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The potential risk from ^{222}radon posed to archaeologists and earth scientists: reconnaissance study of radon concentrations, excavations, and archaeological shelters in the Great Cave of Niah, Sarawak, Malaysia

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Abstract

This reconnaissance study of radon concentrations in the Great Cave of Niah in Sarawak shows that in relatively deep pits and trenches in surficial deposits largely covered by protective shelters with poor ventilation, excavators are working in microenvironment in which radon concentrations at the ground surface can exceed those of the surrounding area by factor of 4:2. Although radon concentrations in this famous cave are low by world standards (alpha track-etch results ranging from 100 to 3075 Bq m_3), they still may pose health risk to both excavators (personal dosemeter readings varied from 0.368 to 0.857 mSv for 60 daysof work) and cave occupants(yr exposure at 15 per day with an average radon level of 608 Bq m giving dose of 26.42 mSv). The data here presented also demonstrate that there is considerable local variation in radon levels in such environments
as these.

1. Introduction

This reconnaissance paper explores the possible risk from exposure to 222radon for archaeologists or earth scientists who carry out long-term excavations of cave infill deposits. This risk appears to have not been the subject of previous investigation. The cave excavations studied are in the west entrance of the Great Cave of Niah in Sarawak in Malaysian Borneo (Fig. 1). This work has focused upon the potential risk that may be associated with any combination of (i) residual and complex microtopography caused by the cleaning and excavating of materials, (ii) poor ventilation created either by the earlier excavationsor by sheltersbuilt to protect key archaeological features, and (iii) possible accelerated release of radon from excavated materials. Previouswork explored the potential health effectsfor

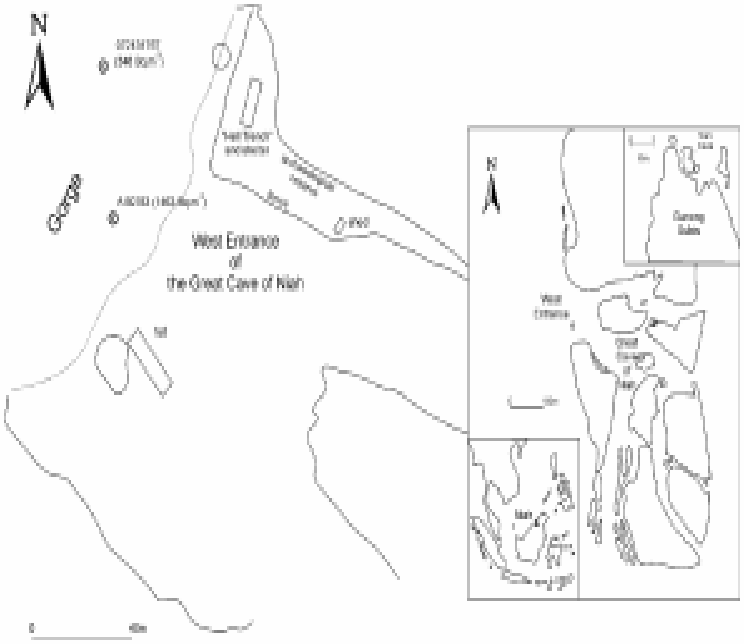


Fig. 1. Location diagram (right) showing Malaysian Borneo, the location of the Subis limestone massif, and the morphology of the Great Cave of Niah and details (left) of the archaeological reserve, the excavation area, (the Hell Trench and shelters), and forest floor study sites.

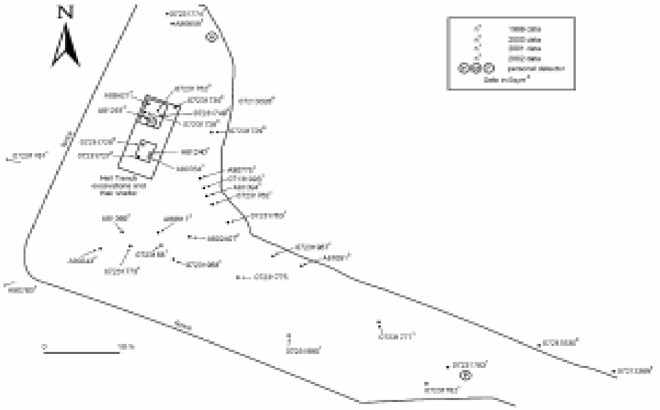


Fig. 2. Detector locations in 1999, 2000, 2001 and 2002, throughout the archaeological reserve together with the position of the archaeological shelter over the Hell Trench.

people working in or living in thiscave with ammonia-rich guano (Pyatt, 2003). Pyatt (2003) noted that visitors to the cave were unlikely to experience adverse effects. The present reconnaissance study examines the radon concentrations associated with the residual microtopography created by the excavationsof Tom and Barbara Harrisson in the 1950s and those of Zuraina Majid in the 1970s. These are illustrated in Barker et al. (2001, 2002a, b, their Figs1 and 3–13), and were located immediately inside the west entrance to the cave (Figs. and 2) which is approximately 150 acrossand 60 high. The B3-deep ‘‘Hell Trench’’ excavation of the Harrissons at this site yielded, in 1958, the oldest remains of modern humans from South East Asia and Australasia. These remains date to about 42,000–44,000 yearsago (Barker et al., 2001, 2002a, b; Gilbertson et al., in press; see also Harrisson, 1970; Majid, 1982). One consequence of this find has been the provision by the Sarawak Museum and the National Parks Service of protective cover to eliminate the impacts of rain water flowing through the cave roof, or of defecating birds and swiftlets. This cover is large perspex shelter that reaches to 10–20 cm above ground level on two sides. It cover sa complex of excavated pitsand trenches that are up to deep—these are simplified in Fig. 1 into two helter. Small-strenches within the scale but active cleaning of facesand further local archaeological excavation took place inside and outside the shelter in the period from 2000 to 2002. As is often the case with such site protection features, ventilation is readily observed to be poor inside the shelter, especially within the contained excavation trenches which may well impact on recorded radon levels. All these features rest on an original cave floor surface that slopes downward from the cave interior toward the cave mouth at 2–8 (Fig. 1). At the cave mouth there isa rampart-like feature coincident with the fence marking the western margin of the archaeological reserve (Fig. 2). This rampart is3–high above the adjacent interior cave surface. The rampart is derived from the collapse of an original curtain-like set of massive stalagmite

columns, only one of which remains standing immediately to the north west of the Hell Trench (Fig. 2). The potential risks from 222radon gasfaced by users of underground caves and mines, such as tour guides or recreational cavers, have recently been described in series of papers (Gillmore et al., 2000a, and references therein). The National Caving Association (1996) in the UK has been aware of the risks from radon and issued guidance for cavers. This guidance is designed to encourage caversto reduce their exposure to elevated radon levels. Friend (1996) used these guidelines to quantify risks to cavers from radon in the UK. In general, the quantitiesof radon that reach soil– ground interfaces, where radon and its daughter elementscan be inhaled, are shown to depend on many factors. These include the uranium content of the bedrock sources and of intermediate reservoirs such as surficial cave infill deposits or the adjacent limestone bedrocks, the permeability of rocks, the nature and frequency of passage ways including faults, fissures, pores, and various meteorological, hydrological, biological, and speleological/topographical factors that affect the concentration of the gasat the ground surface. For human health considerations, the duration and intensity of exposure are clearly important (Gillmore et al., 2001a, b; Gunn et al., 1991). At present, most understanding of the risk to health posed to workers underground by 222radon stems from research on the cellars or basements of domestic, commercial, and industrial buildings, on mines, and on long-term underground storage facilities (Ball and Miles, 1993; Cliff and Gillmore, 2001; Faulkner and Gillmore, 1995; Gillmore et al., 2001a, b, 2002; Green et al., 1992; Sperrin et al., 2000); nowadays, such potential risk is well documented although not necessarily easy to relate to natural cavities or underground dwellings. Radon (222Rn) isa naturally occurring radioactive gasthat isformed in the decay seriesof uranium. 222Radon hasa half-life of 3.82 daysIt decays by alpha-particle emission into series of isotopes known as radon progeny, of which the most 214significant are 218Po and Pb. These two decay oproductsare alsradioactive and decay by alpha-particle emission. As result, if they are retained in the lung they may make substantial contribution to the total radiation dose (490%) (Gillmore et al., 2002; WHO, 2001). These progeny may be inhaled and retained in the lung via aerosol particles (water droplets and/or dust particles) that are both too small to be filtered by nasal hairs and too large to be subsequently exhaled. When retained within the lung these progeny may deliver radiation dose to the lung walls (BEIR VI, 1999). The potential health risks that stem from such exposure to radon and its progeny in everyday life are also well documented (e.g., Darby et al., 1998; ICRP, 1987; Lubin and Boice, 1997; WHO, 1988, 2001). In the United Statesthe Environmental Protection Agency (EPA) estimates that between 15,000 and 22,000 lung cancer deaths per year are caused by radon, based on National Academy of Sciences(NAS) data (BEIR VI, 1999). The NAS estimates that in the United States 12% of all lung cancer deaths(total deathsfrom all causes being 157,400) are linked to radon (BEIR VI, 1999). In the United Kingdom, the National Radiological Protection Board (NRPB) estimated that within the UK around half of the background radiation dose received by the general public comesfrom radon and itsprogeny (Hughes, 1999). Indeed, approximately 2500 deathsfrom lung cancer each year are estimated to be attributed to radon (Dixon, 2001; Kendall and Muirhead, 1997; WHO, 2001). Thisrepresents6% of the annual total of 40,000 lung cancer deathsin the UK, where radon is the second largest cause of lung cancer after tobacco smoking (Kendall and Muirhead, 1997). This paper focuses upon new aspect of professional work in caves. It explores the possible risk, previously unconsidered, posed to particular group of people— archaeologists or earth scientists—who can spend substantial periods of time excavating underground. Excavation in cavesmight have variety of consequences
from exposure to radon—some are obvious, and others less so. The processes of excavation inevitably disturb or remove horizontal and vertical surface materials—such as indurated layers or surface algae and lichen—that might otherwise impede the passage of soil radon into the cave atmosphere. Subsurface cracks, soil pores, and fissures might also open or enlarge, promoting desiccation and perhaps in some cases offering higher rates of gas transmission, and the new surfaces may crumble or fail. All these factors are likely to vary in importance according to the physical properties of the sediments excavated. The ‘‘technique’’ of excavation, notably by ‘‘trowelling’’, will often release ‘‘dust’’ into the near-surface atmosphere in situations where the excavator’s face is relatively close to the ‘‘trowelled’’ surface. This is particularly likely to be the case where surface cave sediments have become desiccated. Archaeological excavation strategies within cave sediments may vary, but whether they employ small-area linear ‘‘trenches,’’ ‘‘sondages,’’ or large-area ‘‘open excavations,’’ it is probable that many excavators will find themselves in some type of ‘‘trench’’ in which local ventilation isrestricted. Ventilation can also be impaired if the excavation is covered by some sort of shelter to prevent water drip or other damage to the excavated surface. It is not unusual for excavationsto take place in those locationsin caves that already have relatively poor ventilation—e.g., Creswell Crags in England (Gillmore et al., 2002). Smaller cavesare likely

to have higher ratiosof cave surface area to atmosphere volume—offering greater proportion of the immediate radon ‘‘source’’ (from rock or surficial deposits) to the cave atmosphere that is the immediate radon ‘‘sink.’’ The complexity of excavation in cavescan result in excavatorsbeing in confined space underground for very long periods. The excavationsat Pin Hole Cave, Creswell Cragsin England in the 1980s, for example; saw one group of supervisors working in the same confined excavation for per day, daysa week, between and monthsunderground per year for period of 2–years(Gillmore et al., 2002; Hunt et al., 1987). In practice, the longer-term work by the excavatorsof cave sedimentsmay resemble or even exceed the long-term occupancy of the underground cellars and storage areas in domestic or commercial buildingsthat have attracted much research on exposure to and remediation of exposure to radon (Denman et al., 1999; Denman et al., 2004 and reference stherein). Several factors combine to make the new investigations of the legacy of past excavations in the Great Cave of Niah particularly appropriate to begin to investigate the potential risk to excavators of cave infill deposits. The general geological, topographical, and environmental features of this cave have been recently summarized in number of publications(Banda and Heward 2000; Barker et al., 2000, 2001, 2002a; Gilbertson et al., in press; Hazebroek and Morshidi, 2001; Hutchinson 1989; Wilford, 1964). In brief, the Great Cave of Niah isa vast (B900 by B600 m) multichambered and multientranced cave (Fig. 1) that isdeveloped within the Subis Limestone Member (Miocene) of the hill massif known asthe Gunong Subis. The SubisLimestone isprimarily algal reef limestones thought to be former shelf-edge patch reef (Azhar et al., 1992). These limestones are associated with and underlain by complex of shales, mudstones, siltstones, and sandstones (Banda, 1998; Liechti et al., 1960). Much of the internal topography of the cave can also be related to the distribution of faults and fissures (Banda and Heward, 2000). There are no reasons to suspect that this cave might have particular problem with radon gasasneither the regional geology (see Hazebroek and Morshidi, 2001; Hutchinson, 1989) nor the local bedrocksindicate any critical close proximity of source minerals for radon gas. The cave mouth of the West Entrance is B150 wide and B60 high (Fig. 1). Beyond it, there isa gorge several hundred meters deep and wide and developed along bedrock faultsin the SubisLimestone. The gorge is occupied by mostly immature but dense tropical rain forest that is illustrated on the cover page of The Sarawak Museum Journal for 2001. Two soils studied beneath rain forest in the adjacent gorge consisted of 20 and 40-cm thicknesses of plant debris overlying Subis Limestone (Fig. 1, Tables1–3), but in considerable areas of the gorge floor, little or no soil was present and trees grew directly out of fissures or joints in the limestone bedrock. The excavation sites studied here were all in surficial deposits of Late Quaternary age (Gilbertson et al., in press). These are all fine grained in texture and contain various admixtures of sand, silt, and clay, from slightly clayey sands to silty clays. These materials had been brought to the site largely by mass-movement, shallow, intermittent fluvial activity and airfall processes within the cave (Hunt and Rushworth, in press). Various sedimentary units of archaeological or geological importance have been recognized and are described in Tables1–and in Barker et al. (2001, 2002a, b) and Gilbertson et al. (in press). Ultimately, the cave infill materials are essentially similar—reflecting their derivation from guano and detritusaccumulating within the cave. The present thickness of sediments collecting as bat or bird guano (Leh and Kheng, 2001) immediately to the east of the archaeological reserve within the cave exceeds15 (Barker et al., 2002b). Episodic relocations of these guano deposits toward the cave entrance by mass-movement and stream flow have been the dominant geomorphic processes acting in this part of the cave and have produced deposits known as Units 3, 3R, 4, and 5. Many of these deposits have been affected by the widespread growth of secondary gypsum within Units and 3R (Barker et al., 2002b). Nevertheless, the red-brown clays, silts, and sands of Unit 2, which are associated with the most ancient human remains and hence the deep and covered excavations, are derived mostly from wash and airfall processes (Hunt and Rushworth, in press). Unit 2C isa yellow silt-clay derived from the collapse and decay of limestone and speleothem debris in the cave entrance area. The locations associated with excavation that were monitored within the cave for radon can be broadly classified into four broad combinations of residual micro-topography and ventilation (Figs. 1–3, and Tables1–4): (a) bedrock ledgeseroded in the Subis Limestone, some above and beyond the cave infill sediments; (b) deep, confined pits and trenches up to 2.5 deep in Unit with current excavations associated with very poor ventilation as result of the presence of substantial protective cover reaching to nearly the ground surface on two sides; (c) shallower pits and excavations, some associated with local current excavation
and othersretaining 100% cover of algae

Table 1
Radon detector site details and radon concentrations noted in the West Entrance to the Great Cave of Niah in 1999 and 2000

Radon detector numbers	Bqm $^{-3}$	Exposure dates dd/mm/yr-dd/mm/yr	∼ Cave mouth	Cave wall < 1m Distant	Depth below present general land surface	Distance into cave from cave entrance (m)	In natural gully or gorge	On sedimentary unit (n) or bedrock of Subis Limestone	Surface leaf litter thickness (m)	In rain forest	% Cover algae/lichen moss = E	Distance to nearest excavation (m): E—active excavation site	Date of nearest excavation/ face cleaning	In "pit"	On "plinth"	Under artificial shelter ∼ poor ventilation	Substantial "foot passage"	Same location as detector	Not recovered
07213328	100	04-09-99–11-11-99		✓		40		SL				1	1970s						
07213330	n/a	04-09-99 -		✓		100		SL				10	1970s						✓
07213369	100	04-09-99–11-11-99		✓		110		SL				1	1970s						
07231752	453	31-08-00–27-04-01			1	12		2/2-2C				1	2000	✓		✓	✓	07231727 A81261 07231728 A81764	211 DAYS
07231727	878	31-08-00-07-09-00			0.7	19		2/1-2/2				0	2000	✓		✓	✓	07231752 07231728 A80764	
07231728	965	31-08-00-07-09-00			1.5	19		2/1-2/2				0	2000	✓		✓	✓	07231727 A80764	
07231729	849	31-08-00-07-09-00			-0.5	25		2/2-4				0	2000				✓	A81245	
07231730	844	31-08-00-07-09-00			1	15		2/2-2C			100	1	2000	✓	✓	✓	✓	.A80427 07231752 07231749 07231752	
07231749	838	31-08-00-07-09-00			0.6	12		2/2 -2C				0	2000	✓		✓	✓	A80427 A81261 0721752 07231730	

Detectors are solid-state nuclear track detectors utilizing CR39 (polyallyl-digilycol-carbonate) plastic. Detectors placed on: SL, Subis Limestone, 1–5 are Late Quaternary sedimentary units described in the text.

Table 2
Radon detector site details and radon concentrations noted in the West Entrance to the Great Cave of Niah in 2001

Radon detector numbers	Bqm $^{-3}$	Exposure dates dd/mm/yr–dd/mm/yr	∼ Cave mouth	Cave wall < 1m Distant	Depth below present general land surface	Distance into cave from cave entrance (m)	In natural gully or gorge	On sedimentary unit (n) or bedrock of Subis Limestone	Surface leaf litter thickness (m)	In rain forest	% Cover algae/lichen moss = E	Distance to nearest excavation (m): E—active excavation site	Date of nearest excavation/ face cleaning	In "pit"	On "plinth"	Under artificial shelter ∼ poor ventilation	Substantial "foot passage"	Same location as detector	Not recovered
07131993	283.1	11.04.01–27.04.01		✓		23		5			100	1	1960s		✓		✓	07231762 07231763	
07231762	555	17.04.01–27.04.01		✓	0.4	26		5				E						07131993 07231763	
07231763	504	17.04.01–27.04.01		✓	0.3	26.5		4/5				E		✓				07131993 07231762	
07231767	346.9	11.04.01–27.04.01			2	−20	✓	SL	0.05	✓	100	40							
07231768	444	29.03.01–27.04.01				17		3			100	1	1960s				✓	A80817 07231988	
07231773	384.4	11.04.01–27.04.01				18		3			100	3	1960s					A81069 A80343	
07231774	902.5	11.04.01–27.04.01	✓			7		2C			100	2	1960s					A80859	
07231775	268	11.04.01–27.04.01				32		5			100	3	1960s			✓-but ventilated			
07231777	313.1	11.04.01–27.04.01				80		5				6	1960s						
07231782	414.4	11.04.01–27.04.01			0.03	62		5				E		✓				07231783	
07231783	628.1	11.04.01–27.04.01			0.2	66		5				E		✓				07231782	
07231987	262	11.04.01–27.04.01		✓		52		5				3	1960s				✓		
07231988	380.6	11.04.01–27.04.01				23		3R			100	3	1960s					A80407 07231768	
07231995	243.8	11.04.01–27.04.01				41		5				3					✓		

Detectors are solid-state nuclear track detectors utilizing CR39 (polyallyl-digilycol-carbonate) plastic. Detectors placed on SL, Subis Limestone, 1–5 are Late Quaternary sedimentary units described in the text.

Table 3
Radon detector site details and radon concentrations noted in the West Entrance to the Great Cave of Niah in 2002

Radon detector numbers	Bq m^{-3}	Exposure dates dd/mm/yr–dd/mm/yr	~Cave mouth	Cave wall <1m Distant	Depth below present general land surface	Distance into cave from cave entrance (m)	In natural gully or gorge	On sedimentary unit (n) or bedrock of Subis Limestone	Surface leaf litter thickness (m)	In rain forest	% Cover algae/lichen moss = E	Distance to nearest excavation (m): E—active excavation site	Date of nearest excavation/face cleaning	In "pit"	On "plinth"	Under artificial shelter~poor ventilation	Substantial "foot passage"	Same location as detector	Not recovered
A80343	319	09/04/02–24/04/02				17		3?			100	25	1980					A81069 07231773	
A80407	595	09/04/02–24/04/02				24		3R			100	2	2001				✓		
A80427	1978	09/04/02–24/04/02			1.6	12		2/2/2C				E	2000–02	✓		✓	✓	A81261	
A80764	574	09/04/02–24/04/02			21.9	19		2/1				E	2000–02	✓		✓		A81240 07231728 07231727	
A80776	404	09/04/02–24/04/02			−0.5	23		5				0.5			✓		✓		
A80783	829	09/04/02–24/04/02	✓			−12	✓	SL	0.05	✓		50						A81071	
A80817	191	09/04/02–24/04/02			−0.5	17		3R			100	0.5	2000		✓			7231768	
A80859	148	09/04/02–24/04/02	✓			5		2C			100	3	1960					07231774	
A81069	498	09/04/02–24/04/02				17		3R			100	5	1980					A80343	
A81071	n/a	09/04/02-missing	✓		1–1.5	−12	✓	SL	0.02	✓		50						A80783	✓
A81091	361	09/04/02–24/04/02				24		5			100	0.5	2000–02						
A81094	361	09/04/02–24/04/02		✓	−0.7	23		4/3R							✓				
A81240	1191	09/04/02–24/04/02	✓		2	19		2/1				E	2000–02	✓		✓		A80764 07231728 07231727	
A81245	404	09/04/02–24/04/02	✓		−0.6	25		3R				E	2000–02		✓		✓	07231729	
A81261	1148	09/04/02–24/04/02			0.6	12						E	2000–02	✓		✓		A80427 07231749	

Detectors are solid-state nuclear track detectors utilizing CR39 (polyallyl-digilycol-carbonate) plastic. Detectors placed on SL, Subis Limestone, 1–5 are Late Quaternary sedimentary units described in the text.

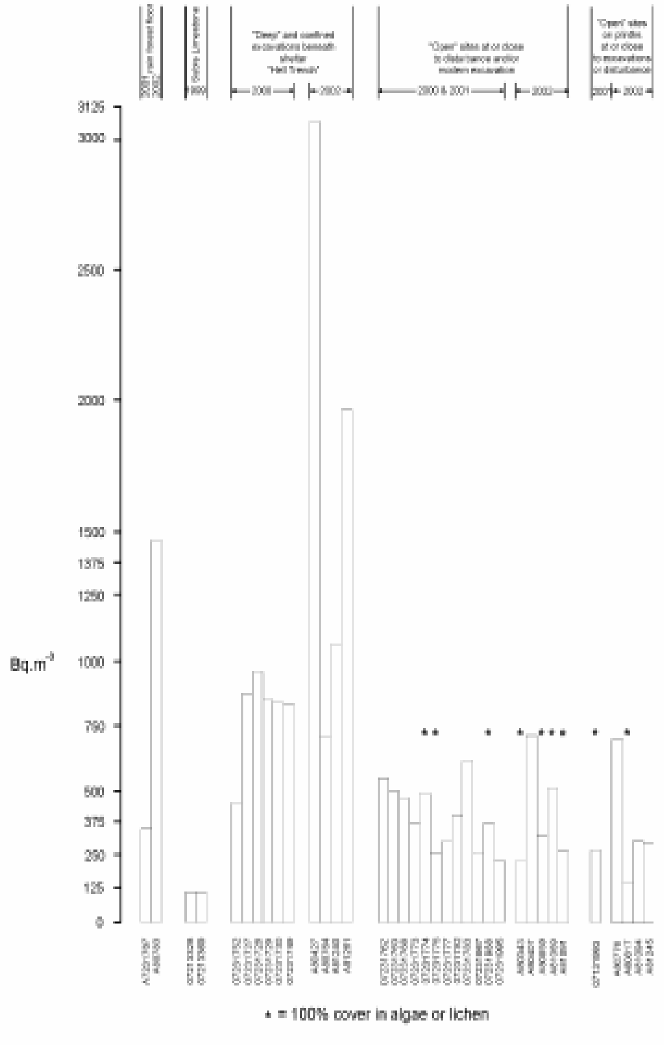
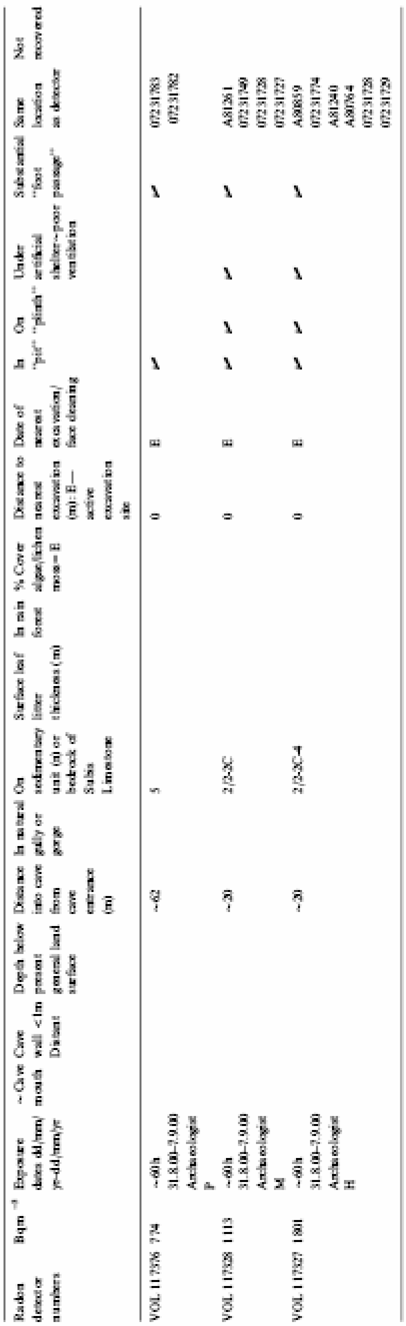


Fig. 3. Radon concentrations on rain forest soils, on Subis Limestone, beneath the archaeological shelter in the deep Hell trench with modern excavations, at open sites at or close to excavation or disturbance and at plinths of surficial sediment at open sites at or close to excavation or disturbance. *100% of surface covered in algae or lichen. Site details associated with each detector are given in Tables 1–4.

developed since the abandonment of the original excavation in the 1950s and 1960s; all are reasonably well-ventilated, not associated with any protective cover, and located in Units2C, 3, 3R, 4, and 5; and (d) residual plinthsof sediment reaching up to and above the surrounding surface, typically associated with (c). Recolonizing unicellular algae, attributed provisionally
to the genus Pleurococcus, have completely covered many but not all these surfaces since their excavation 30 or 40 yearsearlier (Tables1–3). Elsewhere remnant faces are being burrowed by ‘‘robber bees.’’ Disturbance of excavated surfaces by foot passage is restricted through the use of wooden walkways within the protected archeological reserve. Nevertheless, foot passage has visibly disturbed or removed surface materials within and beyond some pits and trenches (Tables1–3). Other surface characteristics are given in Tables1–4. There have been no studies of the micrometeorology in thiscave or in the excavated pitsand trenches, nor have wind velocitiesbeen determined. The presence or absence of significant ventilation near the ground surface is based upon field observation—not actual measurement—the slightest breeze being obvious and important in hot and humid tropical environment. Casual field observation indicates that on occasion the cave iswell ventilated—with departing airflow reaching at least 10 km h_some 150 inside the cave, while during recurrent tropical rainstorms, air and biological debriscan be driven into the cave, with large leaves being moved up to 30 from the cave mouth (Hunt and

Table 4
Radon concentrations noted by Volalpha personal monitors (VOL) that were exposed by three excavators only during actual trench cleaning, excavation, and similar professional activities in three distinct areas of the site (Fig. 3).



Radon detector numbers	Bqm $^{-3}$	Exposure dates dd/mm/yr–dd/mm/yr	~Cave mouth	Cave wall <1m Distant	Depth below present general land surface	Distance into cave from cave entrance (m)	In natural gully or gorge	On sedimentary unit (n) or bedrock of Subis Limestone	Surface leaf litter thickness (m)	In rain forest	% Cover algae/lichen moss=E	Distance to nearest excavation (m): E—active excavation site	Date of nearest excavation/face cleaning	In ''pit''	On ''plinth''	Under artificial shelter–poor ventilation	Substantial ''foot passage''	Same location as detector	Not recovered
VOL 117376	774	~60h 31.8.00–7.9.00 Archaeologist P				~62		5				0	E	✓			✓	07231783 07231782	
VOL 117328	1113	~60h 31.8.00–7.9.00 Archaeologist M				~20		2/2-2C				0	E	✓	✓	✓	✓	A81261 07231749 07231728 07231727	
VOL 117327	1801	~60h 31.8.00–7.9.00 Archaeologist H				~20		2/2-2C-4				0	E	✓	✓	✓	✓	A80859 07231774 A81240 A80764 07231728 07231729	

Rushworth, in press). One part of the excavated area has particularly limited ventilation—the Hell Trench site beneath itsprotective shelter (Figs. 1 and 2). The air gap along the shelter's long sides is in the order of 10–30 cm, the two triangular open ''short'' ends reach to height about m. Inevitably there isrelatively ''dead air'' within thisshelter.

2. Methods

Studies have indicated that the ratio of radon to radon progeny (measure known as ''the equilibrium factor, F '') is relatively constant in homes. As result, the dose from progeny is often described or estimated from measurements of the concentrations of radon in the atmospheric

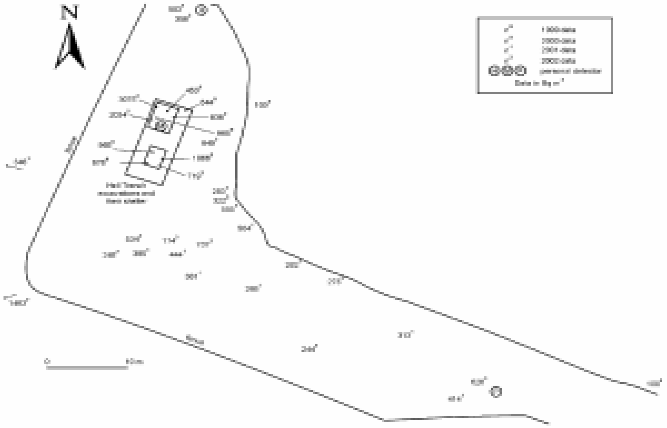


Fig. 4. Map of radon concentrations in 1999, 2000, 2001, and 2002 throughout the archaeological reserve together with the position of the archaeological shelter over the Hell Trench.

environment. This is the method of assessing exposure employed in this account. This is the same approach adopted by Gillmore et al. (2002) in their study of Permian limestone caves in Derbyshire, UK. However, F doesvary in underground environments such as mines, as illustrated by Gillmore et al. (2001a) who noted F of 0.17–0.4, from preliminary studies. Snihsand Ehdwall (1976) measured F in working mines in Sweden, where F varied from 0.4 to 1, with an average from 37 minesof 0.7. The UK Ionising RadiationsRegulations(IRR) (Health and Safety Executive, 1999) uses an F factor of 0.5 (as assumed in this study) to make dose calculations in homes, while UNSCEAR (1988) suggest that for domestic environments typical equilibrium factor is 0.35. Assessing F in minesand cavescan be difficult asit requiresthe use of expensive and vulnerable electronic devices. The use of, for example, alpha track-etch devices, which are very robust but give only an indication of radon levels, is much more practical. Information on radon concentrationsand the exposure of particular excavators have been obtained in two ways. Thirty-eight closed-cup alpha track radon detectors (sometimes also known as solid-state nuclear track detectors) utilizing CR39 (polyallyl-digilycol-carbonate) plastic were deployed. Such detectors respond to the radon concentration in the surrounding air by recording microscopic tracts following impact by alpha particles. After period of exposure the resultant areal density of tracks on the processed CR39 detector was measured. This density is in proportion to the time-integral of the radon concentration, Bq m_3; thisisin turn equal to the average radon concentration (Bq m_3) over the exposure period, multiplied by the exposure period in hours. In these detectors, the CR39 plastic was enclosed in small chamber into which gases could diffuse but from which radon daughters and dust particleswere excluded. Such detectorsaccording to, Haworth and Miles(2002), have an error margin of 710% at 400 GBq m_and 75% at 700 GBq m_3.

Two of these detectors were not recovered at the end of the study period. This represents recovery rate of approximately 95% which ishigh compared with other cases examined by the authors. Overall, the 38 detectors were placed to include asmany potential causesof variation in radon concentration as possible, including the faults and soil surface of the rain forest beyond the cave entrance. Exposure of the devices typically took place within protected area of the archaeological reserve (Fig. 2) for the 10–30 day excavation periods. Two devices resting on the SubisLimestone in cave wall cleftswere left for months. One device (07231752)—thought lost—was found in place months later in the following excavation season. The radon levels were then calculated for the exposure period and recalculated for period similar to that of the other detectors exposed for comparative purposes. Three archaeologists—H, M, and located on Fig. 4—kept diariesof their activitieson site in 2001. They were issued with Volalpha personal monitors that were exposed only during actual trench cleaning, excavation, and similar professional activities in three distinct areas of the site (Fig. 2). Exposure doses to these individuals were calculated on the basisof the diaries that they kept (Table 4). These detectors were form of open track-etch detector made of cellulose nitrate film manufactured by Kodak (LR-115) (Cliff and Gillmore, 2001). In houses, these detectors are usually calibrated assuming an equilibrium factor of 0.5 (as assumed by Gillmore et al., 2002). The film of the personal detector, like that of the closed-cup alpha track detectors, undergoes measurable submicroscopic physical damage when struck by an alpha particle, in this case from both radon gasand progeny. 3. Results and discussion Radon concentrations and site details for each detector are set out in Tables1–4 and shown in Figs. 2–4. Table 4 illustrates dose levels, both recorded and estimated. Concentrations were obtained at three separate periods of time. These are also distinguished in Tables1–4and on Figs. 2–4. Additional measurements at similar but not identical locations and at different periods of time are illustrated in Figs. 2 and 3. Reconnaissance monitoring of radon carried out in 1999 (September 4th–November 11th) at two sites in clefts on bedrock along the northern wall of the cave (Fig. and Table 1) indicated concentrations of 100 Bq m_3. Comparisons with other published cave data indicate that these radon concentrations recorded within the cave are low (see data in Gillieson (1996) and Gillmore et al. (2000a, b, 2002), suggesting that no special risk is posed by naturally occurring radon gas to the many visitors to this famous tropical cave, nor to the present research team working there. These initial data compared with that from all the other detectors indicate that radon concentration Is taking place within all the cave infill surficial deposits and within all the soils that have been studied. Radon concentrations beneath rain forest outside the cave were recorded as347 Bq m_in 2001 and m_1463 Bq m_in 2002 (Tables2 and 3, Figs. 1–4) using detectors placed directly on bedrocks immediately associated with geological faults.

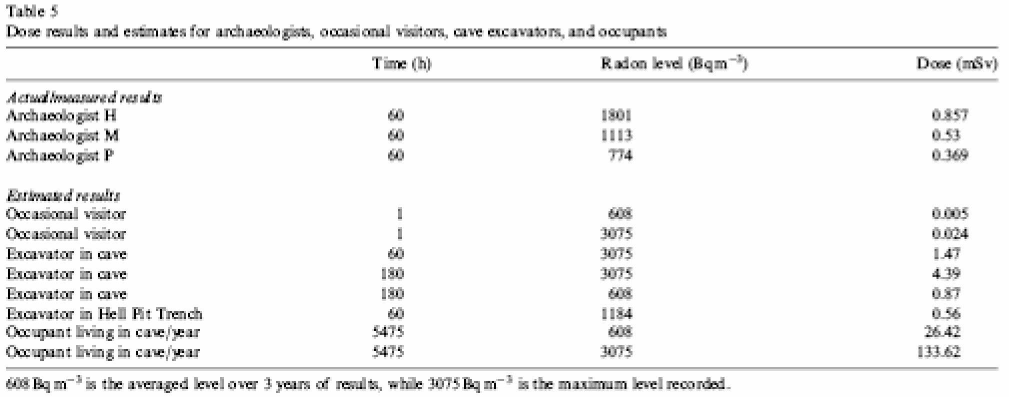


Table 5
Dose results and estimates for archaeologists, occasional visitors, cave excavators, and occupants

	Time (h)	Radon level (Bq m^{-3})	Dose (mSv)
Actual measured results			
Archaeologist H	60	1801	0.857
Archaeologist M	60	1113	0.53
Archaeologist P	60	774	0.369
Estimated results			
Occasional visitor	1	608	0.005
Occasional visitor	1	3075	0.024
Excavator in cave	60	3075	1.47
Excavator in cave	180	3075	4.39
Excavator in cave	180	608	0.87
Excavator in Hell Pit Trench	60	1184	0.56
Occupant living in cave/year	5475	608	26.42
Occupant living in cave/year	5475	3075	133.62

608 Bq m^{-3} is the averaged level over 3 years of results, while 3075 Bq m^{-3} is the maximum level recorded.

The present researchers have not located comparative radon data derived from such tropical forest soils. However, the concentrations of radon gas in soils are controlled by the soils permeability to certain extent (Marley, 2001). The radon evidence suggests that these forest soils, like the cave infill sediments, are acting as local reservoirs for o radon. Radon is also known to concentrate at the surface outcrop of geological faults. Ball et al. (1991) indicated that the presence of major faults might enhance underground fluid flow, which in turn may result in high concentrations of soil-gas radon. For example, Varley and Flowers(1992) noted radon soil gas concentrations as high as900,000 Bq m_near the Sticklepath Fault in Devon. Duddridge and Grainger (1998) sampled radon in soil gas from South Zeal to Lustleigh in Cornwall, UK from 178 points, which gave an average of 101,000 Bq m_3. The highest value, in their study, was 707,000 Bq m_3, recorded on or close to granite intrusion and the Sticklepath Fault. Indeed, Duddridge (1999) proposed that radon soil-gas concentrations can be used to reveal geological faults. There is evidence of radon concentrations fluctuating over time. It is clear that in four cases concentrations have varied by up to 500%; in the other cases more stable situation occurs (Figs 2 and 3; Tables1–3). The contributions of excavation and similar disturbance in this effect are not known at present. Nevertheless, these observed changes in time are not sufficiently large to invalidate basic model of spatial patterning described below that often appears to relate primarily to the excavated microtopography and shelter. Radon concentrations associated with open-area excavations or distorted surficial sediments (i.e., with Units2C, 3, 3R, 4, 5) vary from 174 to 849 Bq m_3. The i removal of surface algae or surface crusts through either local cleaning of excavated faces or shallow excavation did not appear to make any impact on the detected concentrations of radon (Fig. 3; Tables1–3). Also, in the limited evidence available there are no clear indications that radon concentrations in such excavated or disturbed areas differ on the top surface of plinths of surficial sediments from those in surrounding areas (Figs. and 3; Tables1–3). Radon concentrations determined in the sheltered and actively excavated Unit in Hell Trench were found to be markedly higher than those in the surrounding areas (Figs. and 3, Tables1–3). The lowest concentration in such confine was not especially elevated at 453 Bq m_3, but the largest concentration 3075 Bq m_was substantially higher than any recorded in the surrounding area. Indeed radon concentrations in these deep and confined areas were typically in the range 900–1100 Bq m_3. conservative reading of these reconnaissance data suggests that radon concentrations in such confined, poorly ventilated excavations can be higher than those in the surrounding sites, in essentially similar materials, by factor of or more. Several of these trends are especially evident in spatial analysis presented in Fig. 3. The notably higher concentrations that exist within the Hell Trench shelter are emphasized in the spatial analysis—again suggesting the significance of poor ventilation, deep trenches, and active excavation at the site. This map of radon concentration across the archaeological reserve also suggests that no clear patterns exist at the open sites on Units2C, 3, 3R, 4, and beyond the Hell Trench excavation and shelter. Radon concentrations were neither notably raised nor lowered adjacent to the cave wall. There were no evident changes in radon concentration with increasing proximity to the cave mouth. In brief, local spatial variations outside the shelter are evident, but they have no clear associations. This might be because of local, regularly occurring—and perhaps seasonally and meteorologically dependant-patterns of turbulence or air composition in the sampled areas. The meteorological conditions were different enough during the sample periods to account for perhaps some of the variability between replicates in the different seasons. These spatial relationships are also partially reflected in the concentration data from the personal dose meters (Table 4). Excavator working at the eastern margin of the site returned Volalpha reading that translates to 774 Bq m_ while he was excavating adjacent to CR39 detectors that recorded 414 and 628 Bq m_(Fig. 4). The notably higher concentration equivalent of 1113 Bq m_was recorded by excavator who was active in the cleaning and excavation of materials in the deep Hell Trench beneath its shelter. This simple relationship between maximum exposure and confined deep excavations only partly holds for worker H. Thisperson recorded the highest radon concentration. He had excavated near vertical exposure of surficial archeologically rich sediments by cave wall that was above buried subterranean swallow hole at (Fig. 4) and in moderately confined location produced by 5–10- wide overhang of limestone bedrock. The reasons for the small-scale and local differences between the personal detectors and static collectors at any one site are unknown at present. One factor at might be that enhanced radon seepage from the swallow hole into the static collector was effectively entering in quiet air whereas the Volalpha personal detector was in air that was disturbed and diluted by the activity of the excavator. Using the data from the CR39 detectors, if we assume maximum radon gas level in the atmosphere of 3075 Bq m_3, the effective dose received in mSv can be calculated (after Gillmore et al., 2001a) using the following formula and an equilibrium factor of 0.5: Effective dose ðmSVÞ ¼ Rn concentration; Bq m_Þ_ðduration; hoursÞ: 126; 000 This means that in an environment recording 3075 Bq m_3, the effective dose received would be 0.024 mSv per hour. If worker worked for 10 days at per day that would be total dose of 1.47 mSv. Alternatively an excavator working for 30 days at per day would receive dose of 4.39 mSv (see Table 5). This dosage is significant if it is taken in the context of the Ionising Radiations Regulations of the responsible UK Government Agency (Health and Safety Executive, 1999) that suggest dose limits per year for member of the public of mSv. The IRR also specify an Action Level of 400 Bq m_averaged over 24 h, which, in the overground workplace, Denman et al. (1999) showed would result in dose similar to radiation worker's limit of mSv. However, the assumption that radon is levels would be constently at the maximum level recorded in this study is unlikely. If instead an average radon level of 608 Bq m_istaken for the cave entrance asa whole and calculated from all years of data (and readings taken outside the cave system are excluded), then calculations indicate that if an excavator attended three 10-day excavations in three yearsat exposure per day (total of 180 h), the dose received would be 0.87 mSv (see Table 5). This is below the IRR recommended maximum dose per year for member of the public. Each 10-day excavation exercise provides an exposure of 0.289 mSv per annum. However, if worker worked in Hell Trench pit for period of 10 days (based on the higher average radon levels of 1184 Bq m_noted in this trench compared to levels in ethe cave asa whole), their dose would in theory be 0.56 mSv, if calculated from the CR39 detector data (Table 5). This is over half the dose recommended in the UK for member of the public in year, but it hasbeen received in only 10 days. The dosemeter and diary for indicates working in radon levelsof 1801 Bq m_for over 60 h, which givesa calculated dose of 0.857 mSv. The dosemeter for M, who worked mostly in Hell Trench pit, suggests radon levels of 1113 Bq m_and dose of 0.53 mSv over 60 (Table 5). These are less than would be expected from the CR39 detectors. person ''living'' in the cave over the course of year, assuming 15 occupancy per day, is calculated to receive dose of 26.42 mSv, based upon an average radon gaslevel of 608 Bq m_3, following the CR39 data. This is a very high dose and is above the 20 mSv maximum dose for an UK classified worker. It is over that of the recommended limit for an UK radiation worker and 26 times greater than the limit suggested for member of the public. If levels were at the maximum level recorded then the dose would be 133.62 mSv, an unlikely but possible scenario, equivalent to an excess risk of 0.0045 lung cancers or in 200 risk. This has implications for the cave guards, who do live in the cave, and legal guano collectors who spend significant periods in the cave. Friend (1996) has estimated the approximate risk of death from exposure to radon experienced during ‘‘standardized single’’ caving trip. It was assumed that typical caving trip would last and lead to dose received of 0.1 mSv. risk relationship of 0.056 chance of death per Sv estimated from ICRP (1993) suggested that typical trip would create chance of the order of in 1,000,000 of dying from lung cancer induced by exposure within the cave. Friend (1996) suggested that the risk of death to recreational caver from an ‘‘accident’’ within cave during trip is around 25 in 1,000,000. However, his comparison of radon-induced death with accidental death may not compare readily with the risks to archaeological excavators within caves. In an archaeological excavation, for example, the risk of death by accidentsisprobably lower than that employed by Friend (1996), while the exposure time may be far greater. Friend’s(1996) estimation of death from radon-induced cancer in cavershouldstrue only for the average radon level that he has suggested for UK caves, based in part on maximum value of 46,080 Bq m_ in the Peak District. Gillmore et al. (2001a, b, 2002) clearly demonstrated that radon levels in such environments can be far higher than the maximum that he records, based on Hyland (1995). Thus the average for UK caves may be much higher than Friend (1996) assumes in his estimations. Such comparisons of the risks of excavation, exploration, and habitation for the Niah caves, as elsewhere, awaits user data upon which to base an estimation. The sources of the radon detected in Niah Cave are at present not clear. It appears likely from the present evidence that radon is diffusing up along geological faultsfrom granitic or other mineralized rock sources located well below the ground surface. It is also possible that oil-rich fluids containing radon gas squeezed out of the adjoining clastic rocks (particularly shales) by tectonic activity may also be important. In addition, the physical properties of the guano might be locally significant. The guano within the cave is visibly porous and likely to be permeable to gases and fluids. Dykes (pers comm. to COH, 2003) notes that the KSAT properties of the guano are very high, approximately equivalent to medium sand. It is biological concentrate likely to contain traces of uranium since it includes the remains not only of insects eaten by bats and birds but also of fruit, pollen, other vegetable matter, and especially the corpses of many of the bats and swifts themselves. Nevertheless, despite these uncertainties concerning provenance and concentration, overall radon concentrations in this cave are low by world standards. They pose little risk to the occasional visitor to this famous cave (see Table 5). 4. Conclusions In this reconnaissance study of radon concentrations in the Great Cave of Niah in Sarawak, excavators working in relatively deep pits and trenches in surficial deposits that are largely covered by protective shelters causing poor ventilation are shown to be working in microenvironment in which radon concentrations can exceed those of the surrounding area by factor of two or more. Limited evidence from personal dosemeters supports this view. Local variability in radon concentrations through time and space has been observed and awaits further investigation. Overall, radon concentrations in this famous cave are very low by world standards. It is clear that they pose no special threat to its visitors but the cave guards and guano collectors may well be at some considerable risk.

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