Miloš Briestenský, Fabrizio Ambrosino, Iveta Smetanová, Lenka Thinová, Stanka Šebela, Josef Stemberk, Lucia Pristašová, Concepción Pla, and David Benavente. Radon in dead-end caves in Europe. *Journal of Cave and Karst Studies*, v. 84, no. 2, p. 41-50. DOI:10.4311/2021ES0101

RADON IN DEAD-END CAVES IN EUROPE

Miloš Briestenský[1,C], Fabrizio Ambrosino[2], Iveta Smetanová[3], Lenka Thinová[4], Stanka Šebela[5], Josef Stemberk[1], Lucia Pristašová[6], Concepción Pla[7], and David Benavente[8]

Abstract

We report the results of 3-years of Radon-222 monitoring in six show caves across Europe, selected with the feature of having only one, or no natural entrance, defined as dead-end caves. The caves are located in Spain, Slovakia, Slovenia, and Czechia. The consecutive monitoring was performed between January 2017 and January 2020. Continuous measurements of the radon activity concentration using spectrometry detection and analysis of the α-particles of ^{222}Rn progeny were performed. Meteorological parameters influencing gas flow were recorded inside and outside of the caves. Although the radon activity concentrations differed from one cave to another, all six of the studied caves revealed very similar trends, showing evident seasonal variability with higher values in summer and lower values in winter. The measured values of radon activity concentrations ranged between 633 and 26,785 Bq/m^3. The temperature differences between the inside and outside of the caves is the main radon movements driving force. The results of this study have significant practical implications, making it possible to provide cave administrators with recommendations regarding employee or visitor time-limited access to the investigated caves. Ours is the first comparative study encompassing the most interesting dead-end caves in Europe.

INTRODUCTION

Radon-222 is a naturally-occurring inert radioactive gas with a half-life of 3.824 d, originating from the radioactive decay of ^{226}Ra in the ^{238}U radioactive decay chain in the Earth's crust (Stein, 1987). Only a fraction of the radon atoms created in a mineral grain emanates into the void space between grains, where they are dissolved in water or mixed in soil gases, and are thus transported by convection toward the ground surface and the atmosphere (Nero, 1988; Sabbarese et al., 2020a). This transport is influenced by a number of geophysical and geochemical parameters (Etiope and Martinelli, 2001; Ambrosino et al., 2020a). Radon represents the most significant source of ionizing radiation exposure: up to 70 % of natural background radiation or 50 % of all irradiation sources (UNSCEAR, 2000; Ambrosino et al., 2020g). Radon poses a substantial threat to human health when a buildup occurs in confined spaces, such as dwellings and workplaces, where people spend long periods of time (Field, 2007; Pantelić et al., 2019; Ambrosino et al., 2020b). Decades of epidemiological studies concerning the effects of radon on human health show a statistically significant increase in lung cancer risk from prolonged indoor exposure (Darby et al., 2001). Underground working and living spaces with little or no ventilation are the most significant in terms of potential human exposure to radon (Sabbarese et al., 2020a). In particular, caves are recognized as special indoor occupational environments where extremely elevated concentrations of ^{222}Rn may occur (Cigna, 2005; Sainz et al., 2007; Ambrosino et al., 2019a). Therefore, radon releases represent a significant phenomenon that may affect the utilization of caves. This aspect poses a threat to human health for persons working in such localities (cavers, tour guides, maintenance personnel, employees working in shops built over cave entrances, etc.) and visitors (Field, 2007). Many recommendations concerning indoor radon concentrations have been made and a reference level of 300 Bq/m^3 in workplaces is strictly recommended by the Council Directive of the European Union (2013/59/Euratom) (Euratom, 2014). A large body of world literature investigating the distribution of radon in caves focuses on two main areas: radiation protection (Lario et al., 2005; Thinová et al., 2005b; Field, 2007; Bahtijari et al., 2008), and tracing the underground airflow (Šebela et al., 2010; Ambrosino et al., 2020c; Pla et al., 2020; Sabbarese et al., 2020b).

European caves, known for centuries, are of great interest to cavers and scientists alike. Generally, publicly accessible caves are usually monitored, but there are many caves under exploration without any monitoring. Radon activity concentrations are mainly influenced by air circulation due to the geomorphological situation of each cave (Cigna, 2005; Field 2007). Some caves have more than one entrance at different elevations with convective circulation of air. The main force controlling this type of circulation are differences in air density (Wigley, 1967; Badino, 2010). The second

[1]Institute of Rock Structure and Mechanics, Czech Academy of Sciences, V Holešovičkách 41, 18209 Prague, Czechia
[2]Department of Physics „Ettore Pancini", University of Naples „Federico II", Italy
[3]Earth Science Institute, Slovak Academy of Sciences, Dúbravská cesta 9, 840 05 Bratislava, Slovakia
[4]Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague, Břehová 7, 11519 Prague, Czechia
[5]Karst Research Institute ZRC SAZU, Titov trg 2, SI-6230 Postojna, Slovenia
[6]State Nature Conservancy of the Slovak Republic, Slovak Caves Administration, Hodžova 11, 031 01 Liptovský Mikuláš, Slovakia
[7]Department of Civil Engineering, University of Alicante, Carretera San Vicente del Raspeig s/n, 03690 Alicante, Spain
[8]Department of Earth and Environmental Sciences, University of Alicante, Carretera San Vicente del Raspeig s/n, 03690 Alicante, Spain
[C]Corresponding author: briestensky@irsm.cas.cz

type of air circulation is barometric circulation, which responds to differences between the inner and outer barometric pressure (Richon et al., 2005; Badino, 2010; Gregorič et al., 2013). This type of circulation usually occurs in caves with one entrance (dead-end caves) or in caves with small entrances. Dead-end caves are distinctive due to their limited ventilation and stable regime of CO_2 concentrations (Czuppon et al., 2018; Prelovšek et al., 2018). The radon may often reach very high concentrations within passages in vast underground karst systems, defined as dead-end passages (e.g., Pisani rov, Postojna Cave in Slovenia) (Gregorič et al., 2013).

The present research provides a comprehensive survey of the distribution of radon levels in representative dead-end caves with different geological and structural settings located across Europe. Six caves were selected in Spain, Czechia, Slovakia, and Slovenia (Fig. 1). The monitoring period was between January 2017 and January 2020, during which time the meteorological parameters inside and outside of the caves were also recorded. Ours is the first such comparative study concerning dead-end caves. The marginal aim of our work was to show the seasonal radon trends and the influence of meteorological factors in order to understand the common characteristic features of these types of caves. Moreover, this study represents one step further in addressing public health issues relating to radon gas exposure in caves, and in creating greater awareness of the necessity for the implementation of thorough indoor air quality monitoring protocols (Sabbarese et al., 2021).

DESCRIPTION OF THE SELECTED CAVES

Here we describe the main features of the six investigated dead-end caves across Europe. The main meteorological data, i.e. temperature, air pressure, and relative humidity, monitored inside the caves, by means of the appropriate sensors connected to a data-logger, are also reported.

Rull Cave (Spain)

Rull Cave (38° 48' 40″ N; 00° 10' 38″ W, Fig. 1) is located in Vall d'Ebo, in the south-east of Spain (Alicante province). Rull Cave developed in massive Miocene conglomerates that were deposited on Cretaceous limestones (Pla et al., 2016). These materials conform to the host rock of the cave, which has a thickness varying from 9 m to 23 m. Above the cave, the soil has a discontinuous thickness of approximately 1 m, with a coarse to fine texture mainly composed of quartz (Pla et al., 2017). Rull Cave is located in an area with a Mediterranean or warm climate (Csa climate type, Koppen–Geiger Classification) and with hot and dry summers (Garcia-Anton et al., 2017). The cave is defined as having an individual central chamber (20 m high) described as being almost round in shape with a surface of 1,535 m^2. It has a single entrance located at the top of the cave (Pla et al., 2017) (Fig. 2a). Temperatures in Rull Cave range between 15 and 17 °C, the mean relative humidity reaches about 98 % and the pressure ranges between 933 and 985 hPa. ^{222}Rn measurements have been taken continually since 2016 by a RADIM 5WP monitor (Pla et al., 2020).

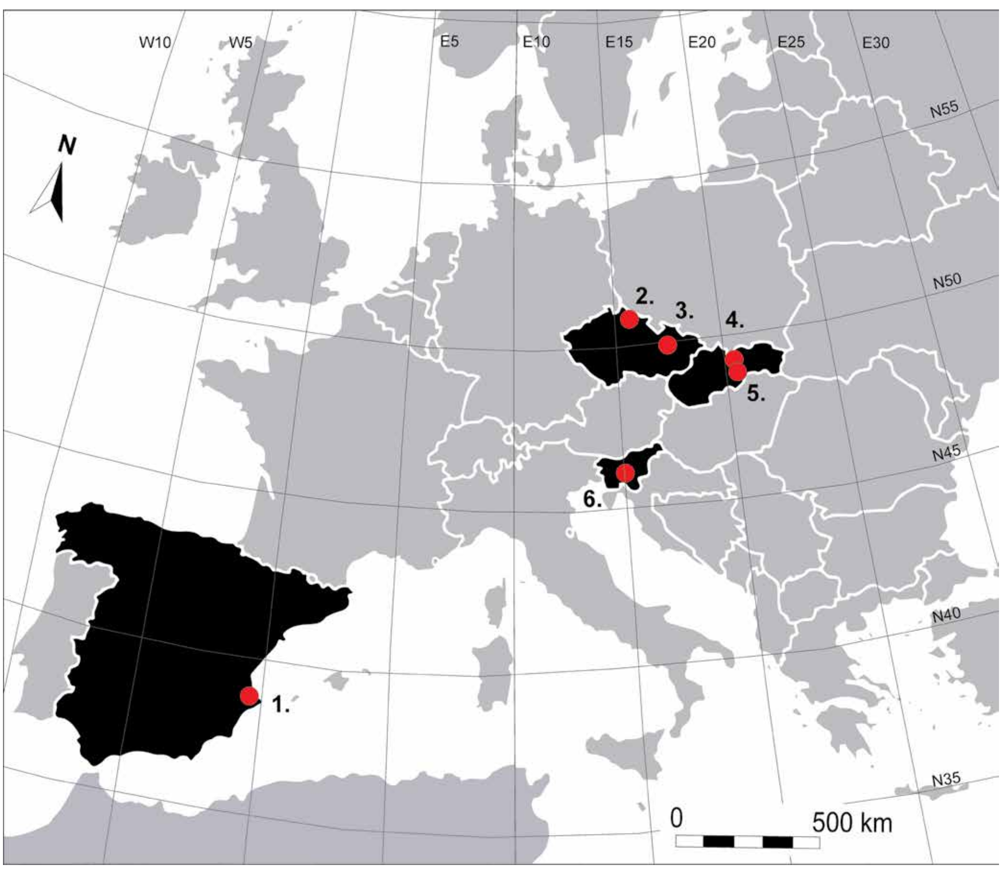

Figure 1. Location of the studied dead-end caves: 1. Rull Cave (Spain), 2. Bozkov Dolomite Caves (Czechia), 3. Mladeč Caves (Czechia), 4. Važecká Cave (Slovakia), 5. Ochtinská Aragonite Cave (Slovakia), 6. Županova Cave (Slovenia). (Source: modified from Google Earth).

Bozkov Dolomite Caves (Czechia)

Bozkov Dolomite Caves (50° 38' 51″ N; 15° 20' 18″ E, Fig. 1) are located in the region of Lugian, in the north-west of Czechia (North Bohemia

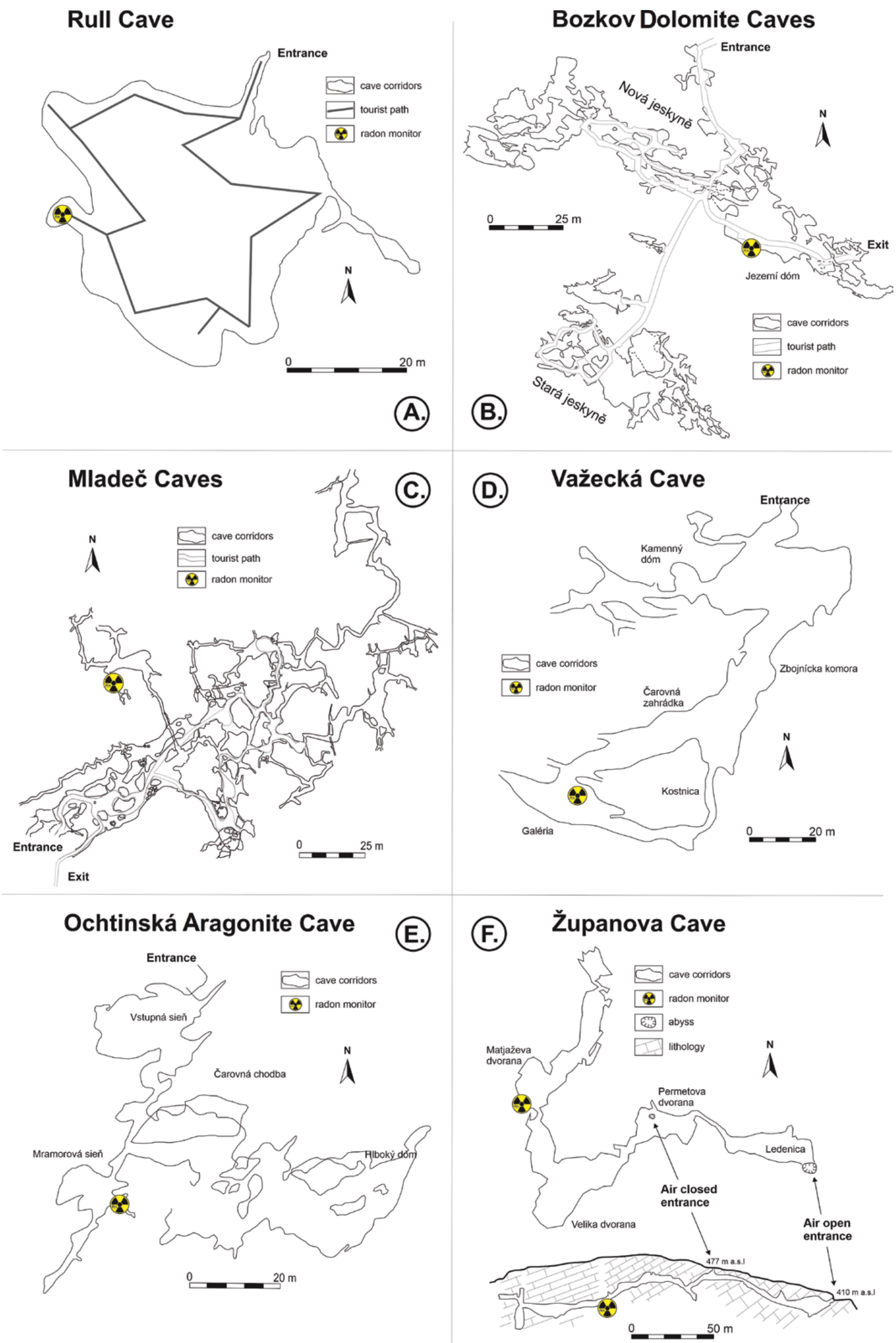

Figure 2. Plan view of the six studied dead-end caves with the locations of the radon monitors.

region, Liberec province). The significant Lugian-Jílovice-Kyšperk Fault intersects the cave system and the lentil of calcareous metamorphosed dolomites that are corroded by groundwater (Rovenská et al., 2008). The caves originated in the karstic mass in the Železný Brod crystalline region, which originated in the Silurian period (Rovenská and Thinová, 2010). The caves consist of two independent systems with two entrances (one used as an exit for visitors), which are connected by an artificial tunnel (Fig. 2b). The entrance to the underground space was discovered by dolomite miners in the 1940s. Lower parts of the caves are flooded, and some lakes are visible from the tourist path. The average temperature in the cave is between 7.5 °C and 9 °C, relative humidity is near to 100 %, and the pressure ranges between 935 hPa and 990 hPa. The cave tour is 350 m long (Rovenská and Thinová, 2010). Continuous radon monitoring began in the caves in 2001, using a RADIM 3A monitor and passive solid-state nuclear track detectors to obtain average seasonal concentrations (Rovenská et al., 2008; Thinová and Burian, 2008).

Mladeč Caves (Czechia)

Mladeč Caves (49° 42′ 23″ N; 17° 00′ 57″ E, Fig. 1) are situated on the edge of the eastern Třesín ridge in the eastern part of Czechia, within the Bohemian Massif (Olomouc province). The caves are formed in Devonian calcite limestones (Stránský and Thinová, 2017). The Třesín Threshold represents a significant borderline between the NW situated Mohelnice Basin and the Uničov-Litovel Depression (northern Upper Morava Graben part). Moreover, this line creates a borderline between two geomorphological provinces: the Western Carpathians and the Czech Highlands (Ambrosino et al., 2020d). The Graben is a part of the Nisa-Morava fault zone, which is defined by slow, brittle, active deformations, low-magnitude seismicity, and daily CO_2 fluxes (Špaček et al., 2015). The total length of the

Mladeč Cave corridors is 1,250 m (Hromas, 2009). The cave corridors were formed by groundwater from Hradečka Stream on three levels and they are defined as phreatic or deep phreatic caves (Hromas, 2009). The corridors generally follow the N-S and NW-SE oriented faults and the steep layers. The NW-SE striking lineaments are associated with the Haná Fault Zone here. The caves have two openings, one is used as an entrance and the other as an exit (Fig. 2c). The temperature in the caves is between 9 °C and 12.5 °C, mean relative humidity is 80 %, and the pressure ranges between 952 hPa and 1020 hPa. Continuous radon monitoring began in 2011 using a RADIM 3A monitor (Ambrosino et al., 2020d; Stránský and Thinová, 2017).

Važecká Cave (Slovakia)

Važecká Cave (49° 03' 23″ N; 19° 58' 19″ E, Fig. 1) is situated in the northern part of the Low Tatra Mts. on the north edge of the Važec Karst area, in the north of Slovakia (Žilina province). It developed at the contact of the Kozie chrbty Mts. and the Podtatranská Basin, in the Middle Triassic dark-grey limestones of the Gutenstein Formation of the Hronic Unit (Droppa, 1962). Tectonic activity of the WNW-ESE faults and flood-water injections from the Biely Váh River into exposed and faulted carbonates led to the modeling of the underground cave spaces (Bella et al., 2016). Moreover, previous morphological features were remodeled by slab and block breakdown, forced by frost weathering during the last-glacial stages (Bella et al., 2016). The cave is located almost at the bottom of the Biely Váh river valley, just 8 m above the river bed. It is 530 m long and consists of subhorizontal halls, without any significant vertical segmentation (Smetanová et al., 2020). The cave has only one entrance (Fig. 2d). A large part of the cave is filled by fluvial sediments. The temperature in the cave is between 6 °C and 8.5 °C, mean relative humidity is 93 %, and the pressure ranges between 900 hPa and 950 hPa. Continuous radon monitoring began in 2012 using a BARASOL BMC2 probe (Smetanová et al., 2020).

Ochtinská Aragonite Cave (Slovakia)

Ochtinská Aragonite Cave (48° 39' 49″ N; 20° 18' 20″ E, Fig. 1) is located in the south-east of Slovakia (Košice province). It was discovered during the excavation of an adit in 1954 (Bosák et al., 2002). It developed in Lower Devonian crystalline marble and Fe-ochre of the Drnava Formation (Gelnica Group) in the Slovenské rudohorie Mts., belonging to the Inner Western Carpathians (Gaál, 2004). The rock massif here was affected by Hercynian, Alpine orogenesis, as well as by the rejuvenation of Tertiary and Quaternary faults. The general direction of the faults is NE-SW and is often also followed by ankerite accumulations (Gaál, 2004). The cave may be divided into wet parts, like the Marble Hall with an air temperature of 7.8 °C to 8.5 °C, and dry parts, like the Deep Dome with an air temperature of 8.6 °C to 10 °C (Zelinka, 2004). The cave has no known natural entrance and a 145 m long artificial tunnel (Fig. 2e). The cave does not have any particular connection with the outside climate (Zelinka, 2004). Mean relative humidity is approximately 40 %, and the pressure ranges between 915 hPa and 968 hPa. Continuous radon monitoring began in 2016 by RADIM 3A monitor (Ambrosino et al., 2019a).

Županova Cave (Slovenia)

Županova Cave (45° 55' 10″ N; 14° 38' 31″ E, Fig. 1) is situated in the center of Slovenia (Grosuplje province). The cave was created in lower Jurassic limestones (J1, lower and middle Lias), belonging to the External Dinarides (Placer, 2008). Approximately 500 m to the west of Županova Cave principal entrance is Dobrepolje Fault (NW–SE), which separates the uplifted Triassic SW block from the subsided NE block of Županova Cave (Ravbar and Košutnik, 2014). There is also evidence of dextral horizontal movement along the Dobrepolje Fault. The fault is one of the so-called Dinaric oriented (NW–SE) faults in Southern Slovenia, which are still tectonically active. Measurements of air temperature show relative stability in Županova Cave, and it is normally not affected by the external atmosphere (Ravbar and Košutnik, 2014). The monitored values range between 9.4 °C and 9.9 °C. The cave has two entrances, but the second one is closed (Fig. 2f). The first entrance is open throughout the year. Mean relative humidity is approximately 45 %, and the pressure ranges between 933 hPa and 990 hPa. The first short-term monitoring of ^{222}Rn in Županova Cave took place in 1985 (Kobal et al., 1986, with continuous monitoring using a RADIM 3A from 2017 (Ambrosino et al., 2020e).

RADON MONITORING METHODOLOGY

The Radon-222 activity concentration in the Ochtinská Aragonite Cave, Mladeč Caves, Bozkov Dolomite Caves, and Županova Cave is continuously passively monitored using a RADIM 3A monitor. The monitor uses spectrometric detection of alpha particles, with an energy of 6.002 MeV, emitted by radon progeny ^{218}Po decay having a half-live of approximately 3.1 min (Sabbarese et al., 2017a; Stránský and Thinová, 2017). Detection of alpha particles is based on electrostatic collection on a silicon detector, using a hemispherical metallic chamber with a volume of 8.3×10^{-4} m^3 (the detection efficiency is 0.8 count m^3/ Bqh). The background elimination is provided once per year, by deleting alpha particles at 5.30 MeV from radon progeny ^{210}Po (half-life of 138.4 d) that contribute to a long-lasting background on the silicon detector surface (Ambrosino, 2020), In very damp environments, the radon gauge is placed in a plastic box containing a bowl with a desiccant ($CaCl_2$) inert toward radon, to avoid the extreme influence of relative humidity on the radon measurements (Ambrosino et al., 2020d). Measurement intervals are set to 30 minutes, and for statistical analysis, the daily averages are considered.

A "cave" version of the RADIM 3A monitor, the RADIM 5WP (desiccant inside the monitor, lower sensitivity), has been used for continuous measurements of ^{222}Rn activity concentrations by diffusion in the Rull Cave (Legarda et al., 2010; Pla et al., 2020). The working principle of the device is similar to the newest model described above: the radon activity concentration is determined by measuring the gross α-activity of the radon decay products ^{218}Po and ^{214}Po, which are collected electrostatically (after decay of the radon in a diffusion chamber) on the surface of a Si-semiconductor detector (Ambrosino et al., 2018a). The detection efficiency is 0.4 imp Bq/(h m^3). Measurement intervals are set to 30 minutes, and the daily averages are used.

In Važecká Cave, radon activity concentrations are continuously monitored using BARASOL BMC2 multi sensors. The radon diffuses inside a detection volume (1.48×10^{-3} m^3) through three cellulose filters, which trap all of the solid daughter products (Smetanová et al., 2020). The sensor is an implanted silicon detector with a depleted depth of 100 μm and sensitive area of 400 mm^2. It enables spectrometric detection of decay of ^{222}Rn and its daughter products in the detection volume (window set at between 1.5 MeV and 6 MeV) (Kumar et al., 2009). The sensitivity is 50 imp Bq/(h m^3), measurement intervals are 10 minutes, and the daily averages are taken.

In all of the dead-end caves (except Bozkov Dolomite Cave and Važecká Cave), the radon monitors are located in relatively deep areas with no public access (Fig. 2), where parameters such as ventilation and aerosol spectrum are not influenced by the movement of visitors (Thinová et al., 2005b; Ambrosino et al., 2020d).

RESULTS AND DISCUSSION

The time series of ^{222}Rn activity concentration measurements in the six investigated dead-end caves, and meteorological air parameters inside and outside of the caves, are for the period between January 2017 and January 2020. Such a long period is appropriate and accurate for defining the annual regime in the caves and for estimating the radon activity concentrations, and enables seasonal/periodic trends to be highlighted. In fact, neither 1- to 3-month long measurements nor a half-year to one-year long intervals may be used to correctly estimate radon activity concentrations (Somlai et al., 2011). The daily ^{222}Rn time series recorded in the monitored European dead-end caves between 2017 and 2020 are shown in Figure 3. Short data drop-outs occurred in the recorded radon time series in some of the caves due to failure of the data logging network. These were filled-in using the well-proven SSA spectral method (Ambrosino et al., 2019b), which *eigendecomposes* the time series and subsequently reconstructs them, recursively imputing the missing values using additive component regressions (Ambrosino et al., 2020a; Golyandina and Osipov, 2007). The measured radon value ranges are 633−4,321 Bq/m^3 for Rull Cave (Spain), 1,336−8,456 Bq/m^3 for Bozkov Dolomite Caves (Czechia), 2,865−11,483 Bq/m^3 for Mladeč Caves (Czechia), 3,560−26,785 Bq/m^3 for Važecká Cave (Slovakia), 3,571−11,913 Bq/m^3 for Ochtinská Aragonite Cave (Slovakia), and 743−6,769 Bq/m^3 for Županova Cave (Slovenia).

There are major differences in the radon activity concentrations among the dead-end caves (Fig. 3). The radon concentrations in Važecká Cave (Slovakia) are nearly double the general levels of the other five caves, highlighted in Fig. 3 by the secondary y-axes. The speleological characteristics of the investigated dead-end caves, i.e. the karst rocks and bedrock types, their origin, composition and ^{226}Ra content, influence the radon concentration levels (Sabbarese et al., 2017b; UNSCEAR, 2000). Discontinuities, such as cracks, faults, and fractures, permit the efficient transport of soil gases containing radon and CO_2 (Gregorič et al., 2013; Smetanová et al., 2020). Such transport occurs only if these discontinuities are not completely filled by water-carried silt or clay particles unless they are loosened by rock movements. Then, the nature of the dead-end cave characterized by limited ventilation and relative few entries, contributes to the accumulation of an increase in gas levels inside the caves. The caves appear not to be affected by proximity to nearby caves, and they do not show similar radon activity concentration values. On the other hand, the six dead-end caves exhibit very similar behavior, having an annual periodic trend. More precisely, radon levels in all of the caves reflect seasonal changes, with an increase during the start of the warm period, from around March, and a decrease during the start of the cold period, from around September. Therefore, during the cold or warm season, the radon values tend to stabilize for about three months. This periodicity, more pronounced in some of the caves but always clearly notable, suggests that natural ventilation largely controls the underground accumulation of radon.

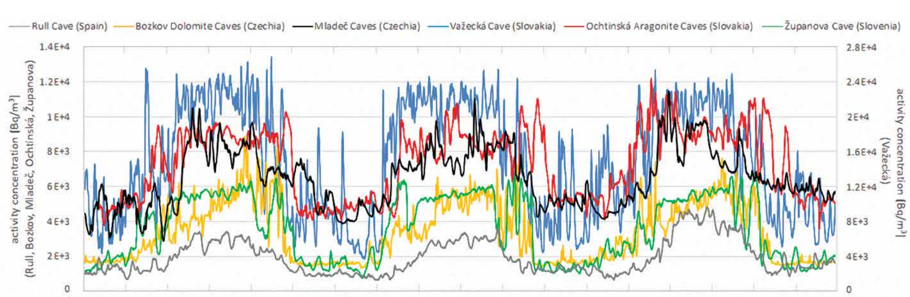

Figure 3. Daily ^{222}Rn time series of the six studied European dead-end caves for January 2017–January 2020.

To investigate this aspect, the recorded meteorological parameters were taken into account during the data processing. These parameters are monitored inside the caves alongside radon, while outside they are measured using a Weather Station data-logger located nearby. The meteorological trends of the six caves have been shown separately in several studies with different scopes during the last decade (Rovenská and Thinová, 2010; Ambrosino et al., 2020f; Pla et al., 2020; Smetanová et al., 2020). The current 2017−2020 meteorological monitoring values show a similar trend to those mentioned in the previous publications. The meteorological data are not reported in the present work so to not burden this paper with many figures. Instead, a cross-correlation study using the Matlab tool between the meteorological parameters and the ^{222}Rn activity concentrations in all of the caves was performed to find the dominant factor driving the radon variability (Ambrosino et al., 2019b). The results (not shown) conclude that the difference between the outer and inner air temperatures almost exclusively controls the ^{222}Rn changes, with an average value equal to 0.82 °C and a mean lag time impact on ^{222}Rn being one week at most. The high values of outer-inner temperature differences correspond to the high radon activity concentration levels, and vice versa. This strong dependence is also clearly visible in Fig. 4, where the two independent signals are compared for all of the caves. In the winter, significantly lower radon levels are observed compared to the summer (Sainz et al., 2018) because during the winter and early spring, cold and dense outside air enters the caves along the floor, and the soil gas with radon remains in the deeper areas of the rock massive (Kamra, 2015). This natural convective circulation, as a result of internal-external buoyancy temperature differences, causes the air flow outside to carry the radon continuously emanated from the bedrocks with it, resulting in a decrease in the radon concentrations in the caves (Rowberry et al., 2016). The ventilation mechanism is stronger in the summer when the difference between the outer-inner and concurrently noon-midnight temperature is higher, and the soil gas is drawn from the bedrock area into the cave. Therefore, due to the outdoor temperatures in the summer being higher than the constant temperatures in the caves, more radon is pulled out of the subsoil, because the inner cooler denser air keeps the radon emitted from the rocks in the caves, resulting in significantly high radon concentrations (Rovenská and Thinová, 2010).

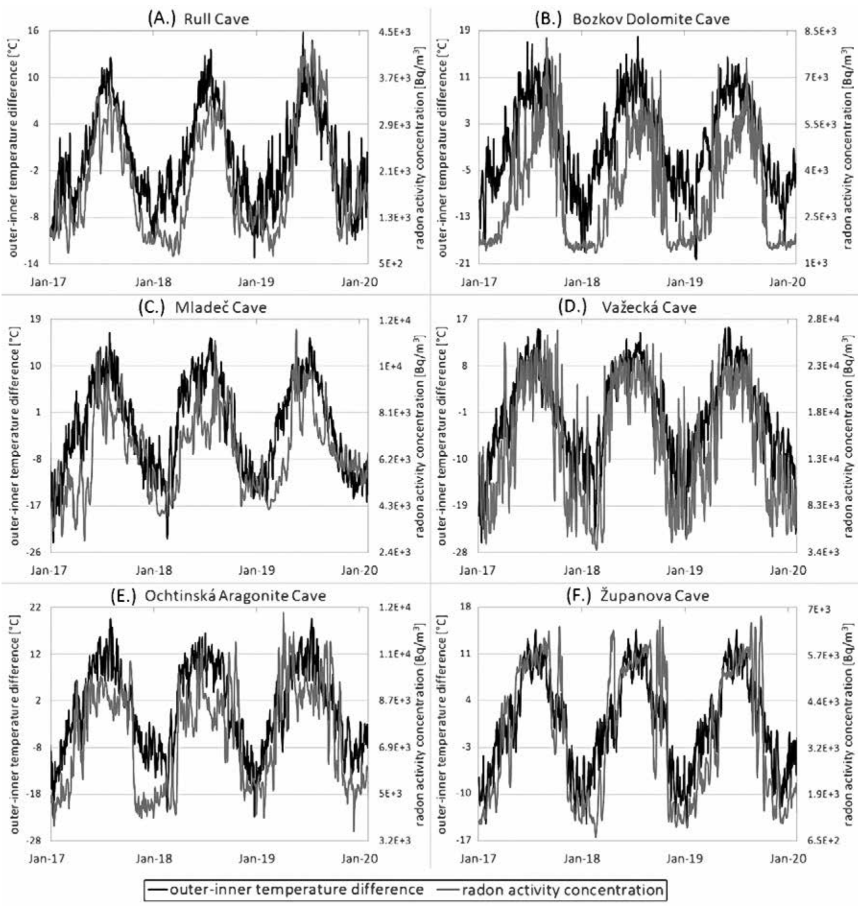

Figure 4. ^{222}Rn activity concentrations vs. the difference between outer and inner air temperatures in the six studied dead-end caves across Europe from January 2017–January2020 (the letters indicating the caves reflect those used in Figure 2). The much higher radon concentrations in Važecká Cave (Slovakia) are shown on the secondary y-axes.

To isolate the seasonal cycles, a 24-hour running continuous Pearson's (linear) correlation with a half hour step (i.e., a sort of daily correlation over time, was run using the Matlab tool) (Press et al., 2007). Similar to the seasonal variations, the diurnal variations in all of the caves are mainly influenced by the temperature difference, with a mean correlation coefficient R of 0.77. Therefore, diurnal and seasonal air exchange due to the convective circulation effect results in diurnal and seasonal fluctuations in natural gas and aerosol concentrations (Bezek et al., 2012; Sainz et al., 2018). Sifting through the literature dedicated to the issues of ^{222}Rn monitoring in caves, it is worthy to note how such a seasonal-periodic modulation found in the present work is characteristic only in dead-end caves (Zelinka 2004; Richon et al., 2005; Perrer et al., 2007; Oh and Kim, 2011; Turek et al., 2015; Ambrosino et al., 2018b; Czuppon et al., 2018; Sainz et al., 2018; Pla et al., 2020; Smetanová et al., 2020). In fact, it emerges that the show caves with more than one entry or large entries exhibit entirely different behavior with variable radon patterns not implicit for any dominant meteorological factor other than a combination of them, as is the case of Driny Cave in Slovakia (Rowberry et al., 2016), Olibano Cave in Italy (Ambrosino et al., 2019c), Zbrašov Ara-

Table 1. Pearson's (linear) correlation coefficients of ^{222}Rn time series for the six studied dead-end caves.

Location	Correlation Coef., *R*
Ochtinská - Županova	0.82
Ochtinská - Važecká	0.72
Ochtinská - Bozkov	0.75
Ochtinská - Mladeč	0.60
Županova - Važecká	0.83
Županova - Bozkov	0.82
Županova - Mladeč	0.72
Važecká - Bozkov	0.76
Važecká - Mladeč	0.68
Bozkov - Mladeč	0.68
Rull - Ochtinská	0.62
Rull - Mladeč	0.76
Rull - Bozkov	0.76
Rull - Važecká	0.70
Rull - Županova	0.73

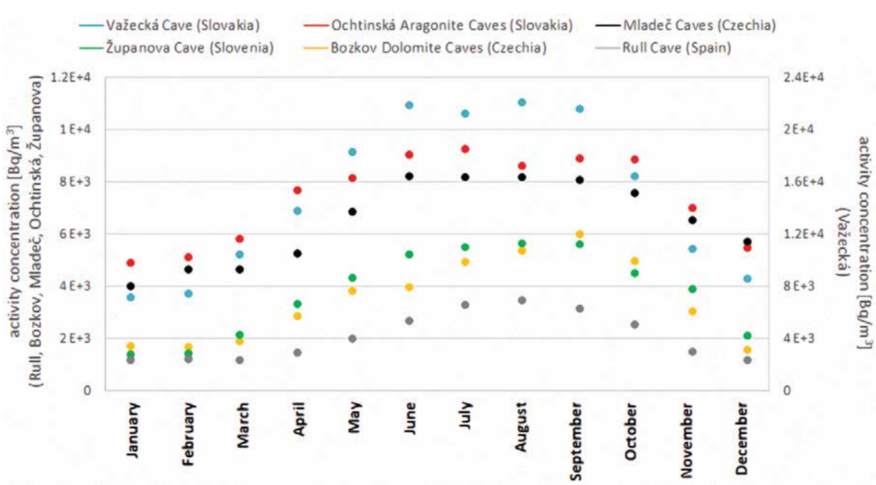

Figure 5. Average monthly variations per mean year of ^{222}Rn activity concentrations in the six studied dead-end caves, for the monitoring period January 2017–January 2020. The much higher radon concentrations in Važecká Cave (Slovakia) are shown on the secondary y-axes.

gonite Caves in Czechia (Briestenský et al., 2014), Jenolan Caves in Australia (Zahorowski et al., 1998), Tapolca Cave in Hungary (Somlai et al., 2009), Maomaotou Big Cave in China (Tang et al., 2020), and others all over the world.

Two additional analyses were performed to determine the degree of similarity among the six studied caves qualitatively visible in Figure 3, and also to highlight the seasonal variations of the ^{222}Rn time series: a Pearson's (linear) correlation analysis (Press et al., 2007) of ^{222}Rn signals among the caves (Table 1), and the monthly average of ^{222}Rn activity concentration levels per mean year (Fig. 5). The results of the correlation analysis in Table 1 show how the six dead-end caves have similar radon levels, with *R* values greater than or equal to 0.6, and with a maximum *R* of 0.83 and mean values of *R* 0.73 ± 0.06. These high correlation coefficient values, together with Figure 5, confirm and summarize what has been constantly stated in our paper (i.e., the periodic annual seasonality of the ^{222}Rn signals in the dead-end caves with overall levels increasing from the cold to the warm season (Perrer et al., 2007; Dueñas et al., 2011; Oh and Kim, 2011; Sainz et al., 2018).

Figures 3 and 5 validate the high radon activity concentrations, ranging from 633 Bq/m^3 to 26,785 Bq/m^3, recorded inside all of the dead-end caves. The latest European Union Directive on ionizing radiation protection (2013/59/Euratom) establishes a reference level for the annual average of indoor radon activity concentrations in air of 300 Bq/m^3 (Euratom, 2014), which also extends to all show caves and agencies granting permission for activities in non-tourist caves (Field, 2007; Dumitru et al., 2015). All of the investigated dead-end caves are well above the European Union reference level for indoor radon gas of 300 Bq/m^3, whereby posing a potential radiological health hazard to cave guides, cavers, and also occasional visitors and employees (Lario et al., 2005; Thinová et al., 2005a; Somlai et al., 2009; Ambrosino et al., 2020f). Our survey on dead-end caves may be a further contribution to the radon concentration monitoring effort in caves worldwide, also aiming to put in evidence on the risk level due to radon inhalation and its human health impact on people in dead-end caves. Therefore, we expect these results to be of great interest to the administrative staff of the investigated show caves and, at the same time, agencies involved in granting permits to access these caves, to inform employees and the public about the high levels of radon in the caves, especially during the summer, and to recommend adequate local regulations.

CONCLUSIONS

Dead-end show caves are underground environments with no significant ventilation, a relatively stable climate, and only one or two small entry points. In this study, six dead-end caves across Europe were continuously monitored with the aim of investigating the ^{222}Rn levels in relation to meteorological parameters. Different elevated radon activity concentrations, ranging from 633 Bq/m^3 to 26,785 Bq/m^3, were recorded during January 2017 to January 2020. The environments of the caves show a very similar behavior (calculated mean linear correlation factor *R* of 0.73 ± 0.06), with stable ^{222}Rn activity concentrations and particular periodic trends indicating strong seasonal changes, higher in the summer rather than in the winter. Air density differences between cave air and the outside atmosphere may create density-driven flows, resulting in air exchange between the cave and the atmosphere outside. Because air density is influenced by temperature, the temperature gradient between the outer and inner atmospheres of the dead-end caves is the dominant meteorological parameter (mean cross-correlation factor *R* of 0.82) determining the variation in radon levels. All of the investigated dead-end caves exceed the European reference level of indoor annual average radon concentration of 300 Bq/m^3. The results obtained in this work may help to improve the characterization of special dead-end cave environments, and underline the importance of radon monitoring to assess the radiation risk for people entering and remaining for a certain time. The presented paper is a first comprehensive radon survey focused on dead-end show caves in Europe.

ACKNOWLEDGEMENTS

The authors would like to express thanks to the involved caves Administrations for the support provided during the investigation. Our work was also supported by: the Centre of Advanced Applied Sciences [CZ.02.1.01/0.0/0.0/16–019/0000778], the CzechGeo-EPOS project 'Distributed system of permanent observatory measurements and temporary monitoring of geophysical fields in the Czech Republic' [CZ.02.1.01/0.0/0.0/16_013/0001800], the Long-term Conceptual Development Research Organization [RVO: 67985891], the Spanish Ministry of Science, Innovation, and Universities [grant number RTI2018-099052-B-I00], the Regional Government of Comunidad Valenciana (Spain) [grant number AICO/2020/175], the Scientific Grant Agency of the Ministry of Education, Science, Research and Sport of the Slovak Republic (VEGA project no. 2/0083/18 and 2/0015/21).

REFERENCES

Ambrosino, F., 2020, Study on a peak shape fitting model for the analysis of alpha-particle spectra: Applied Radiation and Isotopes, v. 159, p. 109090. https://doi.org/10.1016/j.apradiso.2020.109090.

Ambrosino, F., Buompane, R., Pugliese, M., Roca, V., and Sabbarese, C., 2018a, RaMonA system for radon and thoron measurement: Nuovo Cimento C, v. 41, no. 6, p. 222. https://doi.org/10.1393/ncc/i2018-18222-5.

Ambrosino, F., De Cesare, W., Roca, V., and Sabbarese, C., 2019c, Mathematical and geophysical methods for searching anomalies of the Radon signal related to earthquakes: Journal of Physics: Conference Series, v. 1226, p. 012025. https://doi.org/10.1088/1742-6596/1226/1/012025.

Ambrosino, F., Pugliese, M.,Roca, V., and Sabbarese, C., 2018b, Innovative methodologies for the analysis of radon time series: Nuovo Cimento C, v. 41, no. 6, p. 223. https://doi.org/10.1393/ncc/i2018-18223-4.

Ambrosino, F., Roca, V., Buompane, R., and Sabbarese, C., 2020b, Development and calibration of a method for direct measurement of ^{220}Rn (Thoron) activity concentration: Applied Radiation and Isotopes, v. 166, p. 109310. https://doi.org/10.1016/j.apradiso.2020.109310.

Ambrosino, F., Sabbarese, C., Roca, V., Giudicepietro, F., and De Cesare,W., 2020a, Connection between ^{222}Rn emission and geophysical-geochemical parameters recorded during the volcanic unrest at Campi Flegrei caldera (2011-2017): Applied Radiation and Isotopes, v. 166, p. 109385. https://doi.org/10.1016/j.apradiso.2020.109385.

Ambrosino, F., Sabbarese, C., Roca, V., Giudicepietro, F., and Chiodini, G., 2020c, Analysis of 7-years Radon time series at Campi Flegrei area (Naples, Italy) using artificial neural network method: Applied Radiation and Isotopes, v. 163, p. 109239. https://doi.org/10.1016/j.apradiso.2020.109239.

Ambrosino, F., Thinová, L., Briestenský, M., and Sabbarese, C., 2019a, Analysis of Radon time series recorded in Slovak and Czech caves for the detection of anomalies due to seismic phenomena: Radiation Protection Dosimetry, v. 186, no. 2-3, p. 428–432. https://doi.org/10.1093/rpd/ncz245.

Ambrosino, F., Thinová, L., Briestenský, M., and Sabbarese, C., 2019b, Anomalies identification of Earth's rotation rate time series (2012–2017) for possible correlation with strong earthquakes occurrence: Geodesy and Geodynamics, v. 10, no. 6, p. 455–459. https://doi.org/10.1016/j.geog.2019.06.002.

Ambrosino, F., Thinová, L., Briestenský, M., Giudicepietro, F., Roca, V., and Sabbarese, C., 2020d, Analysis of geophysical and meteorological parameters influencing ^{222}Rn activity concentration in Mladeč caves (Czech Republic) and in soils of Phlegrean Fields caldera (Italy): Applied Radiation and Isotopes, v. 160, p. 109140. https://doi.org/10.1016/j.apradiso.2020.109140.

Ambrosino, F., Thinová, L., Briestenský, M., Šebela, S., and Sabbarese, C., 2020e, Detecting time series anomalies using hybrid methods applied to Radon signals recorded in caves for possible correlation with earthquakes: Acta Geodaetica et Geophysica, v. 55, p. 405–420. https://doi.org/10.1007/s40328-020-00298-1.

Ambrosino, F., Thinová, L., Briestenský, M., and Sabbarese, C., 2020f, Study of ^{222}Rn continuous monitoring time series and dose assessment in six European caves: Radiation Protection Dosimetry, v. 191, no. 2, p. 233–237. https://doi.org/10.1093/rpd/ncaa159.

Ambrosino, F., Thinová, L., Hýža, M., and Sabbarese, C., 2020g, ^{214}Bi/^{214}Pb radioactivity ratio three-year monitoring in rainwater in Prague: Nukleonika, v. 65, no. 2, p. 115–119. https://doi.org/10.2478/nuka-2020-0018.

Badino, G., 2010, Underground meteorology - "What's the weather underground?": Acta Carsologica, v. 39, no. 3, p. 427–448. https://doi.org/10.3986/ac.v39i3.74.

Bahtijari,M., Vaupotič, J., Gregorič, A., Stegnar, P., and Kobal, I., 2008. Exposure to radon in the Gadime Cave, Kosovo: Journal of Environmental Radioactivity, v. 99, p. 343–348. https://doi.org/10.1016/j.jenvrad.2007.08.003.

Bella, P., Littva, J., Pruner, P., Bosák, P., Šlechta, S., Hercman, H., and Čížiková, K., 2016, Geological setting, morphology and evolution of the Važecká Cave, Slovakia: Acta Carsologica Slovaca, v. 54, no. 1, p. 5–31.

Bezek, M., Gregorič, A., Kávási, N., and Vaupotič, J., 2012, Diurnal and seasonal variations of concentration and size distribution of nano aerosols (10–1100 nm) enclosing radon decay products in the Postojna Cave, Slovenia: Radiation Protection Dosimetry, v. 152, no. 1-3, p. 174–178. https://doi.org/10.1093/rpd/ncs218.

Bosák, P., Bella, P., Cílek, V., Ford, D.C., Hercman, H., Kadlec, J., Osborne, A., and Pruner, P., 2002, Ochtiná Aragonite Cave (Western Carpathians, Slovakia): Morphology, mineralogy of the fill and genesis: Geologica Carpathica, v. 53, no. 6, p. 399-410.

Briestenský, M., Thinová, L., Praksová, R., Stemberk, J., Rowberry, M.D., and Knejflová, Z., 2014, Radon, carbon dioxide and fault displacements in central Europe related to the Tōhoku earthquake: Radiation Protection Dosimetry, v. 160, no. 1-3, p. 78–82. https://doi.org/10.1093/rpd/ncu090.

Cigna, A.A., 2005, Radon in caves: International Journal of Speleology, v. 34, no. 1–2, p. 1–18. https://doi.org/10.5038/1827-806X.34.1.1.

Czuppon, G., Demény, A., Leél-Ossy, S., Ótvari, M., Molnár, M., Stieber, J., Kiss, K., Kármár, K., Surányi, G., and Harzpra, L., 2018, Cave monitoring in the Béke and Baradla caves (Northeastern Hungary): implications for the conditions for the formation cave carbonates: International Journal of Speleology, v. 47, no. 1, p. 13–28. https://doi.org/10.5038/1827-806X.47.1.2110.

Darby, S., Hill, D., and Doll, R., 2001, Radon: A likely carcinogen at all exposures: Annals of Oncology, v. 12, no. 10, p. 1341–1351. https://doi.org/10.1023/A:1012518223463.

Droppa, A., 1962, Speleologický výskum Važeckého krasu (Speleological research of Važec karst area): Geografical Journal, v. 14, no. 4, p. 264–293. https://doi.org/10.1016/j.radmeas.2011.06.039.

Dueñas, C., Fernández, M.C., Cañete, S., Pérez, M., and Gordo, E., 2011, Seasonal variations of radon and the radiation exposure levels in Nerja cave, Spain: Radiation Measurements, v. 46, no. 10, p. 1181–1186. https://doi.org/10.1016/j.radmeas.2011.06.039.

Dumitru, O.A., Onac, B.P., Fornós, J.J., Cosma, C., Ginés, A., Ginés, J., and Merino, A., 2015, Radon survey in caves from Mallorca Island, Spain: Science of The Total Environment, v. 526, p. 196–203. https://doi.org/10.1016/j.scitotenv.2015.04.076.

Etiope, G., and Martinelli, G., 2001, Migration of carrier and trace gases in the geosphere: An overview: Physics of Earth Planet Interiors, v. 129, p. 185–204. https://doi.org/10.1016/S0031-9201(01)00292-8.

Euratom, 2014, Council Directive 2013/59/Euratom of 5 December 2013 laying down basic safety standards for protection against the dangers arising from exposure to ionising radiation, and repealing Directives 89/618/Euratom, 90/641/Euratom, 96/29/Euratom, 97/43/Euratom and 2003/122/Euratom: Official Journal of the European Union, v. 57, p. 1–73.

Field, M.S., 2007, Risks to cavers and cave workers from exposures to low-level ionizinga radiation from ^{222}Rn decay in caves: Journal of Cave and Karst Studies, v. 69, no. 1, p. 207–228.

Gaál, Ľ., 2004, Geológia Ochtinskej aragonitovej jaskyne: Slovenský kras, v. 42, p. 37–56.

Garcia-Anton, E., Cuezva, S., Fernandez-Cortes, A., Alvarez-Gallego, M., Pla, C., Benavente, D., Cañaveras, J.C., and Sanchez-Moral, S., 2017, Abiotic and seasonal control of soil-produced CO2 efflux in karstic ecosystems located in oceanic and Mediterranean climates: Atmospheric Environment, v. 164, p. 31–49. https://doi.org/10.1016/j.atmosenv.2017.05.036.

Golyandina, N., and Osipov, E., 2007, The “Caterpillar”-SSA method for analysis of time series with missing values: Journal of Statistical Planning and Inference, v. 137, p. 2642–2653. https://doi.org/10.1016/j.jspi.2006.05.014.

Gregorič, A., Vaupotič, J., and Gabrovšek, F., 2013, Reasons for large fluctuation of radon and CO_2 levels in a dead-end passage of a karst cave (Postojna Cave, Slovenia): Natural Hazards and Earth System Sciences, v. 13, p. 287–297. https://doi.org/10.5194/nhess-13-287-2013.

Hromas, J., 2009, Caves, *in* Mackovčin, P., and Sedláček, M., eds., Protected Natural Areas of the Czech Republic, Bundle XIV, p. 382–385.

Kamra, L., 2015, Seasonal emanation of radon at Ghuttu, northwest Himalaya: Differentiation of atmospheric temperature and pressure influences: Applied Radiation and Isotopes, v. 105, p. 170–175. https://doi.org/10.1016/j.apradiso.2015.08.031.

Kobal, I., Burger, J., Smodiš, B., and Škofljanec, M., 1986, Radon concentrations in Slovene tourist Caves: Naše jame, v. 28, p. 11–17.

Kumar, A., Singh, S., Mahajan, S., Bajwa Singh, B., Kalia, R., and Dhar, S., 2009, Earthquake precursory studies in Kangra valley of North West Himalayas, India, with special emphasis on radon emission: Applied Radiation and Isotopes, v. 67, no. 10, p. 1904–1911. https://doi.org/10.1016/j.apradiso.2009.05.016.

Lario, J., Sánchez-Moral, S., Cañaveras, J.C., Cuezva, S., and Soler, V., 2005, Radon continuous monitoring in Altamira Cave (northern Spain) to assess user’s annual effective dose: Journal of Environmental Radioactivity, v. 80, no. 2, p. 161–174. https://doi.org/10.1016/j.jenvrad.2004.06.007

Legarda, F., Idoeta, R., Alegría, N., and Herranz, M., 2010, An active radon sampling device for high humidity places: Radiation Measurements, v. 45, no. 1, p. 122–128. https://doi.org/10.1016/j.radmeas.2010.01.003.

Nero, A.V., 1988, Radon and its decay products in indoor air: an overview, *in* Nazaroff, W.W., and Nero, Jr., A.V., eds., Radon and its Decay Products in Indoor Air, New York, John Wiley & Sons, p. 1–53.

Oh, Y.H., and Kim, G., 2011, Factors controlling the air ventilation of a limestone cave revealed by ^{222}Rn: Geosciences Journal, v. 15, no. 1, p. 115–119. https://doi.org/10.1007/s12303-011-0010-3.

Pantelić, G., Čeliković, I., Živanović, M., Vukanac, I., Nikolić, J.K., Cinelli, G., and Gruberc, V., 2019, Qualitative overview of indoor radon surveys in Europe: Journal of Environmental Radioactivity, v. 204, p. 163–174. https://doi.org/10.1016/j.jenvrad.2019.04.010.

Perrier, F., Richon, P., Gautam, U., Tiwari, D.R., Shrestha, P., and Sapkota, S.N., 2007, Seasonal variations of natural ventilation and radon-222 exhalation in a slightly rising dead-end tunnel: Journal of Environmental Radioactivity, v. 97, no. 2-3, p. 220–235. https://doi.org/10.1016/j.jenvrad.2007.06.003.

Pla, C., Cuezva, S., Garcia-Anton, E., Fernandez-Cortes, A., Cañaveras, J.C., Sanchez-Moral, S., and Benavente, D., 2016, Changes in the CO_2 dynamics in near-surface cavities under a future warming scenario: factors and evidence from the field and experimental findings: Science of the Total Environment, v. 565, p. 1151–1164. https://doi.org/10.1016/j.scitotenv.2016.05.160

Pla, C., Cuezva, S., Martinez-Martinez, J., Fernandez-Cortes, A., Garcia-Anton, E., Fusi, N., Crosta, G.B., Cuevas-Gonzalez, J., Cañaveras, J.C., Sanchez-Moral, S., and Benavente, D., 2017, Role of soil pore structure in water infiltration and CO2 exchange between the atmosphere and underground air in the vadose zone: A combined laboratory and field approach: Catena, v. 149, p. 402-416. https://doi.org/10.1016/j.catena.2016.10.018.

Pla, C., Fernandez-Cortes, A., Cuezva, S., Galiana-Merino, J.J., Cañaveras, J.C., Sanchez-Moral, S., and Benavente, D., 2020, Insights on climate-driven fluctuations of cave ^{222}Rn and CO_2 concentrations using statistical and wavelet analyses: Geofluids, v. 2020. https://doi.org/10.1155/2020/8858295.

Placer, L., 2008, Principles of the tectonic subdivision of Slovenia: Geologija, v. 51, no. 2, p. 205–217. https://doi.org/10.5474/geologija.2008.021.

Prelovšek, M., Šebela, S., and Turk J., 2018, Carbon dioxide in Postojna Cave (Slovenia): spatial distribution, seasonal dynamics and evaluation of plausible sources and sinks: Environmental Earth Sciences, v. 77, p. 289. https://doi.org/10.1007/s12665-018-7459-6.

Press, W.H., Teukolsky, S.A., Vetterling, W.T., and Flannery, B.P., 2007, Numerical Recipes: The Art of Scientific Computing, Third Edition: New York, Cambridge University Press, 745 p.

Ravbar, N., and Košutnik, J., 2014, Variations of karst underground air temperature induced by various factors (Cave of Županova jama, Central Slovenia): Theoretical and Applied Climatology, v. 116, p. 327–341. https://doi.org/10.1007/s00704-013-0955-4.

Richon, P., Perrier, F., Sabroux, J-C., Trique, M., Ferry, C., Voisin, V., and Pili, E., 2005. Spatial and time variations of radon-222 concentration in the atmosphere of a dead-end horizontal tunnel: Journal of Environmental Radioactivity, v. 78, p. 179–198. https://doi.org/10.1016/j.jenvrad.2004.05.001.

Rovenská, K., and Thinová, L., 2010, Seasonal variation of radon in the Bozkov cave: Nukleonika, v. 55, no. 4, p. 483–489.

Rovenská, K., Thinová, L., and Ždímal, V., 2008, Assessment of the dose from radon and its decay products in the Bozkov dolomite cave: Radiation Protection Dosimetry, v. 130, no. 1, p. 34–37. https://doi.org/10.1093/rpd/ncn114.

Rowberry, M.D., Martí, X., Frontera, C., Van De Wiel, M.J., and Briestenský, M., 2016, Calculating flux to predict future cave radon concentrations: Journal of Environmental Radioactivity, v. 157, p. 16–26. https://doi.org/10.1016/j.jenvrad.2016.02.023.

Sabbarese, C., Ambrosino, F., Buompane, R., Pugliese, M., and Roca, V., 2017a, analysis of alpha particles spectra of the radon and thoron progenies generated by an electrostatic collection detector using new software: Applied Radiation and Isotopes, v. 122, p. 180–185. https://doi.org/10.1016/j.apradiso.2017.01.042.

Sabbarese, C., Ambrosino, F., De Cicco, F., Pugliese, M., Quarto, M., and Roca, V., 2017b, Signal decomposition and analysis for the identification of periodic and anomalous phenomena in radon time-series: Radiation Protection Dosimetry, v. 177, no, 1-2, p. 202–206. https://doi.org/10.1093/rpd/ncx159.

Sabbarese, C., Ambrosino, F., D'Onofrio, A., and Roca, V., 2020a, Radiological characterization of natural building materials from the Campania region (Southern Italy): Construction and Building Materials, v. 268. https://doi.org/10.1016/j.conbuildmat.2020.121087.

Sabbarese, C., Ambrosino, F., Chiodini, G., Giudicepietro, F., Macedonio, G., Caliro, S., De Cesare, W., Bianco, F., Pugliese, M., and Roca, V., 2020b, Continuous Radon monitoring during seven years of volcanic unrest at Campi Flegrei caldera (Italy): Scientific Reports, v. 10, p. 9551. https://doi.org/10.1038/s41598-020-66590-w.

Sabbarese, C., Ambrosino, F., and D'Onofrio, A., 2021, Development of radon transport model in different types of dwellings to assess indoor activity concentration: Journal of Environmental Radioactivity, v. 227, p. 106501. https://doi.org/10.1016/j.jenvrad.2020.106501.

Sainz, C., Quindós, L.S., Fuente, I., Nicolas, J., and Quindós, L., 2007, Analysis of themain factors affecting the evaluation of the radon dose in workplaces: the case of tourist caves: Journal of Hazardous Materials, v. 145, p. 368–371. https://doi.org/10.1016/j.jhazmat.2006.11.033.

Sainz, C., Rábago, D., Celaya, S., Fernández, E., Quindós, G., Quindós, L., Fernández, A., Fuente, I., Arteche, J.L., and Quindós, L.S., 2018, Continuous monitoring of radon gas as a tool to understand air dynamics in the cave of Altamira (Cantabria, Spain): Science of the Total Environment, v. 624, p. 416–423. https://doi.org/10.1016/j.scitotenv.2017.12.146.

Šebela, S., Vaupotič, J., Košťák, B., and Stemberk, J. 2010, Direct measurement of present-day tectonic movement and associated radon flux in Postojna Cave, Slovenia: Journal of Cave and Karst Studies, v. 72, no. 1, p. 21-34. https://doi.org/10.4311/jcks2009es0077.

Smetanová, I., Holý, K., Luhová, L., Csicsay, K., Haviarová, D., and Kunáková, L., 2020, Seasonal variation of radon and CO_2 in the Važecká Cave, Slovakia: Nukleonika, v. 65, no. 2, p. 153–157. https://doi.org/10.2478/nuka-2020-0025.

Somlai, J., Hakl., J., Kávási, N., Szeiler, G., Szabó, P., and Kovács, T., 2011, Annual average radon concentration in the show caves of Hungary: Journal of Radioanalytical and Nuclear Chemistry, v. 287, p. 427–433. https://doi.org/10.1007/s10967-010-0841-9.

Somlai, J., Szeiler, G., Szabó, P., Várhegyi, A., Tokonami, S., Ishikawa, T., Sorimachi, A., Yoshinaga, S., and Kovács, T., 2009, Radiation dose of workers originating from radon in the show Cave of Tapolca, Hungary: Journal of Radioanalytical and Nuclear Chemistry, v. 279, no.1, p. 219–225. https://doi.org/10.1007/s10967-007-7307-3.

Špaček, P., Bábek, O., Štepancíková, P., Švancara, J., Pazdírková, J., and Sedláček, J., 2015, The Nysa Morava zone: an active tectonic domain with Late Cenozoic sedimentary grabens in the Western Carpathians' foreland (NE Bohemian Massif): International Journal of Earth Sciences, v. 104, no. 4, p. 963–990. http://dx.doi.org/10.1007/s00531-014-1121-7.

Stein, L., 1987, Chemical properties of radon, in Hopke, P.K., ed., Radon and Its Decay Products: occurrence, properties, and health effects: Washington, D.C., American Chemical Society, p. 241–251.

Stránský, V., and Thinová, L., 2017. Radon concentration time series modeling and application discussion: Radiation Protection Dosimetry, v. 177, no. 1-2, p. 155–159. https://doi.org/10.1093/rpd/ncx207.

Tang, W., Lan, G., Yang, H., Yin, J.-J., and Pu, J., 2020, Variations and influence factors of ^{210}Pb-specific radioactivity in modern calcite depositions in a subtropical cave, South China: Applied Geochemistry, v. 113, p. 104468. https://doi.org/10.1016/j.apgeochem.2019.104468.

Thinová, L., Berka, Z., Brandejsova, E., Ždímal, V., and Milka, D., 2005a, Effective dose calculation using radon daughters and aerosol particles measurement in Bozkov Dolomite Cave: International Congress Series, v. 1276, p. 381–382. https://doi.org/10.1016/j.ics.2004.11.114.

Thinová, L., and Burian, I., 2008, Effective dose assessment for workers in caves in the Czech Republic-experiments with passive radon detectors: Radiation Protection Dosimetry, v. 130, no. 1, p. 48–51. https://doi.org/10.1093/rpd/ncn118.

Thinová, L., Fronka, A., and Milka, D., 2005b, Personal dosimetry enhancement for underground workplaces: Acta Polytechnica, v. 45, no. 5, p. 44–47. https://doi.org/10.14311/770.

Turek, K., Stefanov, P., Svetlik, I., Orcikova, H., and Simek, P., 2015, Radon and CO_2 concentration screening in Bulgarian caves: International Journal of Geoheritage, v. 3, no. 2, p. 14–23. https://doi.org/10.17149/ijg.j.issn.2210.3382.2015.02.003.

UNSCEAR, 2000, Sources and effects of ionizing radiation – Annex B: Exposures from natural radiation sources, UNSCEAR 2000 Report Vol. I, Vienna, Austria, United Nations Scientific Committee on the Effects of Atomic Radiation, 156 p.

Wigley, T.M.L., 1967, Non-steady flow through a porous medium and cave breathing: Journal of Geophysical Research, v. 72, no. 12, p. 3199–3205. https://doi.org/10.1029/JZ072i012p03199.

Zahorowski, W., Whittlestone, S., and James, J.M., 1998, Continuous measurements of radon and radon progeny as a basis for management of radon as a hazard in a tourist cave: Journal of Radioanalytical and Nuclear Chemistry, v. 236, no. 1–2, p. 219-225. https://doi.org/10.1007/BF02386346.

Zelinka, J., 2004, Prehľad najnovších poznatkov z mikroklimatického monitoringu ochtinskej aragonitovej jaskyne (Summary of the newest knowledges of the microclimatic monitoring in the Ochtinská Aragonite Cave): Slovenský kras, v. 42, p. 109–120.