of Environmental Protection. 1988. *Sampling design, data collection and analysis, Statewide scientific study of radon.* Task 3 Draft Report.

Neznal, M, Neznal, M, and Šmarda, J. 1996. Assessment of radon potential of soils - a five-year assessment. *Environment International* 22(Suppl. 1): 819-828.

Neznal, M, Neznal, M, and Šmarda, J. 1997. Intercomparison measurement of soil-gas radon concentration. *Radiation Protection Dosimetry 72(2)*: 139-144.

Neznal, M, Neznal, M, and Jiránek, M. 2000. Comparison of calculated and measures soil-gas radon concentration and radon exhalation. 16-26 in *Radon Investigations in the Czech Republic VII and Fifth International Workshop on the Geological Aspects of Radon Risk Mapping.* Barnet, I, and Neznal, M.(editors). (Prague: Czech Geological Survey and Radon corp.)

O'Connor, P J, Gallagher, C, Van den Boom, G, Hagendorf, J, Muller, R, Madden, J S, Duffy, J T, McLuaghlin, J P, Grimley, S, McAulay, I R, and Marsh, D. 1992. Mapping of ^{222}Rn and ^{4}He in soil gas over a karstic limestone-granite boundary: correlation of high indoor ^{222}Rn with zones of enhanced permeability. *Radiation Protection Dosimetry* 45(1-4): 215-218.

Oliver, M A, and Badr, I. 1995. Determining the spatial scale of variation in soil radon concentration. *Mathematical Geology* 27(8): 893-922.

Otton, J K, and Asher-Bolinder, S. 1993. Elevated indoor radon associated with soils developed on Pleistocene limestones in tropical and subtropical latitudes. *Proceeding of the 1993 International Radon Conference* Session IV: 32-47. (American Association of Radon Scientists and Technologists)

Price, P N. 1995a. The regression effect as a cause of the nonlinear relationship between short- and long-term radon concentration measurements. *Health Physics* 69: 111-114.

Price, P N. 1995b. Joint analysis of long- and short-term radon monitoring data from the Northern USA. Presented at the *Sixth International Symposium on the Natural Radiation Environment, Montreal, 1995 June 5-9*.

Price, P N, Nero, A V, and Gelman, A. 1995. Estimation of county mean radon concentrations in Minnesota: a Bayesian analysis. Presented at the *Sixth International Symposium on the Natural Radiation Environment, Montreal, 1995 June 5-9*.

Radiological Protection Institute of Ireland (RPII) 1996. *Radon in Irish Dwellings*. 1:750,000 scale. Dublin.

Reimer, G M. 1992. Using soil gas radon and geology to estimate regional radon potential. *Radiation Protection Dosimetry* 45(1-4): 219-222.

Reimer, G M, and Gundersen, L C S. 1989. A direct correlation among indoor Rn, soil gas Rn and geology in the Reading Prong area near Boyertown, Pennsylvania. *Health Physics* 57: 155-160.

Rose, W R, Hutter, A R, and Washington, J W. 1990. Sampling variability of radon in soil gas. *Journal Geochemical Exploration* 38: 173-191.

Ruckenbauer, F, and Winkler, R. 1999. Comparison of methods to determine radon in soil gas. 273-274 in *Book of Abstracts. Workshop on 'Radon in the Living Environment' April 1999, Athens, Greece.* (EU Directorate General for Science, Research and Development, Radiation Research Unit in collaboration with Nuclear Engineering Section, National Technical University of Athens, Greece).

Schumann, R R (ed.) 1993. Geologic radon potential of EPA Region (1-10*) US Geol. Surv. Open-File Report* 93-292, parts A-J, 1829p.

Schumann, R R, and Gundersen, L C S. 1996. Geologic and climatic controls on the radon emanation coefficient. *Environment International* 22(Suppl. 1): 439-446.

Schumann, R R, Owed, D E, and Asher-Bolinder, S. 1992. Effects of weather and soil characteristics on temporal variations in soil-gas radon concentrations. In: Gates, A E, and Gundersen, L C S. (eds.) *Geologic Controls on Radon*: Geological Society America Special Paper 271, 65-72.

Schutz, M, and Keller, G W. 1994. Problems of radon screening in the upper layer of the soil. *Radiation Protection Dosimetry* 56: 235-237.

Schwartz, M S, and Vulkan, U. 1997. Mapping radon-prone areas - a geophysical approach. *Environmental Geology* 31 (3-4): 167-173.

Sesana, L, Raineri S, Valsecchi R, and Facchini U. 1999. Study of Rn-222 in the soil. *Nuovo Cimento Della Societa Italiana di Fisica C-Geophysics and Space Physics* 22 (3-4): 457-462.

Shweikani R, Giaddui T G, and Durrani S A. 1995. The effect of soil parameters on the radon concentration values in the environment. *Radiation Measurements* 25 (1-4) 581-584

Schwenke, J R, and Butine, M D. 1994. The analysis of radon survey data. *Environmetrics* 5. 71-82.

Sharman, G. 1991. Radiometric investigation of radon in soil gas over Jurassic rocks of Northamptonshire, England. *Environmental Geochemistry & Health* 13(3): 146-147.

Sharman, G. 1992. Seasonal and spatial variations in Rn-222 and Rn-220 in soil gas and implications for indoor radon levels. *Environmental Geochemistry & Health* 14(4): 113-120.

Sharman, G. 1995. *Radon, an environmental hazard: a geological case study of Northamptonshire.* Unpublished PhD, University of Leicester.

Shi, Y C, and Xu, Y F. 1995. Variability of soil radon attributed to meteorological causes and its applications. *Science in China Series B - Chemistry, Life Sciences & Earth Sciences*. 38: 504-512.

Siehl, A, Stegmann, R, Lehmann, R, and Valdiva-Manchego, M. 2000. Mapping the geogenic radon potential in Germany. 92-99 in *Radon Investigations in the Czech Republic VII and Fifth International Workshop on the Geological Aspects of Radon Risk Mapping.* Barnet, I, and Neznal, M.(editors). (Prague: Czech Geological Survey and Radon corp.)

Slunga, E. 1988. Radon classification of building ground. *Radiation Protection Dosimetry* 24 (1-4): 39-42.

Snihs, J O. 1992. Swedish Radon Programme. In *Radon 2000 Conference Proceeedings.* O'Riordan, M C O, and Miles, J C H. (eds.) *Radiation Protection Dosimetry* 42(3): 177-184.

Soil Survey of England and Wales, 1984. *Soils and their use in Midland and Western England.* Bulletin No. 12.

Steck, D J, Baynes, S A, and Noak, A P. 1996. Regional and local variation of indoor radon and radon source potentials. *Environment International* 22(Suppl. 1): 729-737.

Strutt, M H, Ball, T K, and Talbot, D K. 1995. Seasonal variation in radon emanation over a shale & karstic limestone contact zone. In *Energy & the Environment*, Abstracts of the 13th European Conference of the Society for Environmental Geochemistry & Health.

Talbot, D K. 1994. *A new, laboratory based, analytical method for the assessment of levels of radon contamination in the built environment.* Unpublished MSc. thesis. Loughborough University of Technology.

Talbot, D K, Appleton, J D, Ball, T K, and Strutt, M H. (1998) A comparison of field and laboratory analytical methods for radon site investigation. *Journal Geochemical Exploration* 65: 79-90.

Verger, P, Hubert, Ph, Cheron, S, Bonnefous, S, Bottard, S, and Brenot, J. 1994. Use of field measurements in radon mapping in France. *Radiation Protection Dosimetry* 56: 225-229.

Varley N R, and Flowers A G. 1998a. The influence of geology on radon levels in SW England. *Radiation. Protection Dosimetry* 77 (3): 171-176.

Varley N R, and Flowers A G. 1998b. Indoor radon prediction from soil gas measurements. *Health Physics*. 74(6): 714-718.

Vincent, P, and Gatrell, A. (1993) *The spatial distribution of radon gas in Lancashire (UK). A kriging study.* Private communication.

Voutilainen, A, and Mäkeläinen, I. 1993. Radon risk mapping using indoor monitoring data - a case study of the Lahti area, Finland. *Indoor Air* 3: 369-375.

Wagner, E P. 1983. Radon monitoring in northern communities. *Chronic Disease in Canada* 4(1): 6-7.

Washington, J W, and Rose, A W. 1992. Temporal variability of radon concentration in the interstitial gas of soils in Pennsylvania. *Journal Geophysical Research* 97(B6): 9145-9159.

Woods, M J, Dean, J C J, Jerome, S M, and Modna, D K. 2000. Review of rapid methods for assessing radon levels in domestic premises. *Department of the Environment, Transport and the Regions Report* DETR/RAS/99.012

Winkler, R, Ruckenbauer, F, and Bunzl, K. 1999. Radon concentration in soil gas: a comparison of the variability resulting from different methods, spatial heterogeneity, and seasonal fluctuations. 240-241 in *Book of Abstracts. Workshop on 'Radon in the Living Environment' April 1999, Athens, Greece.* (EU Directorate General for Science, Research and Development, Radiation Research Unit in collaboration with Nuclear Engineering Section, National Technical University of Athens, Greece).

Wrixon, A D, Green, B M R, Lomas, P R, Miles, J C H, Cliff, K D, Francis, E A, Driscoll, C M H, James, A C, and O'Riordan, M C. 1988. *Natural radiation exposure in UK dwellings.* NRPB-R190.

Yokel, F Y, and Tanner, A B. 1992. Site exploration for radon source potential. *US National Institute of Standards and Technology Report.* NISTIE-5135, 61 pp.

Zhu H-C, Charlet J M, and Poffijn, A. 2000. Comparison of large-scale radon risk map for southern Belgium with results of high resolution surveys. 46-51 in *Radon Investigations in the Czech Republic VII and Fifth International Workshop on the Geological Aspects of Radon Risk Mapping.* Barnet, I, and Neznal, M.(editors). (Prague: Czech Geological Survey and Radon corp.)

APPENDIX 1: Land use recorded at soil investigation sites in Northamptonshire

GEOLOGY	LAND USE
Northampton Sheet 185:	
Winter	
Upper Lias Clay	Ploughed and harrowed, re-seeded pasture.
Boulder Clay	Permanent Pasture.
Summer	
Upper Lias Clay	Re-seeded pasture.
Boulder Clay	Permanent pasture.
Winter	
Northampton Sand	Rape Field- ploughed and harrowed.
Boulder Clay	Permanent pasture, ridge and furrow.
Summer	
Northampton Sand	Rape crop
Boulder Clay	Permanent pasture, ridge and furrow.
Middle Lias Silts	Pasture on moderate slope
Boulder Clay	Permanent pasture, ridge and furrow.
Sands and Gravels	Permanent pasture, ridge and furrow. Moderate slope
Wellingborough Sheet 186	
Blisworth Limestone	Wheat Field.
Boulder Clay	Wheat field.
Northampton Sand	Wheat field.
Boulder Clay	Wheat field
Upper Lias Clay	Wheat field
Boulder Clay	Wheat field
Kettering Sheet 171:	
Winter	
Blisworth Limestone	Pasture.
Boulder Clay	Re-seeded pasture.
Summer	
Blisworth Limestone	Pasture.
Boulder Clay	Re-seeded pasture.
Upper Lias Clay	Pasture with ridge and furrow.
Boulder Clay	Pasture with ridge and furrow.
Northampton Sand	Wheat field.
Boulder Clay	Wheat Field.

APPENDIX 2: Land use recorded at soil investigation sites in Derbyshire

SITE	LAND USE
Summer	
D1	Potato crop growing
D2	Permanent pasture, sheep grazing
D3	Permanent pasture, recently mown for silage
D4	Permanent pasture
D5	Permanent pasture
D6	Permanent pasture, recently mown for silage
D7	Permanent pasture
D8	Permanent pasture
D9	Permanent pasture, cattle grazing
D10	Permanent pasture, hay crop standing
D11	Permanent pasture, sheep grazing
D12	Permanent pasture, sheep grazing
D13	Recently ploughed arable land
D14	Recently ploughed arable land
D15	Roadside verge
Winter	
D4	Permanent pasture, horses grazing
D6	Permanent pasture, sheep grazing
D8	Permanent pasture
D11	Permanent pasture, sheep grazing
D13	Arable land, early signs of crop growth

APPENDIX 3: Data used in calculating GEORP (Derbyshire site investigations).

2.1 County GEORP

Solid Geology	*Drift Geology*	*No. of house radon measurements*
Magnesian Limestone	None	844
Magnesian Limestone	Boulder Clay	No data available
Monsal Dale Limestone	None	834
Monsal Dale Limestone	Boulder Clay	No data available
Longstone Mudstone	None	261
Longstone Mudstone	Boulder Clay	19
LCM Shale	None	1834
LCM Shale	Boulder Clay	185
Crawshaw Sandstone	None	636
Crawshaw Sandstone	Boulder Clay	99

2.2 5 km Grid Square GEORP

Solid Geology	*Drift*	*5km Grid Square*	*No. of readings*
Magnesian Limestone	None	450 360	32
Magnesian Limestone	Boulder Clay	450 360	No data available
Monsal Dale Limestone	None	425 350	12
Monsal Dale Limestone	Boulder Clay	425 350	No data available
Longstone Mudstone	None	420 370	29
Longstone Mudstone	Boulder Clay	420 370	19
LCM Shale	None	435 345	351
LCM Shale	Boulder Clay	435 350	No data available
Crawshaw Sandstone	None	435 350	26 (Data for 435 370)
Crawshaw Sandstone	None	435 345	26 (Data for 435 370)
Crawshaw Sandstone	Boulder Clay	435 355	No data available

Table A-3-1. Summary of Derbyshire site investigation site GEORP data

Site	50k Sheet	Grid square (1 km)	Bedrock Geology	Drift Geology	Wetness Class	GEORP County	No. County	GEORP 5-km grid	No. 5-km grid
D1	112	450 362	Magnesian Limestone	None	1	1.5	844	0.9	32
D2	125	436 349	LCM Crawshaw Sdst.	None	1.5	2.1	636	2.1	26*
D3	125	436 349	LCM Shale	None	4	0.5	1834	0.1	351
D4	125	436 349	LCM Shale	None	4	0.5	1834	0.1	351
D5	125	438 350	LCM Shale	Boulder Clay	4	0.5	185	nd	0
D6	125	438 350	LCM Crawshaw Sdst.	None	1.5	2.1	636	2.1	26*
D7	111	425 358	Matlock Limestone	Boulder Clay	4	nd	0	nd	0
D8	111	425 358	Matlock Limestone	None	1	14.5	834	15.7	114
D9	111	425 359	Matlock Limestone	None	1	14.5	834	15.7	114
D10	111	421 371	Longstone Mudstone	Boulder Clay	4	22.9	0	21.9	19
D11	111	421 370	Longstone Mudstone	None	4	20.0	261	10.3	29
D12	111	421 371	Longstone Mudstone	None	4	20.0	261	10.3	29
D13	112	450 361	Magnesian Limestone	None	1	1.5	844	0.9	32
D14	112	451 361	Magnesian Limestone	Boulder Clay	4	nd	0	nd	0
D15	112	436 358	LCM Crawshaw Sdst.	Boulder Clay	4	0.4	99	nd	0

*No.= number of house radon measurements; * data for adjacent 435 370*

APPENDIX 4: Summary of soil characteristics of Derbyshire sites

Site No	*Bedrock Geology*	*Drift Geology*	*Geology Map Sheet*	*Wetness Class (Avg.)*	*1:250,000 Soil Map Symbol*	*Principal (Secondary) Association*	*Wetness Class*	*Geology*
D1	Magnesian Limestone	None	112	1.0	511a	Aberford	1	Permian and Jurassic Limestones
D2	LCM Crawshaw Sst	None	125	1.5	541f	Rivington 1	1-2	Well drained loams on sst
					541g	(Rivington 2)	1-3	Earth and podsols over Carb sst, shale (most Wetness 1)
D3	LCM Shale	None	125	4.0	712a	Dale	4	Carboniferous mudstone and shale
D4	LCM Shale	None	125	4.0	712a	Dale	4	Carboniferous mudstone and shale
D5	LCM Shale	Boulder Clay	125	4.0	711p	Dunkeswick	4-3	Drift mainly from Carboniferous shales
					713f	(Brickfield 2)	4-3	Till or head on Carboniferous shale and sst.
D6	LCM Crawshaw Sst	None	125	1.5	541f	Rivington 1	1-2	Well drained loams on sst
					541g	(Rivington 2)	1-3	Earth and podsols over Carb sst, shale (most Wetness 1)
D7	Matlock Limestone	Boulder Clay	111	4.0	711p	Dunkeswick	4-3	Drift mainly from Carboniferous shales, other Carb rocks
D8	Matlock Limestone	None	111	1.0	541p	Malham 2	1	Silty aeolian drift over limestone (Carb)
D9	Matlock Limestone	None	111	1.0	541p	Malham 2	1	Silty aeolian drift over limestone (Carb)
D10	Longstone Mudstone	Boulder Clay	111	4.0	711p	Dunkeswick	4-3	Drift mainly from Carboniferous shales
					713g	(Brickfield 3)	4,3	Greyish till or Head from Carboniferous or other Palaeozoic sdts and shale
D11	Longstone Mudstone	None	111	4.0	712a	Dale	4	Carboniferous mudstone and shale
D12	Longstone Mudstone	None	111	4.0	712a	Dale	4	Carboniferous mudstone and shale
D13	Magnesian Limestone	None	112	1.0	511a	Aberford	1	Permian and Jurassic Limestones
D14	Magnesian Limestone	Boulder Clay	112	4.0	711m	Salop	4	Reddish drift from Permo-Trias
D15	LCM Crawshaw Sst	Boulder Clay	112	4.0	713f	Brickfield 2	4	Till or head on Carboniferous shale and sst.
					713a	(Bardsey)	1,5	Carb. mudstones and shales; sandstone and sandstone Head; coals (Wet 1 over sst)

APPENDIX 5: Background information on radon

Useful information is given in the following free publications which can be obtained by writing to: The Department of the Environment, Publications Despatch Centre, Blackhorse Road, London SE99 6TT.

Radon - a householder's guide
Radon - a guide for homebuyers and sellers
Radon: you can test for it
Radon - a guide to reducing levels in your home

You can get advice about radon, its health risks and details of how to order the radon test from the NRPB Radon Freephone on 0800 614529 or by post from NRPB, Chilton, Didcot, Oxfordshire OX11 0RQ.

Accumulations of radon in dwellings can be fairly easily and inexpensively dealt with. You can get practical advice about construction work to reduce radon levels from the Building Research Establishment (BRE) Radon hotline on 01923 664707.

Protective measures may need to be installed during the construction of new dwellings in areas with Moderate to Very High radon potential. Practical guidance on where such measures are required and on construction methods is given in the BRE publication: Radon: Guidance on protective measures for new dwellings.

The Ionising Radiation Regulations, 1985, require employers to take action when radon is present above a defined level in the workplace. Advice may be obtained from your local Health and Safety Executive Area Office or the Environmental Health Department of your local authority. The BRE publishes a guide: Radon in the workplace.

BRE publications may be obtained from Construction Research Communications Ltd, 151 Roseberry Avenue, London EC1R 4QX (Tel: 0171 505 6622; Fax: 0171 505 6606).

Geological radon potential assessment methods are described in the British Geological Survey Technical Report WP/95/2 *Radon and background radioactivity from natural sources: characteristics, extent and relevance to planning and development in Great Britain* which may be obtained from the Sales Desk, British Geological Survey, Keyworth, Nottingham NG12 5GG (Tel: 0115 936 3241; Fax: 0115 936 3488).

A comprehensive list of publications about radon with details of prices and how to obtain them is published in the *Environmental Radon Newsletter*, Issue 16 (Autumn 1998) available from the NRPB, Dealing with radon emissions in respect of new development

DETR

NATURAL ENVIRONMENT RESEARCH COUNCIL

ISBN 0-85272-377-6