ELSEVIER

Journal of
Environmental Radioactivity 62 (2002) 165–179

JOURNAL OF
ENVIRONMENTAL
RADIOACTIVITY

www.elsevier.com/locate/jenvrad

Radon in the Creswell Crags Permian limestone caves

G.K. Gillmore [a,*], P.S. Phillips [b], A.R. Denman [c], D.D. Gilbertson [d]

[a] *Department of Environmental Science, University of Bradford, Bradford, West Yorkshire, BD7 1DP, UK*

[b] *School of Environmental Science, University College Northampton, Boughton Green Road, Park Campus, Northampton, NN2 7AL, UK*

[c] *Medical Physics Department, Northampton General Hospital, Cliftonville, Northampton, NN1 5BD, UK*

[d] *School of Conservation Sciences, University of Bournemouth, Dorset House, Talbot Campus, Fern Barrow, Poole, Dorset, BH12 5BB, UK*

Received 18 June 2001; received in revised form 16 October 2001; accepted 5 November 2001

Abstract

An investigation of radon levels in the caves of Creswell Crags, Derbyshire, an important Site of Special Scientific Interest (SSSI) shows that the Lower Magnesian Limestone (Permian) caves have moderate to raised radon gas levels (27-7800 Bq m^{-3}) which generally increase with increasing distance into the caves from the entrance regions. This feature is partly explained in terms of cave ventilation and topography. While these levels are generally below the Action Level in the workplace (400 Bq m^{-3} in the UK), they are above the Action Level for domestic properties (200 Bq m^{-3}). Creswell Crags has approximately 40,000 visitors per year and therefore a quantification of effective dose is important for both visitors and guides to the Robin Hood show cave. Due to short exposure times the dose received by visitors is low (0.0016 mSv/visit) and regulations concerning exposure are not contravened. Similarly, the dose received by guides is fairly low (0.4 mSv/annum) due in part to current working practice. However, the risk to researchers entering the more inaccessible areas of the cave system is higher (0.06 mSv/visit). This survey also investigated the effect of seasonal variations on recorded radon concentration. From this work summer to winter ratios of between 1.1 and 9.51 were determined for different locations within the largest cave system. © 2002 Elsevier Science Ltd. All rights reserved.

* Corresponding author. Tel.: +44-1274-235-398; fax: +44-1274-234-231.
E-mail address: g.k.gillmore@bradford.ac.uk (G.K. Gillmore).

PII: S0265-931X(01)00159-X

Keywords: Radon; Health; Caves; Creswell Crags; Magnesian limestone

1. Introduction

1.1. Radon in caves

Wind direction and air temperature are important in cave airflow at Creswell Crags, as shown by Coles, Gilbertson, Hunt, & Jenkinson, (1989) and Smithson (1982) and hence are likely to influence radon concentrations within these and other similar caves (Gillmore, Sperrin, Phillips, & Denman, 2000). According to Hyland (1995) there are over 3000 caves in Great Britain, and most are in Carboniferous limestone. This study is unusual in that it examines caves in Permian limestones, which contain dolomite. Such dolomitic limestones generally have less well developed karstic landforms (Waltham, Simms, Farrant, & Goldie, 1997) so caves such as those at Creswell are less common than caves in Carboniferous limestones.

1.2. Radon and health

^{222}Rn, an inert, odourless radioactive gas with a half life of 3.82 days, is produced within the decay series of ^{238}U (Fig. 1; Phillips, 1995), which is a ubiquitously distributed element within the earth's crust. Uranium is often redistributed by ground water and redeposited into limestones and dolomites (Hand & Banikowski, 1988). The raised radon levels in some caves may also be due in part to the presence of

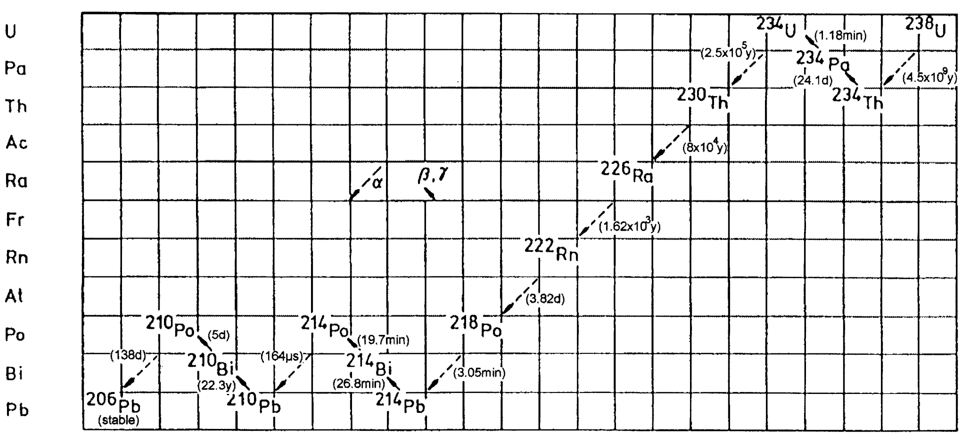

Fig. 1. Principal decay scheme of ^{238}U (after Phillips, 1995). For half-life, y=year, d=day, min=minute, s=second, μs=millisecond.

^{238}U and ^{226}Ra in both ancient and modern sediments that have collected in the passageways (Bottrell, 1991). It migrates through two processes; emanation and exhalation. Emanation is the movement of radon from the site of production to rock pore spaces, while exhalation is the movement from pore spaces to the environment. When it decays radon releases solid charged particles. The health effect of radon originates from the inhalation of these short-lived radon decay products, but not of the inhalation of ^{222}Rn itself. Radon is a noble gas and therefore it is almost completely exhaled after inhalation. The radon decay products however, are very reactive and can attach to aerosol particles, which are partly deposited inside the lung during inhalation. Due to their short half-life of less than 30 min they decay inside the lung damaging the tissue (Denman & Phillips, 1997; Jacobi, 1993) before transport processes can become effective. It has been suggested that radon in homes causes some 2500 lung cancer deaths each year in the UK (Thompson, Hine, Poole, & Greig, 1998), while Miller (2000) suggests that in the USA radon is responsible for 6000–36,000 of the 130,000 lung cancer deaths, with a best estimate of 13,600 deaths. Henshaw, Eatough, & Richardson (1990) have also suggested that the incidence of myeloid leukaemia, cancer of the kidney, melanoma and certain other cancers show significant correlation with radon exposure in the home. In the USA it is estimated that radon and its airborne decay products account for an estimated 55% of the current radiation dose of the population (Miller, 2000; Fig. 2).

Alpha radiation and radioactive decay products are an environmental hazard. Epidemiological and theoretical studies have led the National Radiological Protection Board (NRPB) to propose an Action Level of 200 Bq m^{-3} in domestic properties. The Ionising Radiations Regulations (IRR, 1999) require employers to take action if the average radon levels exceeds 400 Bq m^{-3} in the workplace. As show caves are regarded as workplaces these regulations apply to cave guides. Radon gas, once released, is normally dispersed into the atmosphere, but radon that enters poorly ventilated enclosed spaces, including natural caves and basements of homes, can build up to harmful concentrations (Thompson et al., 1998).

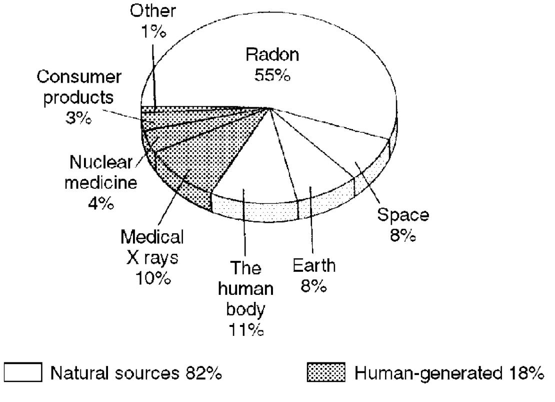

Fig. 2. Natural and human sources of the average annual dose of ionizing radiation received by the population of the USA (data from the National Council on Radiation Protection and Measurements, USA).

There is a significant caving community (Gillmore et al., 2000; Waltham et al., 1997) with many caves receiving thousands of visitors a year. Radon levels in some caves in the Mendip Hills (Gillmore et al., 2000) and Derbyshire (Hyland, 1995; Hyland & Gunn, 1994; Thompson et al., 1998) mean that recreational or occupational cavers will be exposed to levels that exceed those allowed by the Ionising Radiation Regulations (IRR, 1999). Levels within the Creswell Caves are not as high as those noted by the present authors in Carboniferous limestone caves in the Mendip Hills (Gillmore et al., 2000; Sperrin, Denman, & Phillips, 2000), but are not insignificant and are high enough to warrant monitoring.

1.3. Creswell Crags

In the East Midlands, a small gorge of a tributary to the River Poulter, with a relative relief of about 30m, is cut between low cliffs known as Creswell Crags. These cliffs contain a whole series of fairly shallow caves and fissures (the deepest being about 60m horizontally) which are past dwellings, and are the type locality of the archaeological Creswellian culture. The Creswell Crags gorge on the Nottinghamshire/Derbyshire border is found within a band of dolomitic Lower Magnesian Limestone (Kaldi, 1980; Fig. 3). This limestone crops out in a narrow belt running approximately north–south from the Nottingham area to south Northumberland, and approximates to the Cadeby Formation which is Upper Permian in age (Bryant, 1986; Waltham, 1991). This bedrock displays distinctive large scale cross-stratification and accumulated, according to Kaldi (1980), on a shallow marine shelf as subaqueous sandwaves on the margins of the Permian Zechstein sea. A great deal of research has been undertaken on the archaeology of the five world famous Creswell Crag caves (Jenkinson & Gilbertson, 1984), in terms of site geomorphology, artefact studies and faunal analysis. Many of the caves have produced remains of

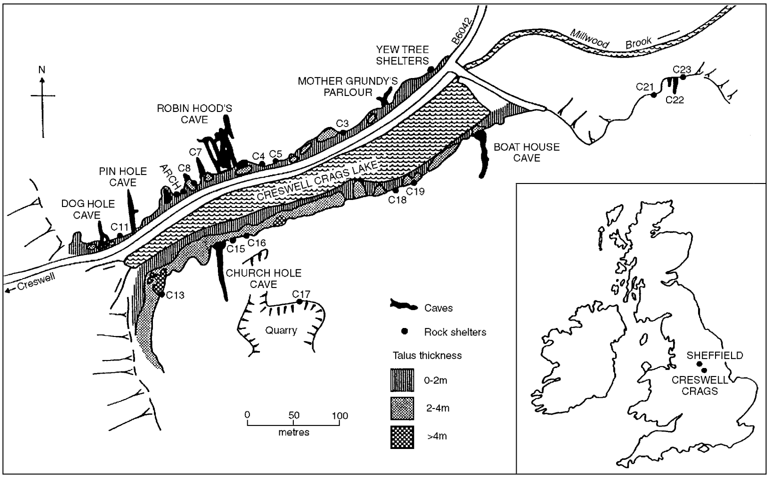

Fig. 3. The distribution of caves and rock shelters at Creswell Crags.

mammoths, woolly rhinoceras, hyaenas, bears, lions, lynx etc. This means that the micro-meteorology (Smithson, 1982, 1985) and geology (Kaldi, 1980) of these caves have to a certain extent been defined and recorded. Dog Hole Cave (Fig. 3) for example consists of a series of phreatic solution cavities formed along a NE–SW axis in the Magnesian Limestone bedrock (Jenkinson & Gilbertson, 1984). It is known that the Creswell area is greatly affected by faulting (Jenkinson, 1984), which is likely to influence cave development and transport pathways for radon gas (Ball, Cameron, Colman, & Roberts, 1991; Varley & Flowers, 1992). High radon levels have been noted in areas of karstified and phosphate rich Carboniferous and Permian limestones in many parts of the UK (Ball & Miles, 1993; Faulkner & Gillmore, 1995; Hyland, 1995; Miles, Green, & Lomas, 1992; Peacock & Taylor, 1966; Thompson et al., 1998).

The impact of geology and micro-meteorology on radon concentrations in cave environments is still under-researched (Ball & Miles, 1993). Several of the caves are relatively simple caverns (e.g. Dog Hole and Pin Hole; Fig. 3), while others are much more complex (e.g. Robin Hood's Cave is the largest in the Creswell area, consisting of four main chambers and a network of tunnels; Figs. 3 and 4). Some caves are ventilated by small shafts, while others are not. This paper therefore examines linked-cave systems and single, poorly and better ventilated ones, in areas of known geology and micro-meteorology. In all cases, the primary microclimatological gradients in these caves can be investigated partly through the surrogate measure of distance into the cave from the cave entrance.

Human access to the cave systems is controlled due to the scientific value of their archaeological contents. This meant that radon detectors could be placed within the system and there would be no significant danger of those detectors being vandalised or removed.

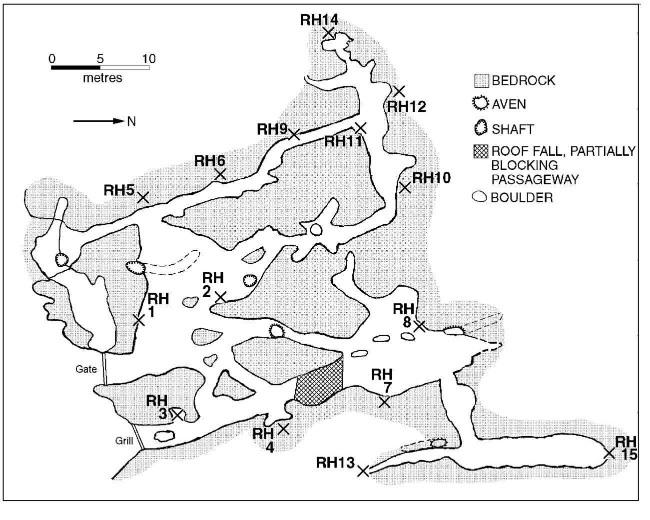

Fig. 4. The distribution of radon detectors and known avens and shafts in Robin Hood's Cave (national grid reference SK 534 742) (see Fig. 3).

The majority of visitors from February to October are school children on educational visits. The caves and visitors centre are generally open daily from February to October, while the caves are only open on Sundays during November to January. Three cave tours are run a day, with each tour lasting approximately an hour.

2. Methods

Measurements were made with a variety of devices, from passive time averaged alpha track-etch to electronic real time devices. The track-etch detectors (type CR39, sensitivity, 2.2 tr (tracks) cm^{-2} kBq m^{-3} h^{-1}) were employed following the method laid out by Green, Lomas, & O'Riordan (1992) and obtained through approved National Radiological Protection Board (NRPB) suppliers. The detectors were left in place for a minimum of 28 days. These alpha track detectors were placed approximately 1 m from the ground surface on ledges along the cave walls, away from water and measurements were taken from the entranceways to the deepest easily accessible points within each cave. Upon removal they were placed back into their protective polythene sachets and sent for analysis. The real time devices employed were Rad7s and a Radhome P.

We have used the standard unit of radiation measurement; the Becquerel (one radioactive disintegration per second) per cubic metre of air (Waltham, 1991). When calculating dose we have assumed, based on ongoing measurements by the authors of the activity concentrations of ^{222}Rn and its progeny in caves and mines with electronic devices, an equilibrium factor (F) of 0.5 (after Gillmore et al., 2000; Gillmore, Phillips, Denman, Sperrin, & Pearce, 2001). UNSCEAR (1988) suggest that for domestic environments a typical equilibrium factor is 0.35. However, these cave environments are very different.

2.1. Radon values at Creswell Crags

Radon levels were determined from November 1999 to November 2000 using alpha track-etch meters. The results are summarised in Tables 1 and 2.

The seasonal variation ratios of the radon concentration (Table 1) is demonstrated for each of the three locations RH15, RH7 and RH1 within Robin Hood's cave (Fig. 4). This is assuming that the measuring period November 1999 to February 2000 is characteristic of winter levels, while the period April to August 2000 is characteristic of the summer levels. The ratios (summer/winter) are 9.51, 2.05 and 1.1 for the cave's deep, main and entrance regions, respectively.

An apparent relationship between radon gas level and position in the cave can be seen from the results when plotted onto the ground plan for Robin Hood's cave, with higher readings generally being at the back of the cave system, away from the entrances and well ventilated areas (Table 1, Fig. 4). There are a few anomalies, one being the high reading at 22.5m (site RH5), compared to the low reading at 22m (site RH4). As can be seen from Fig. 4 these are in different parts of this cave, the reading at 22m being in a well ventilated area fairly close to a grill. The reading

Table 1
Robin Hood's Cave alpha track etch radon results (for sample points see Figs. 3 and 4)

Sample points	Distance from main cave entrance (m)[a]	Radon level, Bq m^{-3})Nov 1999–Feb 2000	Radon level, (Bq m^{-3})Apr–Aug 2000	Radon level, (Bq m^{-3})Aug–Nov 2000
RH1	7.5	27	31	79
RH2	16	82	83	122
RH3	12 (5)	32	97	128
RH4	22 (15)	26	70	80
RH5	22.5	235	187	272
RH6	29	162	–	111
RH7	32 (26)	110	226	292
RH8	35 (31)	270	465	515
RH9	38	136	–	278
RH10	39	265	220	364
RH11	45	–	279	263
RH12	47	286	251	171
RH13	55 (52)	97	780	1113
RH14	55	115	185	151
RH15	60 (55)	335	3187	3161

[a] Distances in brackets refer to distance to grill (Fig. 4) rather than the main entrance.

Table 2
Alpha track etch radon results for Church Hole Cave (CH1-4; see Figs. 3 and 5), Pin Hole Cave (PH1-3; see Figs. 3 and 6), Creswell Crags Visitor Centre lecture theatre (VC1; Fig. 3), Mother Grundy's Parlour (MGP1; Figs. 3 and 7) and Dog Hole cave (DH1; Figs. 3 and 8)

Sample number	Distance from cave entrance (m)	Radon level, (Bq $m-^{3}$)Nov 1999–Feb 2000	Radon level, (Bq $m-^{3}$)Apr–Aug 2000	Radon level, (Bq $m-^{3}$)Aug–Nov 2000
CH1	4	37	34	79
CH2	20	56	62	140
CH3	44	202	41	65
CH4	48	218	226	138
PH1	7	208	65	87
PH2	22	99	110	137
PH3	23	286	87	152
VC1	–	44	42	80
MGP1	17	–	3047	2698
DH1	14	–	182	187

at 55m (site RH13) is also lower than expected. This may be due to a possible entrance for airflow at the end of the tunnel. Water trickles into the cavern at this point. The internal topography of the cave is complex (Figs. 3 and 4), and this is shown in the data.

Additionally, Rad7 (a direct reading radon meter) measurements were also taken

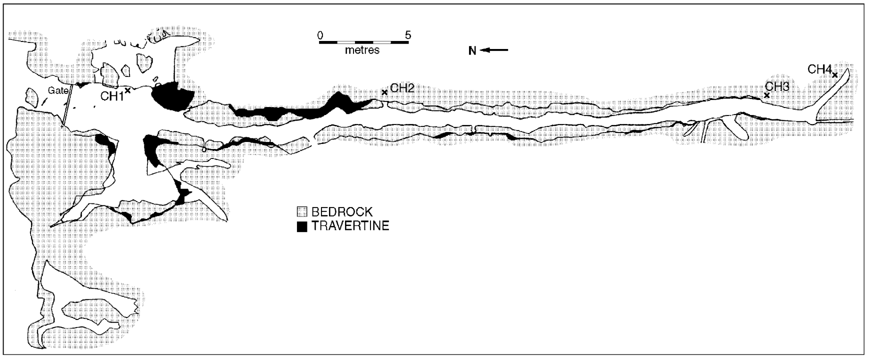

Fig. 5. The distribution of radon detectors, bedrock and travertine in Church Hole Cave (SK 534 742). Plan after Jenkinson (1984).

in April 2000 within Robin Hood's cave at sample point RH15 (Fig. 4), which gave readings of 31 Bq m^{-3} at 12.9 °C and 57 Bq m^{-3} at a temperature of 11.1 °C. These measurements were taken during a particularly wet period in the cave. April 2000 was the wettest April on record since 1818 in England. Parts of the passageway were partially filled with water and so difficult to access, a very rare event in these caves. This probably affected airflow through the cave. In August 2000, at the same sample point 6038 Bq m^{-3} of radon gas was measured at 13.6 °C, while a Radhome P device (another direct radon meter) measured 7800 Bq m^{-3}. The caves were much dryer in August 2000 than in April. Two Rad7 readings were also taken at RH15 and RH5 on the 1st December 2000 at the same time. They gave readings at RH15 of 237 Bq m^{-3} and at RH5 of 77 Bq m^{-3}.

In Church Hole cave (Table 2, Figs. 3 and 5) a very clear pattern emerges. The highest radon concentration was at the back of the cave some 48 m from the entrance.

The distribution pattern of results in Pin Hole cave is not so straightforward as in the previous cave, but the highest reading is still at the back of the cave (Table 2, Fig. 6). The reading at 22 m (site PH2) was taken in a small side pocket that may be ventilated by a small opening to the surface.

Two other caves and Creswell Crag Visitor Centre were also measured for radon gas levels (Mother Grundy's Parlour and Dog Hole Cave; Table 2, Figs. 7 and 8 respectively), but only one sample point was selected. The results for Mother Grundy's Parlour were much higher than anticipated when we consider that this cave has a relatively wide entrance (approximately 6.5 m wide) and is also fairly shallow (sample point MG1 was 17 m from the entranceway; Fig. 7).

2.2. Dose calculations

The dose saving was calculated using the relation that 1 mSv is equivalent to 126 $kBqm^{-3}$ h, which is derived from analysis by the NRPB (Wrixon et al., 1988), and the relation that 10 mSv is equal to 1 Working Level Month (HSC, 1988; ICRP, 1986), assuming an equilibrium factor of 0.5. The equilibrium factor of 0.5 is

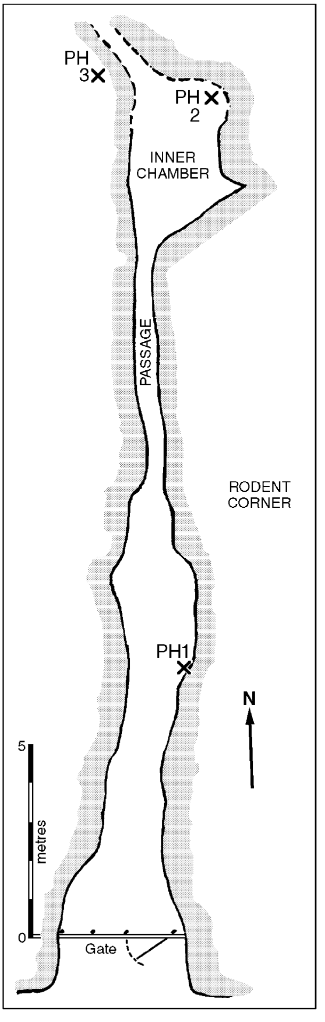

Fig. 6. The distribution of radon detectors in Pin Hole Cave (SK 532 241).

assumed for domestic properties but is also valid for caves (Gillmore et al., 2000). In other words, calculations were made based on the following:-

$$\text{Effective Dose (msV)} = \frac{(^{222}\text{Rn Concentration, Bq m}^{-3}) \times (\text{duration, h})}{126,000}$$

Assuming the equilibrium factor (F) is 0.5 in such caves as these (after Gillmore et al., 2000), and each visit lasted 1 h, exposure to the levels in Mother Grundy's Parlour (at an average of 2873 Bq m^{-3}; Table 2, Fig. 7) would give an the effective dose of approximately 0.023 mSv per visit. This is well under the 1mSv maximum suggested dose for a member of the public for a year (IRR, 1999). If a dedicated

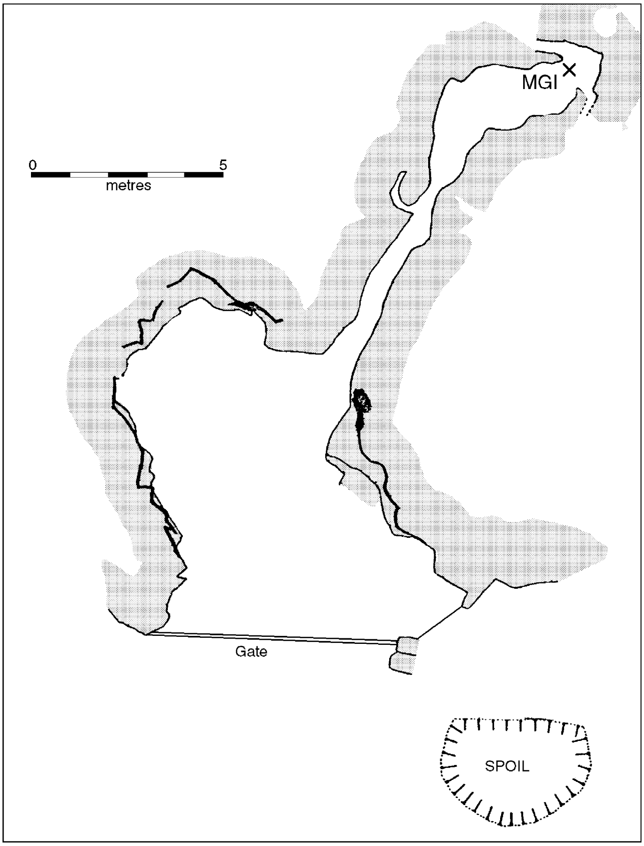

Fig. 7. The distribution of radon detectors in Mother Grundy's Parlour (SK 535 742).

explorer to such caves visited ten times in a year (total 20 h), the total yearly exposure would be approximately 0.46 mSv. However, the most visited cave is Robin Hood's cavern. This cave has the highest radon levels recorded (7800 Bq m^{-3}), but in a relatively inaccessible point. The area visited by the tour guides and members of the general public (measured at points RH1,2,5,7,8; Fig. 4) has an average radon level over a year of 200 Bq m^{-3}, based on the alpha track results (Table 1). If we assume that a guide makes three visits per working day, each of 1 h duration, the dose level would be 0.005 mSv per day.

In the low season the average hours that are spent in the cave by guides would be 48, with 720 h in the high season. That is a total of 768 h. No one person will be exposed for that length of time, this work being divided amongst two or three guides. If we divide the number of hours by three and calculate exposure based on the average for Robin Hood's cave, each guide will receive a yearly dose based on the track etch results of 0.4 mSv. If we instead look at the a worst case scenario of the dose received by researchers in Robin Hoods cave at RH15 using the Radhome P results, each visit could amount to an exposure of 0.06 mSv. It would take 17

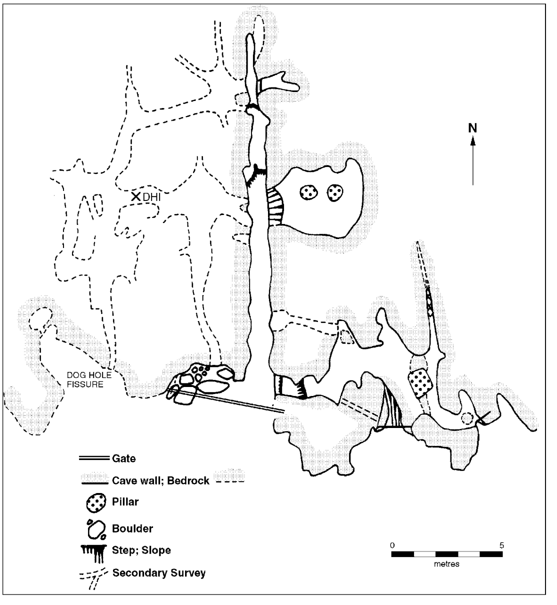

Fig. 8. The distribution of radon detectors in Dog Hole Cave.

hourly visits to be over the 1 mSv recommended maximum for a member of the public (IRR, 1999).

However, for a member of the public each visit would give then a dose level of 0.0016 mSv.

It should be noted that the doses estimated here used the NRPB methodology noted above. ICRP (1994) use a different methodology and using their method, which assumes an equilibrium factor of 0.4, the doses are around a factor of two lower, but the estimates of lung cancers are similar, because lung cancer estimates are based on radon exposure, rather than dose.

3. Discussion and conclusions

The over-riding pattern that emerges from these new data is that radon levels increase with increasing distance into the cave, i.e. away from the greater air ventilation that exists in the entrance areas. Comparisons of these new data with information from earlier studies of homes and workplaces places this new information in a health and safety context.

Waltham (1991) carried out a study of radon in homes in Nottinghamshire and correlated his findings with the underlying geology. While no value in his study exceeded 100 Bq m^{-3}, the highest radon levels with a local mean radon concentration of 58.9 Bq m^{-3} were noted on the fissured, mainly dolomitic limestones of the Cadeby Formation. Waltham concluded that some features within its bedrock geology, such as permeability, have significant influences on the amount of radon in houses. He also concluded that further monitoring on the fissured Cadeby Formation limestones may be appropriate. Radon levels in houses on this limestone were somewhat erratic, and he suggested that the fissured nature of the lithology provided migration pathways for radon. Houses wholly on a single block of limestone were likely to have lower levels. This study suggests that although the Cadeby limestones are not a significantly high density source for radon as suggested by Waltham, they do give rise to raised radon levels in confined areas such as a cave. This limestone is an important aquifer, with ground water flow through joints or fissures (Kaldi, 1980). Fissuring is most pronounced adjacent to faults.

The sediments deposited within the cave system at Creswell may well add to the radon levels within the passageways. The textural facies variations of these infilling sediments in Pin Hole cave are relatively straightforward (Griffin, 1988), while more complex relationships exist in Church Hole cave. Robin Hood's cave is characterised by immense variation in textural and chemical properties of the cave sediments (Griffin, 1988). This may help to explain in part the variations in radon levels observed in Robin Hood's cave (Table 1). Robin Hood's cave and Church Hole cave (Pin Hole cave less so) has received Pleistocene drift material derived from plateaux deposits (Griffin, 1988). All of the caves have received sediment derived from the cave bedrock walls and from aeolian processes.

Smithson (1982) measured cave temperatures at various points and heights within Pin Hole and Church Hole caves from July to early October, 1981. He found that mean monthly temperatures varied by only 0.2 °C in that period. Therefore, temperature variations alone are unlikely to be able to account for the degree of variation recorded in radon levels.

The Creswell Crags Visitor Centre has approximately 40,000 visitors a year (1998 figures, Chambers, pers comm.), but it has been as high as 250,000 in past years (Jenkinson, 1985). With so many visitors (although only a portion of these will visit the one show cave—Robin Hood's cave) the health implication for visitors and guides cannot be ignored. The visitor's centre has a low radon level (Table 2), so the health risk here is minimal. In Robin Hood's cave the entrance section where the visitors stand for talks also has low radon levels (RH1, 2, 5; see Table 1, Fig. 4). The highest levels (7800 Bq m^{-3} at sample point RH15; Table 1, Fig. 4) are as one would expect at the back of the cave in a section with little ventilation. While the time averaged radon level at RH15 (335 Bq m^{-3}) for the winter months (Table 1) is above the Action Level for homes, it is below the level for the workplace. No public visitors would actually visit this part of the system, the only visitors being the warden, guides and researchers.

This paper shows that spring/summer radon levels are much higher at certain points within these caves. There is a considerable seasonal variation factor (up to 9.51 in parts of Robin Hood's cave) which must also be taken into account when assessing the health impact of radon gas levels. This study for the most part supports Hyland's (1995) suggestion that radon levels in caves less than 20m deep (i.e. 20m from the entrance) are often little different from those of the outside atmosphere. In general, in the Creswell caves, radon levels were significantly raised beyond the 20m mark (see Table 1). The one significant exception to this is Mother Grundy's Parlour (Table 2, Fig. 7). Further research work is needed to explain the high levels within this shallow cave. Radon levels are probably raised in areas associated with the fissured Magnesian dolomitic limestones. There is a fissure at the back of Mother Grundy's Parlour which may be acting as a passageway for radon gas. This study suggests that further investigation of this is advisable (Waltham, 1991).

Friend (1996) points out that there are a number of pieces of UK legislation that impact upon those responsible for access to such underground voids as caves. The IRR (1999), a safety regulation made under the Health and Safety as Work Act of 1974, makes a distinction between staff designated as Radiation Workers (i.e. the guides), and members of the public (i.e. visitors). The guides in this study fall into the group of unclassified workers who work to a 6 mSv/annum limit.

The risk of radon exposure for members of the public is shown by this study to be small in the show cave, 0.0016 mSv/visit. Even the guides are not at a significant risk (0.4 mSv/annum) if their exposure is managed appropriately. These levels fall below the 1mSv maximum dose per annum recommended for a member of the public by the IRR (1999), so no action is required to reduce radon levels. However, some care must be exercised by researchers venturing into the most affected areas in these caves (estimated exposure of 0.06 mSv/visit), although under IRR (1999) they will be regarded as staff and hence have a higher recommended maximum dose than a normal visitor.

Acknowledgements

This work was undertaken with the permission and support of staff at the Creswell Crags Visitor Centre, in particular Brian Chambers, Senior Ranger. The figures were compiled by Paul Stroud, IT technician, School of Environmental Science.

References

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

Ball, T. K., Cameron, D. G., Colman, T. B., & Roberts, P. D. (1991). Behaviour of radon in the geological environment: a review. *Quarterly Journal of Engineering Geology*, *24*, 169–182.

Bottrell, S. (1991). Radon production and release from cave sediments. *Cave Science*, *18*, 79–82.

Bryant, I. D. (1986). Petrographic variation associated with hummocky cross stratification in the Permian of Nottinghamshire, England. *Mercian Geologist*, *10*, 203–208.

Coles, G. M., Gilbertson, D. D., Hunt, C. O., & Jenkinson, R. D. S. (1989). Taphonomy and the palynology of cave deposits. *Cave Science*, *16*, 83–89.

Faulkner, K., & Gillmore, G. K. (1995). Geology and radon entry into buildings. In: *The Radon Manual*, (2nd ed.). A Guide to the Requirements for the Detection and Measurement of Natural Radon Levels, Associated Remedial Measures and Subsequent Monitoring of Results (2.21-2.29). Shepperton, Middlesex: The Radon Council Ltd.

Friend, C. R. L. (1996). Radon exposure during underground trips: a set of guidelines for caving and mine exploration in Britain. *Cave and Karst Science*, *23*(2), 49–56.

Gillmore, G. K., Sperrin, M., Phillips, P., & Denman, A. (2000). Radon Hazards, Geology and Exposure of Cave Users: a case study and some theoretical perspectives. *Ecotoxicology and Environmental Safety*, *46*(3), 279–288.

Gillmore, G. K., Phillips, P., Denman, A., Sperrin, M., & Pearce, G. (2001). Radon Levels in Abandoned Metalliferous Mines, Devon, Southwest England. *Ecotoxicology and Environmental Safety, 49,* 281–292.

Green, B. M. R., Lomas, P. R., & O'Riordan, M. C. (1992). Radon in dwellings in England. *National Radiological Protection Board Report, 254,* 1–72.

Griffin, C. M. (1988). *The genesis and diagenesis of cave sediments at Creswell Crags*. Unpublished doctoral dissertation, University of Sheffield, UK.

Hand, B. M., & Banikowski, J. E. (1988). Radon in Onondaga County, New York: Paleohydrology and redistribution of uranium in Paleozoic sedimentary rocks. *Geology, 16*, 775–778.

Health and Safety at Work Act (1974). London: HMSO.

Health and Safety Commission (HSC) (1988). *Approved Code of Practice—Part 3, Exposure to Radon. The Ionising Radiations Regulations, 1985*. London: HMSO.

Henshaw, D. L., Eatough, J. P., & Richardson, R. B. (1990). Radon as a causative factor in induction of myeloid leukaemia and other cancers. *The Lancet, 335,* 1008–1012.

Hyland, R. (1995). *Spatial and temporal variations of radon and radon daughter concentrations within limestone caves*. Unpublished doctoral dissertation, University of Huddersfield, UK.

Hyland, R., & Gunn, J. (1994). International comparison of cave radon concentrations identifying the potential alpha radiation risks to British cave users. *Health Physics, 67,* 176–179.

International Commission on Radiation Protection (ICRP) (1986). Radiation Protection of Workers in Mines, *ICRP Publication 47.* Oxford: Pergamon Press.

International Commission on Radiation Protection (1994). Protection Against Radon-222 at Home and at Work, *ICRP Publication 65.* Oxford: Pergamon Press.

Ionising Radiations Regulations (1999). Health and Safety Executive, Statutory Instrument 3232, HMSO.

Jacobi, W. (1993). *The history of the radon problem, Chapter 3: Uranium mining and the role of the radon daughters*. In The International Commission of Radiological Protection: *Protection against radon at home and at work.* ICRP Publication 65, Oxford: Pergamon Press.

Jenkinson, R. D. S. (1984). Creswell Crags. Late Pleistocene Sites in the East Midlands. British Archaeological Reports, British Series 122, 379 pp.

Jenkinson, R. D. S., & Gilbertson, D. D. (1984). *In the shadow of extinction: a quaternary archaeology and palaeoecology of the lake, fissures and smaller caves at creswell crags SSSI*. England: John R. Collis.

Jenkinson, R. D. S. (1985). Creswell Crags Visitor Centre. In: D. J. Briggs, D. D. Gilbertson, & R. D. S. Jenkinson (Eds.), *Peak District and Northern Dukries Field Guide* (pp. 157–158). Quaternary Research Association.

Kaldi, J. (1980). *Aspects of the sedimentology of the lower magnesian limestone (Permian) of eastern England.* Unpublished doctoral dissertation, University of Cambridge, UK.

Miles, J. C. H., Green, B. M. R., & Lomas, P. R. (1992). Radon affected areas: England. *Documents of the National Radiological Protection Board, 7,* 1–9.

Miller, G. T. (2000). *Living in the environment: principles, connections, and solutions* (11th ed.) (116pp.). USA: Brooks/Cole 116 pp.

Peacock, J. D., & Taylor, K. (1966). Uraniferous collophane in the Carboniferous limestone of Derbyshire and Yorkshire. *Bulletin of the Geological Survey of Great Britain, 25,* 19–32.

Phillips, P. S. (1995). A remarkable story. In: *The Radon Manual.* (2nd ed.). *A Guide to the Requirements for the Detection and Measurement of Natural Radon Levels, Associated Remedial Measures and Subsequent Monitoring of Results* (1.1-1.36). Shepperton, Middlesex: The Radon Council Ltd.

Smithson, P. (1982). Temperature variations in Creswell Crags (Near Worksop). *The East Midland Geographer, 8,* 51–64.

Smithson, P. (1985). Cave microclimate at Creswell Crags: initial surveys. In: D. J. Briggs, D. D. Gilbertson, & R. D. S. Jenkinson (Eds.), *Peak District and Northern Dukeries, field guide* (pp. 159–164). Quaternary Research Association.

Sperrin, M., Denman, T., & Phillips, P. (2000). Estimating the dose from radon to recreational cave users in the Mendips, UK. *Journal of Environmental Radioactivity*, *49*, 235–240.

Thompson, A., Hine, P.D., Poole, J.S., & Greig, J.R. (1998). *Environmental Geology in Land Use Planning: A Guide to Good Practice.* Report to the Department of the Environment, Transport and the Regions. Symonds Travers Morgan, East Grinstead, 80 pp.

UNSCEAR (1988). Sources, effects and risks of ionizing radiation. United Nations Scientific Committee on the Effects of Atomic Radiation—*1988 Report to the General Assembly, with Annexes*.

Varley, N. R., & Flowers, A. G. (1992). Radon and its correlation with some geological features of the south-west of England. *Radiation Protection Dosimetry*, *77*, 171–176.

Waltham, A. C. (1991). Geological influences on radon in houses in Nottinghamshire. *Mercian Geologist*, *12*, 79–86.

Waltham, A. C., Simms, M. J., Farrant, A. R., & Goldie, H. S. (1997). *Karst and caves of Great Britain. Geological conservation review series*. Chapman and Hall 358 pp.

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., & O'Riordan, M. C. (1988). *Natural Radiation Exposure in UK Dwellings*. National Radiological Protection Board Report R190, NRPB, Chilton, UK.