Radon survey in caves from Mallorca Island, Spain

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Abstract: This study reports radon concentration in the most representative caves from Mallorca, to identify those in which the recommended action level is exceeded, thus posing health risks. Two show caves (Campanet and Artà) and three non-touristic caves (Font, Drac, Vallgornera) were investigated. Data were collected at several locations within each cave for three different periods covering one calendar year, from March 2013 to March 2014. Except for Vallgornera, where only one monitoring period was possible, and Artà in which low values were recorded throughout the year, a clear seasonal variability, with higher values in the warm seasons and lower in winter time is conspicuous in all caves. Radon concentrations differed markedly from one cave to another, as well as within the same cave, ranging from below detection limit levels up to 3060 Bq·m^{-3}. The results of this study have significant practical implications, making possible to advance some recommendation for cave administrators and other agencies involved in granting access to the investigated caves.

Keywords: radon concentration, track-etched detector, cave, exposure, health hazard, Mallorca

1. Introduction

Radon (^{222}Rn) activity concentration in caves has been extensively studied all over the world, particularly in the past two decades (Pinza-Molina et al., 1999; Cigna, 2005; Sainz et al., 2007; Alberigi et al., 2011; Somlai et al., 2011). The research related to the presence of this noble gas in caves focuses on two main areas: 1) radiation protection, since caves are enclosed spaces where radon can accumulate to harmful levels (Lario et al., 2005; Thinová et al., 2005; Sainz et al., 2007; Bahtijari et al., 2008; Dumitru et al., 2015), and 2) the use of radon as tracer of underground airflow (Hakl et al., 1997; Gregoric et al., 2011; Valladares et al., 2014). Because the carbonate rocks in which most caves reside have high secondary porosity (conduits, fractures, etc.), ^{222}Rn can be used as an excellent tracer for air movement within a cave, providing valuable information about cave topoclimate, possible active faults, volcanic and seismic activities, earthquake prediction in the cave surroundings, etc. (Racoviță, 1975; Hakl, 1997; Kowalczk & Frolich, 2010).

Knowing that exposure to natural sources of radon has become a significant issue in terms of radiation protection, the health effects caused by its inhalation prompted us to conduct this survey. Radon represents the greatest source of radiation dose (Synnott, & Fenton, 2005) and it is considered the second most important cause of lung cancer after smoking (Alberigi et al., 2011). The results of epidemiological studies show a strong correlation between radon exposure and lung cancer occurrence (Darby et al., 2006). Once inhaled, along with its decay products (polonium, bismuth and lead isotopes) can cause major genetic damages to lung tissues, with dramatic subsequent biological effects (Trută et al., 2014). Decades of studies on radon's health effects revealed the importance of its indoor concentration monitoring.

Concerns about ^{222}Rn exposure are usually related to its concentration in dwellings and workplaces, where people spend most of their time (Sainz et al., 2009). Lately, underground places, representing particular work spaces (mines, caves, storage facilities, etc.), drawn the attention of worldwide scientists. Among these, karst caves are one of the most interesting, in terms of potential human exposure to radon. Although limestone has very low uranium content, ^{222}Rn in caves can reach significant high levels due to poor ventilation (Thinová et al., 2005) and/or high concentration of ^{226}Ra in rocks beneath limestones. A review on radon concentrations in a large number of caves from different countries was published by Field (2007). The data compiled vary from close to ambient level up to 155,000 $Bq \cdot m^{-3}$. Many recommendations concerning indoor radon concentration were issued and recently, an action level of 300 $Bq \cdot m^{-3}$ in workplaces was strictly enforced by the Council Directive of the European Union (2013/59/Euratom) on basic safety standards for protection against the dangers arising from exposure to ionising radiation (Euratom, 2013).

The most exposed people to potential health effects due to substantial levels of ^{222}Rn in caves are the employees working as tour guides, as well as other cave employees (train drivers, electricians, maintenance workers, souvenir vendors, etc.), who are spending most of their working hours underground (Field, 2007). In addition, potential health risk also exists in wild caves, less studied from this point of view, in which knowledge of the radon concentration might be relevant for cavers and scientists (geologists, mineralogists, palaeontologists, etc.). For instance, the time spent by cavers exploring and surveying large cave systems may, in some cases, reach hundreds or even thousands of hours. Scientists are also spending a good amount of time while collecting and documenting the samples for their research. Under these circumstances, the time spent in a cave is likely to vary significantly, according with the purpose of the visit and the frequency of entrances; therefore, prolonged exposure may be involved.

The purpose of our work is to provide a first survey of radon levels distribution in five caves from Mallorca Island, Spain, located in different geological and structural settings. This study identifies possible areas with high ^{222}Rn concentration and outlines the ones presenting health risks. Considering Mallorca's great speleological potential, our data provide valuable information for both cave personnel and tourists in show caves, as well as for cavers and scientists working in wild caves. With one exception (Dumitru et al., 2015), to our knowledge, no other information on ^{222}Rn concentration in caves from this area has been reported and no similar studies were performed. Therefore, we expect these results to be of great interest for the administrative staff of the investigated show caves and, at the same time, for members of the Federació Balear d'Espeleologia and other agencies involved in granting permits to access these caves. Moreover, this survey is a contribution to the radon concentration monitoring effort in caves worldwide.

2. Material and method

2.1. Cave settings

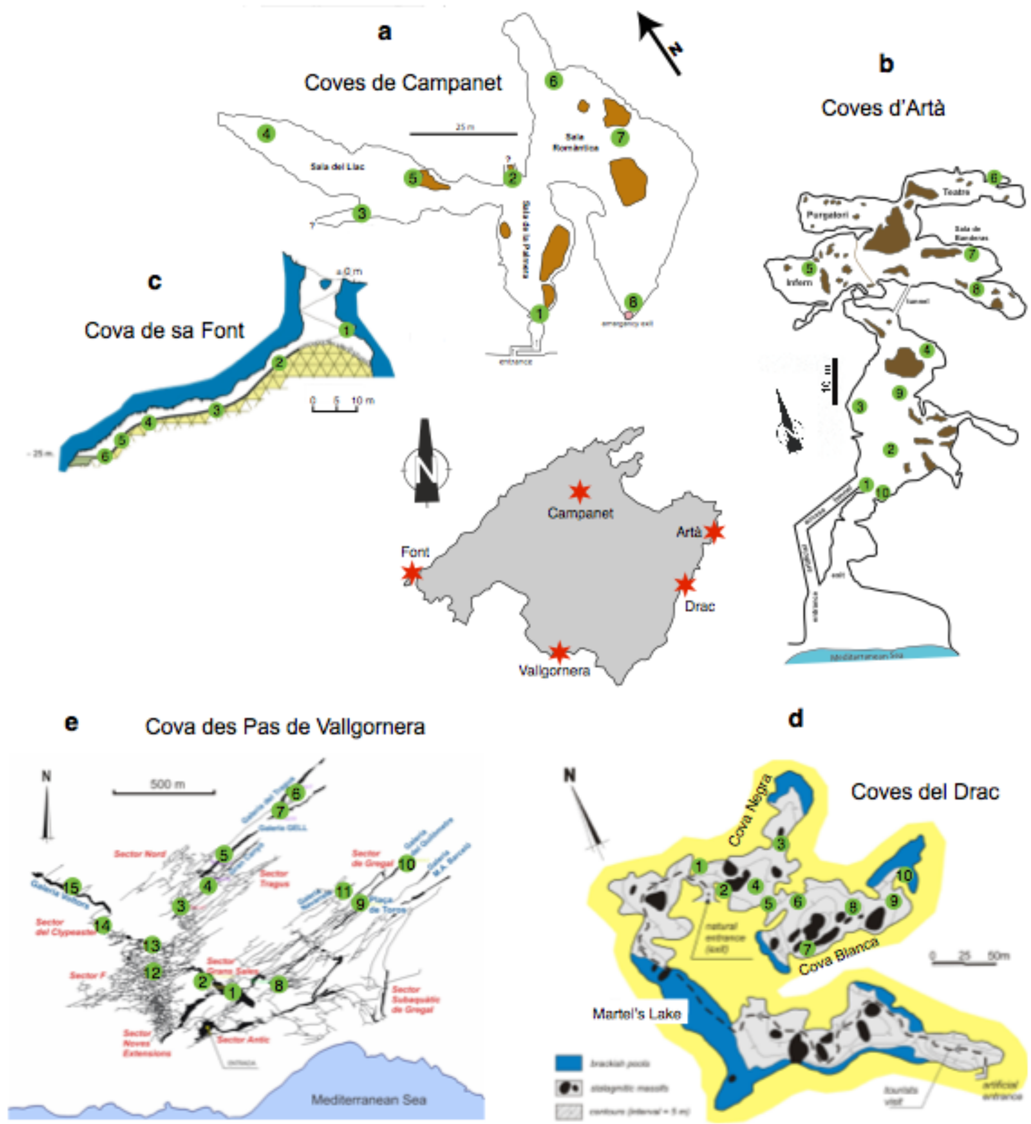
Over 2,000 caves (excluding rock-shelters and very small cavities) are presently known on Mallorca Island, of which five are show caves fitted for tourism (Ginés & Ginés, 2011) whereas the remaining ones are only for cavers and professional scientists. To investigate the radon behaviour on a broad geographical distribution and in caves with different morphologies and bedrock ages, five caves were chosen for our study. Based on the above variables, we measured radon concentration in two show caves: Coves de Campanet (hereafter Campanet) and Coves d'Artà (Artà) and in three non-touristic caves: Cova de sa Font (Font), the non-visited/restricted sectors of the famous Coves del Drac (Drac), and Cova des Pas de Vallgornera (Vallgornera). To facilitate the discussion of the results, a map of each cave showing the distribution of the radon detectors is presented in Figure 1.

Coves de Campanet

Campanet is a short (~400 m) and richly decorated cave developed in Upper Triassic dolomitic rocks (Figure 1a). It is composed of two large chambers close to the entrance (Sala Romàntica and Sala de la Palmera) and a system of narrow and low corridors with a NW orientation ending in another large room (Sala de Llac). This chamber is a cul-de-sac situated at a slightly higher elevation in comparison with the rest of the passages and the air temperature (~22ºC) remains constant year around. The cave has an emergency exit at the southern end in the uppermost part of Sala Romàntica. Considering the air temperature values measured at each sensor location, the pattern of the galleries and their morphology, and using the ventilation classification proposed by Racoviță (1975), a permanent bi-directional air circulation is the best fit for Campanet Cave. This means that the convection cell active during the winter season has its cold and heavier air component entering the cave along the floor pushing the warmer air outside the cave along the ceiling; in summer, the direction of air circulation reverses. This ventilation cell is mainly operating within a few tens or hundreds of meters from the cave entrance, as revealed by our cave air temperature measurements. In all stations throughout Sala de la Palmera and Sala Romàntica values are nearly similar (~24.2ºC in summer and xxx in winter, respectively) and within 1ºC of the surface temperature, whereas at the far end of Sala de Llac it is lower and constant. Eight detectors were placed along the touristic path (Figure 1a).

Coves d'Artà

Artà (formerly known as Cova de s'Ermita) is the oldest touristic cave on the island, operating approximately since 1880 (Ginés & Ginés, 2011). It develops in Upper Jurassic limestones in the north-eastern part of the island and it has an impressive entrance facing the Mediterranean Sea. The total length of its passages and large chambers (> 35 m in height) is ~800 m, all overwhelmingly decorated with massive stalagmites, columns, shields, and massive flowstones. Ten detectors were placed at different elevations along the touristic pathway (Figure 1b). For safety and management reasons, tourists enter currently the cave along an artificial corridor and exit through the natural entrance. The natural cave ventilation could intermittently be slightly altered (locally) when doors of the tunnel open to give access to groups in the cave. Temperature



readings in all stations and during each season reveal similar values (within 1ºC) to those at surface, suggesting the cave is well ventilated.

Fig. 1. *Geographical locations of caves within Mallorca and distribution of radon detectors: a) Campanet; b) Artà; c) Font (profile); d) Drac; e) Vallgornera.*

Cova de sa Font

Font Cave (also known as Cova des Moro) is located in the north-eastern part of Dragonera Islet (at the SW corner of the Mallorca Island). The cave develops in Jurassic limestones and has a vertical entrance followed by a passage that descends at 45º down to -25 m (Ginés & Ginés, 2010). The presence of a freshwater sea-level-controlled pool at the bottom of the cave, made people to build stairs, to easily access this resource. In terms of ventilation regime, Font Cave is a typical cold-air trap cave with intermittent seasonal ventilation (Racoviță, 1975). The cave is well-known for its exceptionally high CO_2 content that in the summer time exceeds 6% in the lowermost part of it, but drops well below 1% during winter time, when the cold and dry air sinks through the natural entrance into the cave and replaces the CO_2-rich warm and moist air therein. In the summer time, however, when cave temperature (T_c) is lower or equal to the surface temperature (T_s), the ventilation completely ceases. During the spring season, the cave ventilation is intermittently-active during days or early morning and late evening, when the difference between T_c and T_s is enough to generate a convection cell. Depending on the temperature differences, the air circulation may operate only near the entrance or all the way to the lowest parts of the cave. The locations of the six detectors placed in this cave are shown in Figure 1c.

Coves del Drac

The touristic sector of Drac Cave (including Martel's Lake) is the Europe's most visited cave and was developed significantly for tourism since 1898 (Ginés & Ginés, 2011). This famous cavern is located in the eastern part of the island and is developed in Upper Miocene calcarenites and limestones, deposited in a reefal environment. Ten radon detectors were deployed along the historical tour route comprising Cova Negra and Cova Blanca. These sections are unrelated to the current touristic part (Figure 1d), and are not impacted by the artificial (forced) ventilation that supplements the natural one across the visited portion of Drac. The historical route presents interest to a number of scientists that are carrying out various types of research. The passages in this part of the cave have an overall descending trend. Therefore, the ventilation regime is almost similar to that in Font, although the winter and spring air circulation is not that pronounced. Monthly temperature and CO_2 readings between October 2011 and March 2014 confirm this ventilation pattern (Boop et al., 2014; Fornós, unpubl. data). The CO_2 concentrations range between 723 and 1072 ppm (in all stations that are 75 m or more from the entrance) during the warm season and decreases to an average of 440 ppm throughout the cave when the winter convection cell is activated. Over the summer period, T_c values remain constant (21.6ºC) and within 2ºC from surface temperature, whereas during the cold season (mean T_c: 17.1ºC), the difference between surface and cave is as high as 7ºC. The presence of a morphological constriction between stations 4 and 5 highly impacts the ventilation down into the Cova Blanca sector.

Cova des Pas de Vallgornera

Vallgornera is the longest cave on Mallorca (over 74 km, including 17 km of submerged passages; Merino et al., 2014) and a scientific treasure, reason why it has been declared a *Natura 2000* site and adequately protected. Access is strictly enforced and only scientific and exploration expeditions are permitted. The cave is located in the southern part of the island and develops in Upper Miocene carbonates (Ginés et al., 2014). It was accidentally discovered in 1968, thus it has no natural entrances, but an artificial well-gated one. Because of its length and complexity, the exact ventilation regime is not yet fully understood. At present, a clear air circulation controlled by barometric changes, establishes in the proximity of the artificial entrance (Boop et al., 2014), but there is no precise information how far into the cave this type of ventilation operates (Merino, pers. comm.). Furthermore, air movements down the artificial entrance shaft, in the Entrance Room, and in some constrictions leading to extensive chambers seem to be highly conditioned by barometric changes, taking into account the large volume of the voids therein. Fifteen detectors were distributed in major chambers along the most important sections of the cave (Figure 1e). The first two detectors recorded radon concentrations in the southern part of the cave, specifically in Sector Grans Sales (*Sala Que no Té Nom*, meaning No Name Room). Detectors 3 to 11 were placed in northern passages developed more than 1 km inland: 3, 4 - Gran Canyó, 5- Galeria del GELL, 6, 7- Galeria del Tragus, 8-11 Galeria Navarrete (within Galeria del Quilòmetre). Four detectors (stations 12 to15) were spread along Galeria Voltors. Among all these locations, *Sala Que no Té Nom* has a special status because it serves as the main camp for all exploration and survey trips longer than one day. For a better visualization, the location of detectors is presented in Figure 1.

2.2. Radon measurements technique

Radon concentration was measured by using solid state nuclear track detectors (SSNTD) CR-39, type RSKS, manufactured by Radosys Ltd. Hungary, in different locations within the investigated caves. Unless constrained by limited access, the detectors were placed in each cave along the main passages, more or less equidistantly. After exposure, they were placed back in their protective radon-proof sachets and sent to the laboratory of Environmental Radioactivity and Nuclear Dating Center, Babes-Bolyai University, Cluj (Romania), for etching and data evaluation. The experimental technique using RadoSys equipment followed the same protocol described in other papers (Sainz et al., 2007; Cosma et al., 2013). The individual error of radon concentration was estimated at less than 12% and average standard deviation for all detectors 6%. Furthermore, the overall accuracy of our laboratory results were checked and ensured by periodically calibrations, as well as by international inter-comparisons with reference laboratories (Jilek & Marusiakova, 2011). The ^{222}Rn concentration was obtained directly from the track density using the same formula published in Dumitru et al. (2015).

2.3. Sites selection and measurement campaigns

The location and distance between the detectors were carefully chosen, to better record the pattern of radon concentration. Depending on the size, complexity, and accessibility of each cave, the number of measurement points differs from one cave to another, ranging between 6 (Font) and 15 (Vallgornera). A total of 49 sites were selected and 117 radon values were obtained in different campaigns extending over a calendar year (March 2013 - March 2014). Three exposure periods of detectors were selected, considering the particular Mediterranean climate of the island, characterized by hot and dry summers (mean annual temperature 25ºC) and cooler (average 10ºC), but not necessarily moist winters. For this reason, seasons were considered as follows: spring (March-June 2013), summer (July-October 2013), and winter (November 2013-March 2014). To record the background level, detectors were exposed outside each of the cave during the same period.

3. Results and discussions

It is well known that ^{222}Rn concentration in caves shows significant seasonal fluctuations (Perrier et al., 2004; Dueñas et al., 2011; Bezek et al., 2012). In order to document such oscillations, a continuous record of radioactivity level inside the cave using integrating techniques is required. The ^{222}Rn concentration can be influenced by a series of factors, such as: radium content and porosity of rocks, cave morphology and ventilation regime (velocity and direction of air flow). From all these, ventilation, which is primarily caused by temperature differences between cave atmosphere and outside air, is a crucial parameter. Despite the fact that all studied caves develop in carbonate rocks, the radon concentration levels are rather different from one to another. Different types of ventilation could cause this, as in some cases there is a minimal airflow and negligible air exchange with the outside atmosphere (Pinza-Molina et al., 1999; Cigna, 2005). None of the investigated caves has artificial ventilation.

Except for Vallgornera, where data collected cover only one interval, and Artà in which the range of values is very small, in all the other caves the seasonal variation is evident. To ease the track of seasonal effect, the three different periods are color coded in a similar manner for all caves in all plots.

3.1. Show caves

Considering that cave administration should ensure there is no health risk associated with radon exposure for the employees guiding the touristic tours, two show caves were investigated in this study: Campanet and Artà.

Coves de Campanet

Twenty-four CR-39 detectors (eight per each season) were placed within the cave along the tourist route, mainly near major tour stops (Figure 1a). The data obtained over three seasons in Campanet Cave are presented in Figure 2. Comparing the results with the action level limit of 300 $Bq \cdot m^{-3}$ annual average concentration in workplaces, it is evident that higher values, all well above this reference were obtained. In addition, one can easily notice that the radon concentration follows a similar distribution pattern throughout the cave, regardless of the season. Lower values are always characteristic to more efficiently-ventilated sites (1, 2, 6-8), whereas higher values were recorded in poorly ventilated passages, all within the Sala del Llac (locations 3-5, Fig. 1a). The accumulation of radon in this section of the cave may be linked with its particular morphology; Sala de Llac is slightly higher in elevation compared to the rest of the cave and the air circulation is restricted in this section.

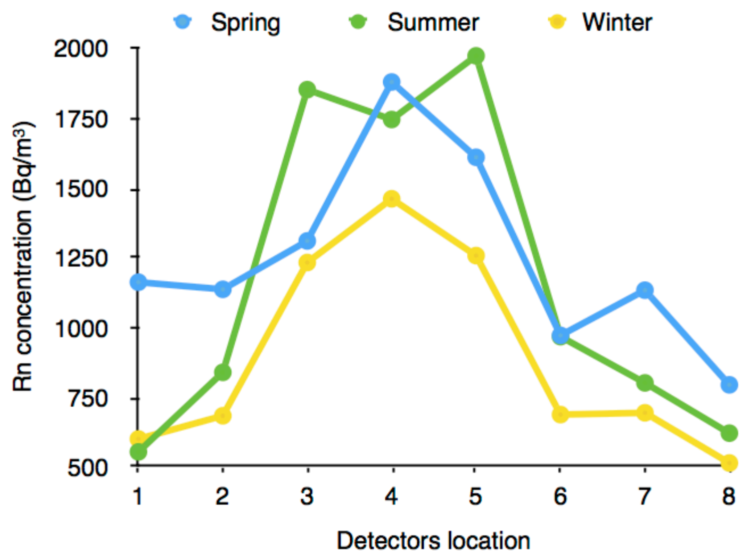


Fig. 2. *Seasonal variation of radon concentration in Campanet Cave.*

As expected, a seasonal variability of ^{222}Rn concentration was observed. During winter and early spring when $T_s < T_c$, the cold, denser, and fresh outside air enters the cave along its floor, forcing the less dense, warmer, and radon-rich air in the outside atmosphere. This type of ventilation is responsible for levels of radon lower than spring or summer throughout the cave. Higher levels were measured during summer, when $T_c < T_s$ trigger a very poor ventilation, which may even cease over periods of the day. Thus, the air circulation is basically looping nearby the cave entrance, causing lower radon concentrations at those respective sites, but instead promotes a significant accumulation deeper inside the cave.

The integrated measurements were confirmed by continuous monitoring in two selected locations and the effective dose received by tour guides was calculated and published elsewhere (Dumitru et al., 2015). Considering the data acquired, our recommendations for the cave administration is to instruct their guides to spend less time with explanations while in stations 3, 4, and 5, and periodically open during summer time for few hours (in the morning or evening) the upper emergency exit to enhance cave's ventilation.

Coves d'Artà

The data collected by using etched track detectors from different locations within Artà Cave are summarized in Table 1. The mean annual concentrations in all 10 investigated sites are well below the recommended radon reference level, varying between 13 and 118 $Bq \cdot m^{-3}$. This range suggests that either the radon gas from natural sources is extremely low at this site or the cave is efficiently ventilated all year around. If the latter, it means that the exchange of radon between the cave and outside atmosphere is very effective, resulting in insignificant concentrations underground.

Since all the results consistently show very low values, no seasonal variations are observed. Although Artà is one of the most visited cave on the island and each guide may spend several hours per day inside it, there is no health hazard, hence there are no measures required to be implemented for monitoring the individual exposure in this cave.

Table 1. Three seasons of integrated radon concentrations (Bq·m^{-3}) at 10 different locations along the touristic path in the Artà Cave and the mean annual concentration for each location.

Detector location in cave	Radon concentration (Bq m^{-3})			Mean annual radon concentration (Bq m^{-3})
	Mar - June 2013	Jul - Oct 2013	Nov 2013 - Mar 2014	
1	36	42	12	30
2	35	67	252	118
3	123	8	78	46
4	25	-	14	13
5	75	32	14	40.
6	71	103	24	66
7	135	47	35	72
8	78	168	23	89
9	68	20	8	32
10	57	16	8	27

3.2. Non-touristic caves

There is not much radon related research reported from wild caves, although cavers and scientists often spend considerable amount of time working in certain cavities and cave systems, which could pose a potential long-term health risk associated with their radon exposure. Three wild caves were investigated and the collected data are summarized hereafter.

Cova de Sa Font

Considering the steeply descending topography of this cave (Figure 1c) and implicitly its ventilation regime only active in winter, comes as no surprise the high radon values measured in all three seasons, particularly in summer (Figure 3).

The radon concentration in the atmosphere of Font Cave shows a clear seasonal pattern, with overall increasing levels from the cold to the warm season. In winter time, significantly lower radon levels, compared with summer, were recorded (average 714 Bq·m^{-3}). This shows efficient ventilation resulting from the activation (when $T_s < T_c$) of the seasonal descending cold and fresh airflow inside the cave. Although such a ventilation regime should generate a gradient throughout the cave with the lowest radon concentrations in its deepest part and the highest close to entrance, the values in stations 1 and 6 fall off this trend. An explanation could be that even during the coldest nights, the air sunk into the cave only reaches the depth of station 5. As for the high value in station 6, this may be related to the location of the detector in a very low (~20 cm in height) side passage of the cave, or to the tendency of radon, which is heavier than air, to accumulate in the deepest parts of the cave.

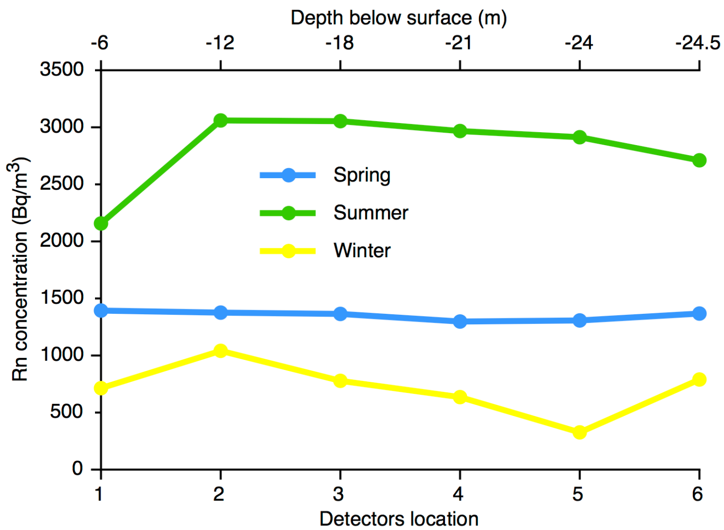


Fig. 3. *Radon concentration in 6 measuring points within Font Cave and its seasonal fluctuations.*

In the spring period (February to June 2013), an almost constant concentration value of about 1350 Bq·m^{-3} (ranging from 1307 to 1394 Bq·m^{-3}) was recorded (Figure 3). This is a consequence of the particular ventilation regime operating between the fully ventilated (winter) and no air circulation (summer) periods. Prior entering the full summer season when the descending ventilation completely ceases, radon gas is slowly building up. However, it is kept at lower levels when compared to summer because in the early part of the interval, overnight T_s is lower than T_c activating the ventilation cell, which is responsible for homogenizing the cave air atmosphere. During the warm season (between July and October 2013), radon builds up inside the cave to even higher levels (average of 2810 Bq·m^{-3}). The lower value in station 1, at 6 m below the surface, might be linked with the occurrence of convection cells during cooler nights, when fresh air invading the upper part of the entrance shaft, dilutes the radon concentration therein.

Normally, in workplaces with radon levels higher that 1000 Bq·m^{-3} measures need to be implemented to reduce its concentration. Unfortunately, there are no typical remedial actions to be used in caves, as forced air ventilation would have destructive effects on its topoclimate, which in turn impacts biota and speleothem formation. The most efficient way to protect workers (scientists and park personnel) against exposure to these very high radon concentrations is to minimize the time spent in the cave. However, because of its very high CO_2 concentration in the deepest part of the cave in the summer time, Font is rarely visited. Thus, a more detailed radon monitoring program may not be justified.

Coves del Drac

The radon measurements were carried out along the historical tour route that nowadays is in the non-touristic part of this famous cave attraction of Mallorca. The recorded data for three seasons are showed in Figure 4. There is a clear relationship between radon concentration and detector location, except for stations 7 and 8 in which unusual levels were recorded. A close look at the cave ventilation regime allows to interpret the results obtained in this cave.

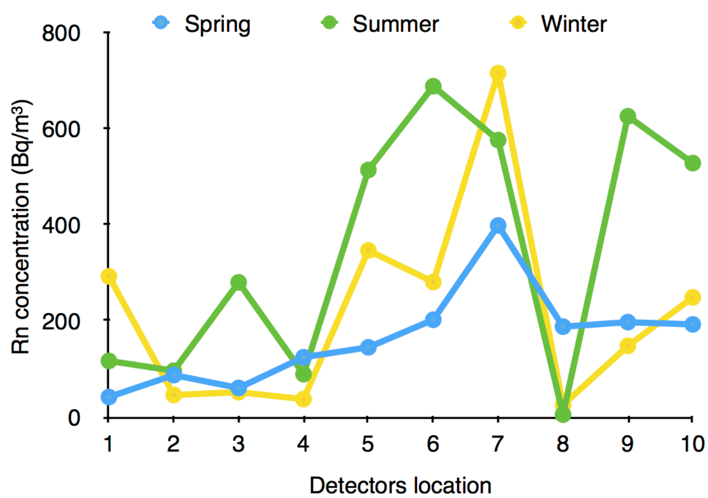


Fig. 4. *Seasonal variation of radon concentration in Drac Cave.*

Considering the ventilation type operating in this part of the cave, one would expect to find, lower radon values in all stations located near the floor and in the inner parts of the cave during the cold season. In contrast, close to the natural entrance and at locations in which the detector was placed in the proximity of the ceiling along which radon is ventilated out of the cave, the values should have been higher. This holds true for all locations except station 7, in which the maximum radon concentration (715 $Bq{\cdot}m^{-3}$) was recorded during the winter period. As this site lays well-off the center of the gallery and at the highest elevation in this section of the cave, we assume that the radon flushed from deeper in the cave accumulated in this side passage like in a trap.

The summer radon concentration curve (Figure 4 green) displays expected values corresponding to each particular cave location, except for the one in site 8, which is an outlier. Our interpretation of the extremely low concentrations measured in station 8 in the two key seasons (winter and especially summer), is either a detector problem (less probable) or a localized ventilation cell active during the summer, responsible for dispersing the radon gas in other parts of the cave. None of the two hypotheses can be further substantiated at this time. The significant increase of radon concentration between station 4 and 5 (in summer and winter) is explained by the location of detector 5 in a poorly ventilated room, right behind a morphological constriction, whereas detector 4 resided in a large, well-ventilated chamber. The slightly higher value recorded in station 3 during the warm season is due to its location at a lower elevation (compare to station 4) inside Cova Negra (Figure 1d).

Because of the outside thermal regime, the cave ventilation between March and June, 2013 (spring season) is characterized by periods when air circulation reaches the deepest parts of the investigated section but also days with air circulation limited to the vicinity of the cave entrance. This is why the Rn concentration curve shows a steady increasing trend from station 1 (entrance) to innermost station 10. The outlier value in station 7 was discussed above.

In view of these results, our recommendation is that researchers (or cavers) working in this part of the cave should avoid excessively long exposure times, especially during summer, as it could present a health risk. Although the touristic part of the cave has both natural and artificial ventilation, a radon monitoring campaign on specific locations (e.g., Concert Hall) along the touristic path would be prudent at a future time.

Cova des Pas de Vallgornera

Due to logistic and cave limitations (length and complexity), only one measurement campaign was carried out. Table 2 summarizes the results obtained in 15 different locations within Vallgornera. The selection of stations is based upon accessibility in galleries and passages throughout the cave, which is an extensive maze (Figure 1e) partially drowned by brackish waters (Merino et al., 2014). Trips to some of the remote areas of the cave (e.g., Galeria del Tragus, Galeria Voltors, etc.) may take as long as 5-6 hours one way. This made the placement and collection of detectors more difficult.

The radon concentrations measured in Vallgornera range between 342 and 1931 $Bq \cdot m^{-3}$. The highest values (998 to 1930 $Bq \cdot m^{-3}$) are associated with station 8 in Sala Blanca and three other location along the relatively isolated Navarrete Gallery, which is part of the inner sections of Galeria del Quilòmetre (Figure 1e), all situated deeper in the cave. Worth mentioning is that even in the *Sala Que no Té Nom*, the largest chamber of the cave (11,000 m^2) the radon level is ~700 $Bq \cdot m^{-3}$ (station 1). This value needs to be taken into consideration when cavers plan to use this chamber as their base camp for long cave survey campaigns. Camping in this area for longer periods of time should be avoided.

Table 2. Radon concentration ($Bq \cdot m^{-3}$) in 15 locations along passages and chambers in Vallgornera Cave, ranging between 342 to 1931 $Bq\ m^{-3}$.

Detector location in cave	Radon concentration (Bq/m^3)
1	699
2	725
3	700
4	692
5	573
6	742

7	342
8	1037
9	998
10	1753
11	1931
12	524
13	683
14	792
15	700

Being a complex underground network, currently with just one artificial entrance that practically seals the cave, the air circulation could depend on several factors, such as changes in the outside air pressure, the morphology and patterns of galleries and chambers (dimension, height), the daily water table oscillations controlled by the small-scale tidal fluctuations of the Mediterranean Sea (a vast percentage of the cave is drowned by brackish water), suspected surface connections through a network of fissures, presence of narrow passages and constrictions, etc. Nonetheless, the issue of air circulation in Vallgornera Cave is poorly known.

In the view of possible potential health hazards caused by inhaling radon and its daughters, the annual effective doses have been estimated (except for Artà where the results show very low values) based on radon concentrations found in each cave and applying the equation of Papachristodoulou et al. (2004). A value of 0.57 was employ for the equilibrium factor between radon and its progeny, as calculated by Cigna (2005) using more than 880 data reported from caves worldwide. Our assessment considers estimated exposure times received from knowledgeable personnel, who carefully integrated the maximum number of hours per month spent inside each cave by those performing research or exploration activities.

In Campanet, effective doses received by tour guides were reported by Dumitru et al. (2015) and depending on the cave location vary between 0.72 and 1.89 mSv y^{-1} (mean annual: 1.23 mSv y^{-1}), with the highest doses in three of the monitored sites within Sala del Llac. Although elevated concentrations were measured in Font, they are considered relatively low in terms of ionizing radiation (doses range from 0.92 to 1.03 mSv y^{-1}), due to short time exposure (max. 12 hours/month). As far as Drac is concerned, a mean annual dose of 0.3 mSv y^{-}1 was calculated, considering a cumulated period of time not exceeding 20 hours/month, during which a relatively small number of researchers enter this part of the cave. Although the measurements carried in Vallgornera do not cover a calendar year, dose estimation is based on the available data. Among all our investigated caves, the highest effective doses were obtained in Vallgornera, ranging from 0.73 to 4.14 mSv y^{-1}, with a mean of 2.26 mSv y^{-1}.

It is worth noting that workers with annual dose higher than 1 mSv y^{-1} are defined as occupationally exposed to radiation (Gruber et al., 2014). For comparison, worldwide average annual effective dose to members of the public from natural ionizing radiation sources is estimated to be 2.4 mSv (UNSCEAR, 2000).

As significant seasonal variation is noticed in almost all investigated caves, an accurate knowledge of the time spent underground and radon concentration has to be taken into account. To avoid effective dose over- or under-estimation, the best way to control workers exposure is the personal dosimetry. Quindos et al. (2015) recommend the development and testing of a new dosimeter that can be easily worn by each worker during exposure time.

4. Conclusions

Here we present a radon survey in five caves (2 touristic and 3 wild) from Mallorca Island. Summarizing our results, radon concentrations differ markedly from one cave to another, as well as within each cave. This is mainly because its migration in underground cavities depends essentially on their overall configuration (horizontal or vertical; single or maze galleries, etc.), passage size, and type of cave ventilation.

The concentration values ranged from levels below the detection limit up to 3060 $Bq \cdot m^{-3}$. Taking into account the radon concentrations obtained, the main conclusion of this study is that, in most measurement sites, ^{222}Rn is lowest in winter and highest in summer. These fluctuations are mainly due to density-driven air circulation changes inside the caves, induced by temperature-related difference between surface and cave.

Below are some particular recommendations to the administration staff of the two touristic caves, Govern de les Illes Balears, and Federació Balear d'Espeleologia for the caves in which values are above the action level:

- In Campanet, it is strongly suggested that air circulation during summer time would be enhanced by periodically opening the emergency door. As the highest recorded values are in locations 3 to 5, guides should avoid offering long explanations at these specific locations.
- As far as Artà Cave is concerned, there are no measures required as the values are well below the reference limit.
- Any scientific work carried out in the non-touristic part of Drac (Cova Blanca and Cova Negra) should be time-limited during summer time (less than 20 hours/month). As for the touristic part, not considered in the present study, a radon monitoring campaign would be reasonable, especially at location where guides spend most of their guiding time, like in the Concert Hall.
- In the case of Font, where the highest radon concentrations were recorded, to avoid any health risk, the administration personnel of the Dragonera Natural Park should limit the access in the cave to the current level (12 hours/month), in particular during the warm season when the values for both radon and CO_2 are the highest.
- With respect to Vallgornera, the only critical location to radon exposure is in the *Sala Que no Té Nom*, if cavers use it for week-long underground camps. It is advisable that at this site, as well as in those along the Navarrete Gallery, cavers or scientists should reduce to minimum

their underground activities and under no circumstances should they spend more than 40 hours/month at any of these locations.

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Figures Caption

Fig.1.Geographical locations of caves within Mallorca and distribution of radon detectors: a) Campanet; b) Artà; c) Font (profile); d) Drac; e) Vallgornera.

Fig.2. Seasonal variation of radon concentration in Campanet Cave.

Fig.3.Radon concentration in 6 measuring points within Font Cave and its seasonal fluctuations.

Fig.4. Seasonal variation of radon concentration in Drac Cave.

Table caption

Table 1. Three seasons of integrated radon concentrations (Bq·m^{-3}) at 10 different locations along the touristic path in Artà Cave and the mean annual concentration for each location.

Table 2. Radon concentration (Bq·m^{-3}) in 15 locations along passages and chambers in Vallgornera Cave, ranging between 342 to 1931 Bq m^{-3}.