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ORIGINAL PAPER

Radon concentrations in the Sudwala cave, South Africa

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Abstract

There has been a growing interest in the effect of radon gas on humans visiting caves. A radon survey was consequently done in the Sudwala tourist cave close to Nelspruit in the eastern part of South Africa to determine the radon exposure of tourists and guides. The Sudwala cave, which evolved in karst geology, is a popular tourist destination. Twenty-eight electret ion chambers were placed in various locations throughout the cave for a period of 24 h. Radon concentrations varied between a minimum of 255 Bq/m^3 and a maximum of 1822 Bq/m^3 with a geometric mean of 750 Bq/m^3. The radon levels were found to be relatively stable up to 600 m from the entrance, after which they sharply increased. This suggests that different processes disperse radon in the initial and deeper parts of the cave. It was concluded that this is the result of natural cave ventilation which is caused by changes in ambient barometric pressure. Despite the measured level being higher than the World Health Organization (WHO)'s mitigation level of 200 Bq/m^3, the occupational exposure is quite low due to the frequency and duration of a typical cave tour and therefore poses no risk to the tourists and tour guides.

Keywords Radon · Cave · Geology · Exposure risk · EICs · Cave breathing

Introduction

Radon gas (^{222}Rn) is an odourless and colourless radionuclide in the decay chain of natural uranium (^{238}U). Radon has a half-life of 3.8 days after which it decays to various alpha, beta and gamma-emitting nuclides. Radon is constantly produced as all rock types contain natural uranium in varying concentrations. High concentrations of uranium in lithology are consequently a major factor that contributes to a high radon potential (Smethurst et al. 2017). The radon nuclide escapes its parent material during the decay process, and radon buildup can readily occur in enclosed areas, such as buildings and natural cavities. Humans occupying these spaces then inhale the radon, which significantly contributes to radiation exposure of the lung tissue. Radon gas and its short-lived products are estimated to be the second largest cause of lung cancer, after cigarette smoke (Pavia et al. 2003) and the WHO recommends action to be taken when indoor radon concentrations exceed 100 Bq/m^3 (WHO 2009).

Natural caves consist of enclosed chambers, passages and tunnels that are surrounded by exposed rockfaces. The poor ventilation in many caves, combined with the exposed rock, creates an ideal environment for radon buildup. Caves worldwide therefore demonstrate very high radon concentrations with mean values well above 500 Bq/m^3 and maximum values running into thousands of Bq/m^3 (Nemangwele 2005).

The Sudwala cave, situated 30 km from Nelspruit in Mpumalanga, South Africa, was formed in a karst system that originated in Pre-Cambrian dolomite lithologies (Green et al. 2015). The soft carbonate rock units dissolved, forming the cave which has a matrix of grid-like tunnels and chambers. The typical geology of the cave is shown in Fig. 1. Dolomite generally contains low concentrations of uranium, commonly in the order of 2 ppm (GEOROC 2021). The predominant dolomite lithology of Sudwala, therefore, suggests that radon levels in the cave could be moderate; however, there are no available records to indicate the radon levels for the Sudwala cave.

The Sudwala cave has a long history of human activity starting with the likely occupation of prehistoric man. During the nineteenth century Somquba, the son of Swazi king Sobhuza, and his followers occupied the cave for

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Fig. 1 Photos of the typical geology found in the tourist area of the Sudwala caves

safety from rival groups. The caves were also used as an ammunition store by the Boer forces during the Second Anglo-Boer War of 1900. In 1965, the caves were finally developed as an attraction and are currently a popular tourist destination in the area (Boshoff 2012).

The cave layout is shown in Fig. 2. Relatively high volumes of tourists frequent the first section of the cave that ends at Fairyland. The second section of the cave is only entered by visitors on the extended tours that need to be pre-booked. These tours only occur once or twice a month and end at the Crystal Chamber. The furthest point of this chamber was dubbed the Sand Chamber. The third section of the cave leading up to Cathedral Aven, located on the far right of Fig. 2, is closed to the public. This study aimed to determine the radon concentrations in the first two sections of the cave and draw conclusions as to the exposure risk to the public and tour guides.

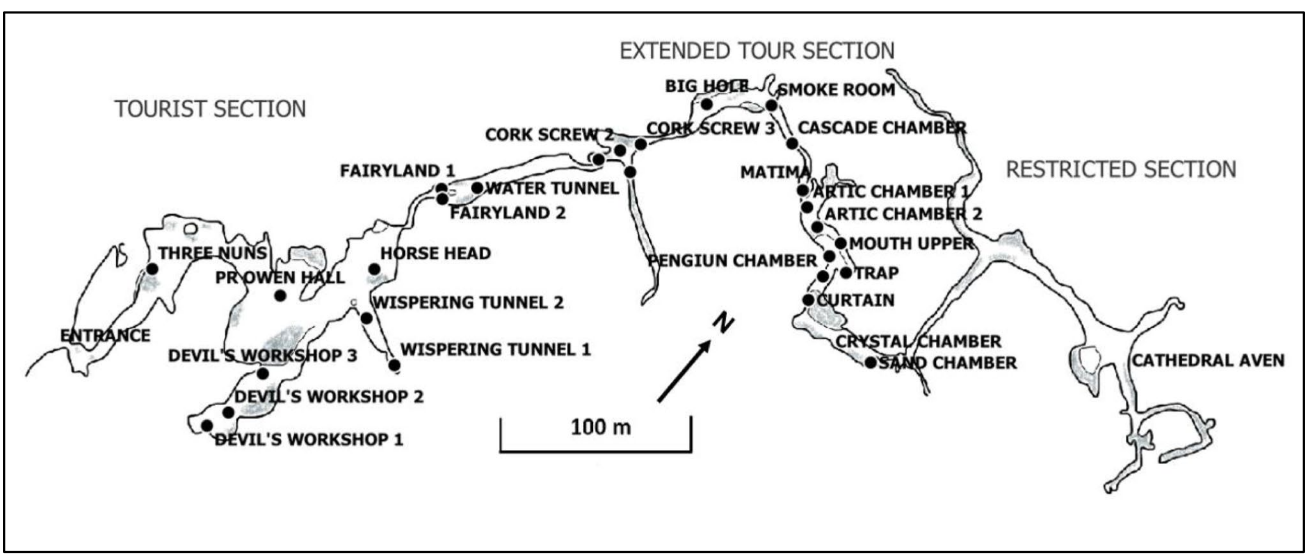

Fig. 2 A map of the Sudwala cave demonstrating some of the main features. The figure was adapted from a map by Jackson (1969). The placement of the electret ion chambers (EICs) is also indicated with black dots

Method

Description of the cave and measurements

Electret ion chambers (EICs) from Rad-Elec Inc, called E-PERM™, were used to determine the radon concentrations at various locations throughout the cave. The initial potential of each electret was measured using a surface potential electret voltage reader (SPER), also from Rad-Elec Inc., before entering the cave. The electrets were carried to the end of the extended tour section of the cave. Different locations for the EICs were identified based on occupancy, surrounding geology, as well as its potential to accumulate radon gas. The EICs were then placed in these locations on the way back to the cave entrance. In total twenty-eight EICs were deployed at the locations also indicated in Fig. 2. In each of these locations, the EICs were placed at least 1 m away from walls and on top of the geological formations.

The deepest accessible chamber of the tourist section of the cave, and the first chamber where electrets were placed, is called the Crystal Chamber. As seen in Fig. 3, this chamber primarily consists of aragonite ($CaCO_3$) crystals. Due to the low concentration of radium (^{226}Ra) in these crystals (Potapov et al. 2020), low radon emission was expected in this chamber. However, the furthest part of this chamber named the Sand Chamber in Fig. 2 had a sand-like substrate on its floor. An EIC was therefore rather placed here to determine if the composition of the substrate elevates the radon concentration. An EIC was also placed in the area leading into the Crystal Chamber, named the Curtain, to determine the radon potential entering the chamber.

A narrow passageway connects the Arctic and Crystal Chambers. This is referred to as the Penguin Chamber, and since the narrowness of the chamber could lead to elevated radon levels, an EIC was also placed here. The Artic Chamber has an elevated ceiling, and three EICs were deployed at different heights. Radon gas is approximately 7.5 times heavier than air, and the three EICs would therefore determine its accumulation from the bottom of the chamber. An EIC was also again placed at the entrance of the chamber. Due to the teeth-like structure of the rock formation on the roof of the Artic Chamber, the placements of the two EICs in this chamber were named Mouth Upper and Mouth Lower, respectively. As their names suggest, these EICs were also placed on different levels to determine the radon concentration at different levels in this chamber. Two routes can be followed from the Arctic to the Penguin Chamber. The first is where the Mouth Upper EIC was placed. The second route, an extremely narrow passageway at the bottom of the chamber, can be followed by the more adventurous spelunker, but at the risk of getting trapped. This location was therefore named the Trap, and an EIC was also placed here due to the narrowness of the chamber, which could elevate radon gas concentrations.

Fig. 3 Photos of the aragonite ($CaCO_3$) crystals found in the furthest chamber of the Sudwala cave, the Crystal Chamber

Obtaining access to the Arctic Chamber requires crawling through a challenging passageway filled with water, and up a slippery incline. This area was therefore named Matima, a Swati word loosely translated as meaning "challenging" or "difficult". An EIC was placed in this passageway since its intricacy could elevate radon concentrations. Leading to this area is a series of narrow passages called the Cascade Chamber, presumably named after a series of cascading rockfalls from the ceiling. This characteristic is also prevalent in the chambers leading up to the Cascade Chamber. The area referred to as the Big Hole in Fig. 2 is an exceptionally large chamber, but the area is only traversed via a small passage beneath rockfall from the ceiling. Since the cascading rockfall could trap radon gas in the lower parts of these chambers, EICs were placed along the passages of the Cascade Chamber and in the Smoke Room, a passage connecting to the Big Hole. The high ceiling of the Big Hole will prevent the buildup of radon gas. An EIC was therefore also placed here for comparison.

The Cork Screw is a series of winding passages with the potential to accumulate radon. This area also has a narrow side passage where radon can accumulate. Due to the intricacy of these passages and their potential to accumulate radon, four EICs were deployed in this area.

Connecting the end of the general tourist area of the cave, Fairyland, to the extended tour area is the Water Tunnel, named after the water that accumulates at the bottom of the tunnel during the rainy season, and the Dental Chamber. The latter is named after the teeth-like stalactites that are formed on the ceiling of the chamber. An EIC was placed at the end of this chamber, just before the series of passages that constitutes the Cork Screw, and one on a man-made wall that separates Fairyland and the Water Tunnel. This was to measure the radon potential of these passages and to determine if any of this gas is transported into the Cork Screw section through ventilation.

Even though the general tourist portion of the cave is generally more open, and the cave entrance mitigates the buildup of radon gas, this area has a high tourist occupancy. The EICs were therefore placed more liberally to determine the potential health risk of this area. Two were placed in Fairyland between two rock formations separated by a water puddle. The narrow space between the two rock formations not only increases radon potential, but the gas is also water-soluble and can accumulate in water from underground sources—such as the puddle found in Fairyland.

Fairyland is separated from the rest of the tourist area by a tunnel. At the entrance of the tunnel is a piece of flowstone resembling a horse's head, seen in Fig. 4, and a narrow horizontal passage called the Whispering Tunnel. Even though the carbonate contents of limestone typically have low uranium levels, and therefore low radon emanation, an EIC was placed here due to the location of the formation in the cave. Two EICs were also placed at different locations in the Whispering Tunnel due to a slight draft felt coming from it, which has the potential to carry radon gas.

The PR Owen Hall, named after the cave's previous owner Philippus Rudolf Owen, is the cave's largest known chamber, measuring 70 m across and 37 m high. It is used as an amphitheatre, capable of housing a seated audience of up to 500 people. Only one EIC was placed on the steps of the amphitheatre due to the size of the chamber preventing the buildup of radon gas. A staircase connects the PR Owen Hall to the Devil's Workshop, located at the top of the amphitheatre. It is the warmest part of the cave with an average temperature of 24 °C. The elevation of the chamber also leads to the buildup of CO_2 gas and 100% humidity. Despite the health risks associated with excessive CO_2 levels, the EICs used in this study cannot be used to determine its concentration. An EIC was nonetheless placed in the back of the Workshop to determine if any of the geology found in this chamber has excessive radon emanation. Two EICs were also placed on the pathway leading from the PR Owen Hall to the Devil's Workshop.

Fig. 4 A photo of the flowstone resembling a horse's head found at the tunnel leading to Fairyland

The last EIC was placed at the Three Nuns, named after the shadow the formation casts on the wall which looks like three nuns kneeling in prayer. This formation is found on the way to the cave's entrance, and a low radon level is therefore expected here.

The EICs were left for 24 h, whereafter their final potentials were measured. This short duration was selected due to the potential of exceptionally high radon concentrations that could be found in the cave. The difference in potential was then used to calculate the airborne radon concentration using the expression

$$RnC = \frac{(V_i - V_f)}{(T)(CF)} - BG \tag{1}$$

with RnC the airborne radon concentration, V_i and V_f the initial and final electret potentials respectively, T the deployment time in hours, CF a linearization coefficient (Kotrappa et al. 1990) and BG the radon concentration equivalent of natural gamma (γ) radiation background. A background radiation correction was made by assuming a typical gamma radiation of 32 Bq/m^3 (Shahbazi-Gahrouei et al. 2013).

Radon map

All the radon measurements were interpolated by the Inverse Distance Weighting (IDW) interpolation function of QGIS. Adelikhah et al. (2021) found IDW more suitable for predicting mean indoor radon concentrations due to the lower mean absolute error (MAE) and root mean square error (RMSE). A graduated red colour ramp based on quartile intervals was selected for the layer. The interpolated radon concentration layer was then constructed and overlaid on a map of the Sudwala cave.

Results and discussion

The airborne radon levels determined from the potential differences of each electret are listed in Table 1. Also listed are the uncertainties, estimated using the expressions given in Kotrappa et al. (1990). The interpolated map of these concentrations superimposed on a map of the cave is shown in Fig. 5. As illustrated, the deeper regions of the cave exhibited elevated concentrations of radon gas. The Sudwala cave only has one discovered opening, which could cause poor ventilation in the deeper parts of the cave. This could

Table 1 A list of the calculated airborne radon levels at the different cave locations

Location	Measured radon concentrations (Bq/m^3)
Trap	1500 ± 75
Sand Chamber	1822 ± 91
Curtain	1355 ± 68
Penguin Chamber	1446 ± 72
Mouth Upper	1179 ± 59
Mouth Lower	1320 ± 66
Artic Chamber 1	913 ± 55
Artic Chamber 2	855 ± 51
Matima	689 ± 41
Cascade Chamber	597 ± 42
Smoke Room	564 ± 39
Big Hole	626 ± 44
Cork Screw 3	588 ± 41
Cork Screw 2	549 ± 38
Cork Screw 1	491 ± 39
Water Fountain	1637 ± 82
Dental Tunnel	469 ± 33
Water Tunnel	406 ± 36
Fairyland 1	499 ± 35
Fairyland 2	495 ± 35
Horse Head	538 ± 38
Whispering Tunnel 1	362 ± 33
Whispering Tunnel 2	482 ± 34
Devil's Workshop 3	503 ± 35
Devil's Workshop 2	343 ± 31
Devil's Workshop 1	323 ± 32
PR Owen Hall	255 ± 28
Three Nuns	255 ± 28

lead to the buildup of radon gas in these areas. It was also found that some of the narrower halls, chambers and tunnels enhanced the accumulation of radon, thus leading to elevated levels in these areas. This phenomenon can also be observed in Fig. 6, where the interpolated radon concentrations are shown superimposed on a side view of the cave.

Listed in Table 2 are the results of similar measurements performed in caves around the world. As can be seen, the minimum concentration of 255 Bq/m^3 measured in the Sudwala cave is comparable to the minimum levels found by these studies. For radon gas in dwellings, the World Health Organization (WHO) advises that mitigation should take place when concentrations exceed 200 Bq/m^3 (WHO 2007). This is primarily due to the extended exposure of a typical inhabitant. Concentrations exceeding 300 Bq/m^3 are considered critical. Since the levels measured in the front of the cave are between these guidelines, the radon gas concentrations found here are generally considered not to be hazardous to the health of tour guides and tourists—especially considering the short periods spent in these areas during a typical tour. The maximum radon level measured in the Sudwala cave is also significantly below those measured in the caves listed in Table 2. Even the geometric mean of 750 Bq/m^3 measured in the Sudwala cave is well below most caves listed in Table 2. The exceptions are the winter and spring measurements in the 57-show caves in Australia. The low concentrations found in the Sudwala cave can be attributed to the generally low concentrations of uranium found in Dolomite (Bell 1963).

Even though the general radon concentrations measured in the Sudwala cave are not particularly high when compared to the levels listed in Table 2, they did show significant spatial fluctuations. The entrance to the cave is fitted with a gate with metal bars and, as such, has constant ventilation during the day and at night when the gate is locked. This reduces the radon concentration found at the entrance. This effect can be observed in Fig. 7 which graphs the change in radon concentration as a function of the distance from the entrance of the cave. At 200 m from the entrance, a slight increase in radon concentration can be observed at the entrance to the PR Owen Hall. The radon level then stays nearly constant up to the Cork Screw junction, approximately 600 m into the cave. From there, a sharp and constant increase can be observed up to the Sand Chamber where the last measurements were taken. However, as also seen in Figs. 5 and 6, the narrow section leading up to the Cork Screw did exhibit elevated radon levels compared to the previous chambers. It is suspected that these levels emanated from a side tunnel leading into the Cork Screw, but no measurements were done here due to its difficult access.

As can be seen from Fig. 7, there is an exponential rise in radon concentrations after 600 m, suggesting a different mechanism of radon diffusion in the deeper part of the cave. As alluded to in Table 2, the maximum and minimum radon values of most caves are strongly dependent on the season. Low radon concentrations are typically measured during the warmer parts of the year, with higher concentrations typically measured during the colder periods (Anderson et al. 2021). This phenomenon is attributed to "cave breathing", which is a natural form of ventilation that occurs due to the difference in barometric pressure between the cave and the surface (Deike 2015). Due to their size, many caves have their own pressure systems, which they try to normalize with the pressure on the surface (Wigley 1967). The pressure on the surface varies with temperature. If the pressure rises due to an increase in temperature, outside air is forced into the cave thereby reducing the mean radon concentration. When the surface barometric pressure falls, the air is expelled from the cave. This process brings radon-rich air from the deeper parts of the cave closer towards the entrance enhancing the mean radon concentration.

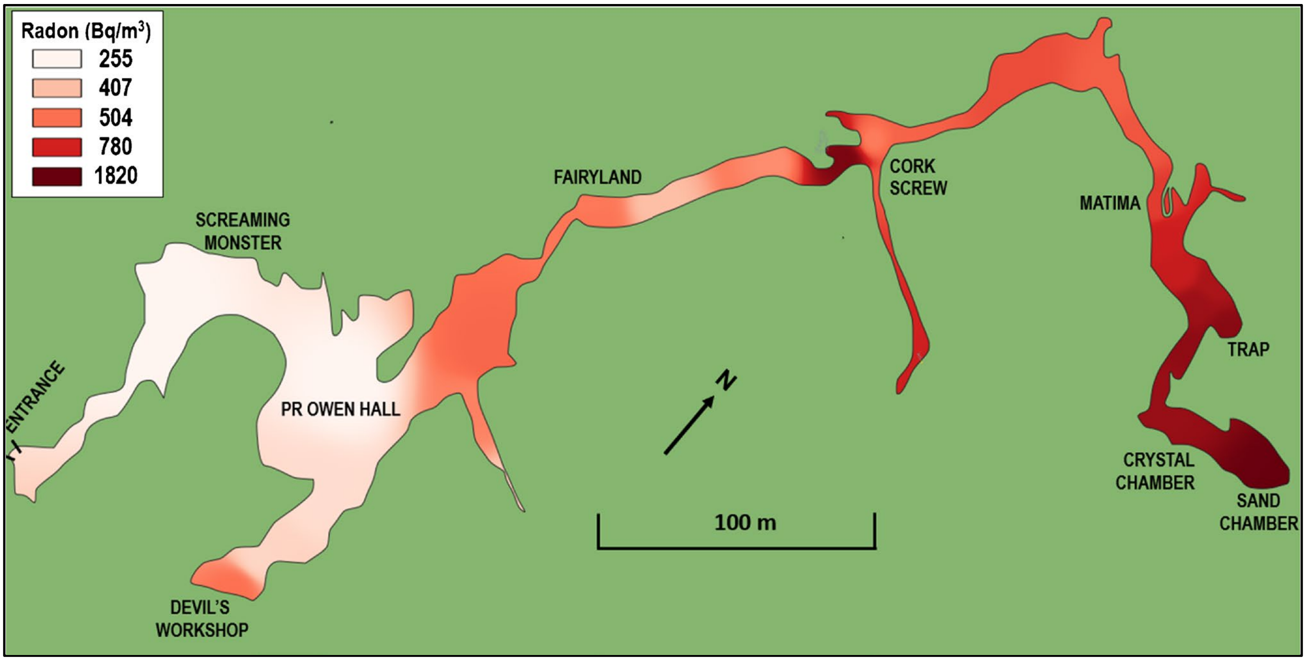

Fig. 5 A radon map of the first two sections of the Sudwala cave. As can be seen, the deeper caverns have higher accumulations of radon gas. The localized buildup of radon gas was measured in narrow chambers and tunnels

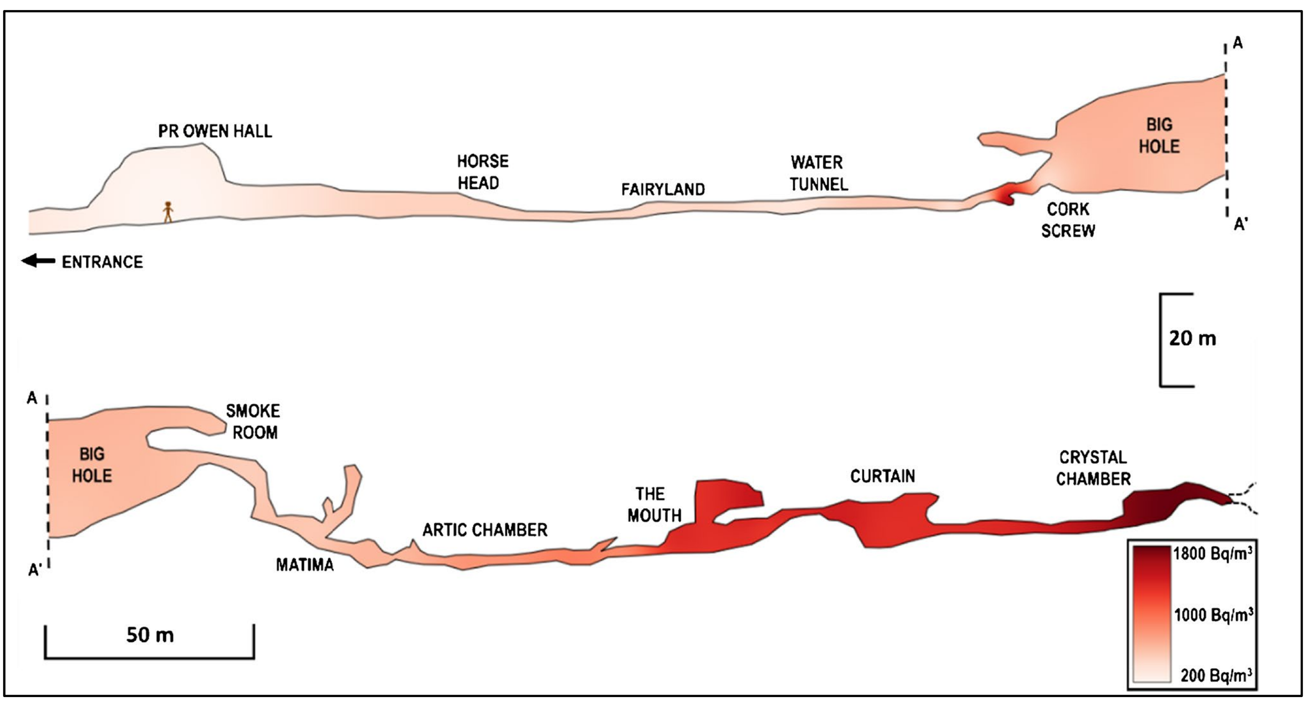

Fig. 6 A side view of the first two sections of the Sudwala cave illustrating the interpolated radon levels. The caverns with lower ceilings allowed radon to accumulate, leading to elevated levels. As expected, the larger chambers measured lower radon concentrations due to their elevated ceilings

It is this effect of cave breathing that diffuses radon in the Sudwala cave. The area around Sudwala has a very moderate climate, resulting in a very stable cave temperature of 17 °C all year round. The first 600 m leading from the cave entrance is well-ventilated due to its wide mouth and large chambers located here. Large volumes of

Table 2 A list of published radon concentrations (Bq/m^3) in caves from different parts of the globe

Country	Number-type of caves	Rn concentration (Bq/m^3)			References
		Min	Max	Mean	
Australia	57-show caves			6330 (annual); 500 (winter); 795 (spring)	Solomon et al. (1996)
Greece	Perama cave			1311 (winter); 925 (summer)	Papachristo-doulou et al. (2004)
Ireland	3-show caves	488	11,285	2040; 5590; 7400	Duffy et al. (1996)
Poland	2-caves	100	3600		Przylibski (1999)
Slovenia	10-caves			2350 (summer) to 27,000 (winter)	Jovanovic (1996)
UK	3-recreational caves	32	12,552		Sperrin et al. (2000)
UK	Limestone	27	7800		Gillmore et al. (1999)
North-Spain	Ultamira cave	186	7120	5562 (summer)	Lario et al. (2005)
Venezuela	Show caves	100	80,000		Sajo-Bohus et al. (1997)
South Africa	3-tourist and adventure	255	1822	750 (winter)	This study

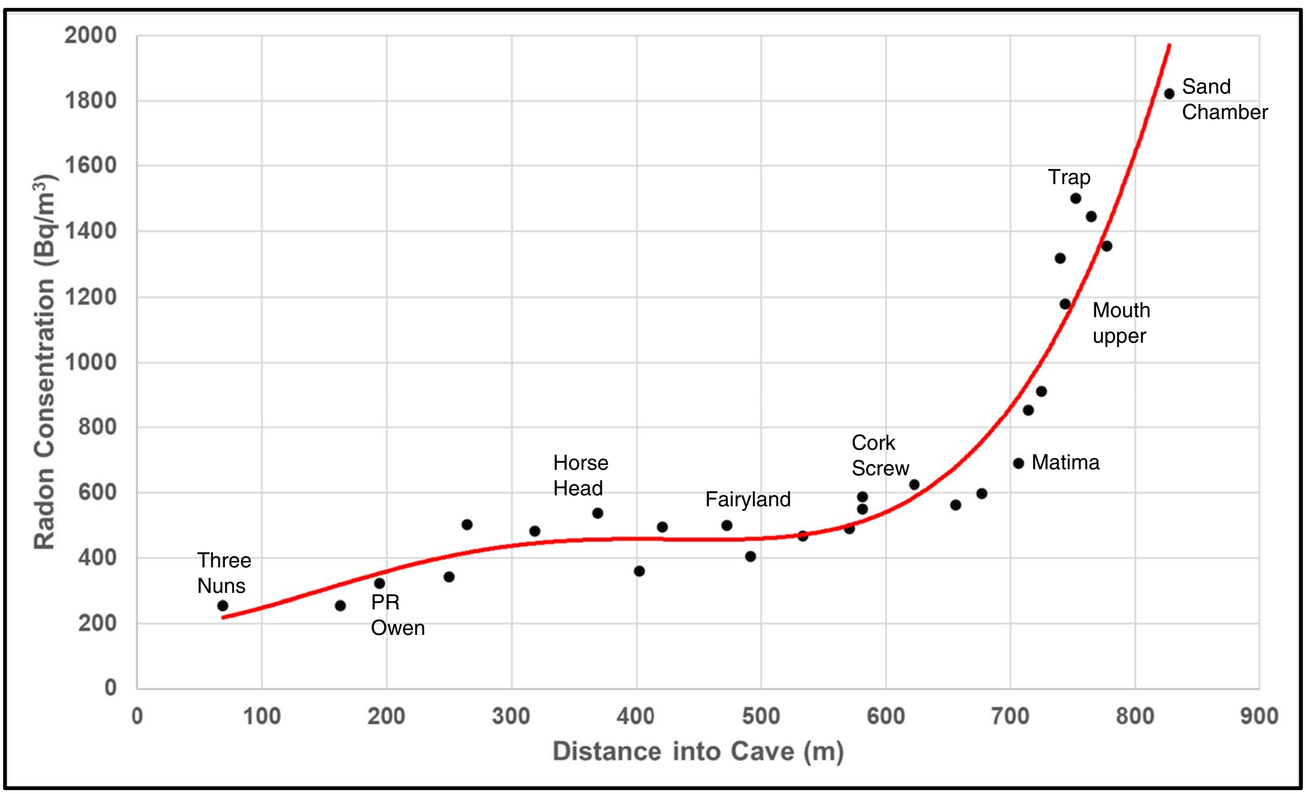

Fig. 7 A graph showing radon concentrations as a function of the distance from the entrance of the cave

low-concentration radon air are therefore forced into these areas of the cave when outside pressure changes occur. The latter part of the cave, past the Cork Screw, is also characterized by large chambers, but ventilation in this part is inhibited by the narrow water tunnel that links these inner chambers to the first part of the cave. It is consequently evident that the inner section (past 600 m) of the cave demonstrates a sharp increase in radon concentrations, as was seen in Fig. 7.

Conclusions

Radon concentrations in the Sudwala cave were determined by placing electrets at various points in the system. The results demonstrated that the Sudwala cave, which has only one opening, has poor ventilation, especially in the deeper parts of the cave. The average radon concentrations found in the Sudwala cave are well within the ranges determined for other caves in the world. Its maximum radon concentration, however, was found to be below that of these caves. The lowest radon concentration in Sudwala was measured at the entrance of the cave, which compares well to the typical concentration found in dwellings. The variation and the exponential increase in radon concentration in the deeper parts of the cave were influenced by the lack of ventilation, with "cave breathing" diffusing radon gas between the different parts of the cave. These results confirm the findings in a similar karstic cave in South Africa, where the distance from the entrance caused changes in the concentrations of radon gas (Nemangwele 2005). The difference in average radon levels in the Sudwala cave can therefore be attributed to two processes that influence radon levels, before and after the Cork Screw. A further investigation into the distribution of radon concentrations in the Sudwala cave with other environmental factors should be considered.

An average tour of the Sudwala cave takes approximately an hour to complete, with the crystal tour taking up to 4 h. The mitigation level of 200 Bq/m^3 stipulated by the WHO, and the hazardous level of 300 Bq/m^3, are based on the occupational exposure by the inhabitant. In this instance, the exposure of tour guides and tourists to the cave, and the duration of the exposure are quite low. The measured radon concentration in the cave, therefore, poses no potential health risk.

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Data Availability All data used to support the findings of this study is contained in the article.

Declarations

Conflict of interest The authors declare no competing interests.

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