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COMMENT

Radon concentration variability and microclimate controls in two Slovene show caves

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Abstract

The study presents 8-years long dataset (2017–2025) of high-resolution radon concentration measurements in Županova Jama and 2-years long dataset (2022–2024) in Postojnska Jama. Radon concentrations from two show caves were compared with outside and cave air temperature as well as atmospheric pressure to assess diurnal and seasonal variability. Županova Jama showed consistently higher radon levels with a 2023 mean of 4030 Bq/m³, compared to 2278 Bq/m³ in Postojnska Jama. Diurnal variations occurred in both caves, with night values typically higher in Županova Jama, while Postojnska Jama displayed day and night concentrations more balanced depending on ventilation regimes. In Postojnska Jama, summer radon maxima followed outside air temperature peaks with a 12–18 h lag. Seasonally, both caves showed higher radon concentrations in summer and lower in winter. Long-term monitoring near Županova Jama revealed an increase in mean outside air temperature (+0.86 °C from 2018 to 2024) and a parallel rise in radon, particularly in 2023–2024. The influence of atmospheric pressure was found to be seasonally dependent at both sites, with higher radon concentrations during periods of stable summer pressure and lower values during higher winter oscillations. Exposure limits indicate safe annual times of 512 h for Postojnska Jama and 284–289 h for Županova Jama, values not hazardous for visitors but important for cave guides. The findings underline the importance of continuous monitoring and cave-specific ventilation management to mitigate long-term health risks.

Keywords Radon concentration · Air temperature · Atmospheric pressure · Radiation exposure levels · Postojnska Jama · Županova Jama · Slovenia

Introduction

Studies of radon (^{222}Rn, radon) concentrations in Slovene caves and karst areas have a long tradition (Kobal et al. 1978; Kobal et al.1986; Kobal et al.1988; Vaupotič et al. 1998; Vaupotič et al. 2001; Vaupotič 2010). The main aims were to determine radon ranges in show caves, analyze seasonal variations, and estimate effective radon doses for workers and visitors. Permanent radon concentration monitoring in Postojnska Jama started in 1995 (Vaupotič et al. 2001) and continues today. Study of karst requires a geosystem approach and integrated monitoring including radon concentration (Stefanov et al. 2025).

Caves are of particular interest for radon research because concentrations can reach extreme values. Up to 80,000 Bq/m³ were reported in Venezuelan caves (Sajó-Bohus et al. 1997), 123,000 Bq/m³ in Shawan Cave, China (Wang et al. 2019), 26,785 Bq/m³ in Važecká Cave, Slovakia (Briestensky et al. 2022), and 20,000 Bq/m³ in Villanova Cave, Italy (Garavaglia et al. 1998). In Croatia's Modrič Cave, seasonal averages reached 13,600 Bq/m³ (Lončarić et al. 2023). In Postojnska Jama, Pisani Rov passage showed annual averages of 25,020 ± 12,653 Bq/m³ and maxima of 44,600 Bq/m³ (Gregorič et al. 2013; Bezuidenhout and le Roux 2024). In most Bulgarian show caves, typical variation is 1,000–2,000 Bq/m³ (Kunovska et al. 2023).

Radon concentration variability in caves is closely linked with microclimatic parameters such as temperature,

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pressure, CO_2, and ventilation (Vaupotič 2008; Gregorič et al. 2013). Radon is therefore an important natural tracer of transport processes at the lithosphere–hydrosphere–atmosphere interface (Cigna 2005). In Postojnska Jama, seasonal changes reflect convective airflow controlled by the temperature difference between the cave and outside air: concentrations rise in summer, while in winter fissures act as chimneys ventilating radon-rich cave air (Kobal et al. 1988; Gregorič et al. 2013). Globally, three seasonal patterns are recognized: (1) high in summer, low in winter; (2) similar in both seasons; or (3) high in winter, low in summer (Wang et al. 2019). In case of Niedźwiedzia Cave (Poland) the unquestionable influence of convective air exchange between the cave and the atmosphere on seasonal and short-term (diurnal) changes in ^{222}Rn activity concentration in cave air was confirmed (Przylibski et al. 2015).

Radon and CO_2 in caves derive from several sources: geogas flux through fractured rocks, clay sediments, and soil layers above the cave (Gregorič et al. 2013). Concentrations depend on radium content, porosity, air and water circulation, pressure, and tectonic activity (Cigna 2005). Hydrological processes dominate radon variability in Bossea Cave, Italy (Biamino et al. 2024), while rainfall-driven permeability changes influence Jenolan Caves, Australia (Whittlestone et al. 2003). Modeling radon sources using effective radium concentration (ECRa) and stored available radon (SAR) has also proved to be useful in heritage preservation (Perrier et al. 2024).

Geological context strongly affects radon potential. Stratigraphy, tectonics, and volcanism are key controls (Etiope 1999; Šebela et al. 2010; Briestenský et al. 2014; Ambrosino et al. 2020a, b, c). Radon derives from rocks, clastic sediments, and cave fills (Whittlestone et al. 2003; Ambrosino et al. 2020b). High radon potential is characteristic of granitic intrusions (SW England), Carboniferous limestones (Derbyshire), and Jurassic ironstones (Northamptonshire), due to uranium-rich soils, organic accumulation, fracturing, and past mining (Scheib et al. 2013). In Creswell Crags caves (UK), radon levels (27–7800 Bq/m^3) rise with distance from the entrance, with summer–winter ratios between 1.1 and 9.5 (Gillmore et al. 2002).

Soil and surface factors also matter. Statistical analyses show that soil water content is the most significant parameter influencing radon, being proportional to radon activity and inversely related to temperature, evapotranspiration, and pressure (Gil-Oncina et al. 2024).

Faults and tectonic activity further enhance radon fluxes. In California, concentrations rise by three orders of magnitude within a few meters of the surface near fault zones (King et al. 1996; Richon et al. 2010). At the Kunlun Fault (China) radon flux exceeded 600 mBq m^{-2} s^{-1} (Richon et al. 2010). In Slovenia, the Ravne Fault yielded 900–32,900 Bq/m^3 (Vaupotič et al. 2010). Soil-gas anomalies of CO_2, Rn, and He are also common in Italian fault zones (Etiope 1999).

Radon anomalies often accompany seismic activity and may precede earthquakes. The short-lived isotope thoron (^{220}Rn, half-life = 55.6 s) is particularly sensitive, recording earthquake signals without interference from other environmental effects. Large ^{220}Rn peaks were observed in Korea in February 2011, preceding the M 9.0 Tōhoku-Oki earthquake ~ 1200 km away (Hwa Oh and Kim 2015). Similarly, anomalous radon and CO_2 concentrations in the Bohemian Massif and Western Carpathians coincided with the same earthquake, interpreted as evidence of contemporaneous global tectonic changes (Briestenský et al. 2014). Long-term radon time series in Czech and Italian sites also revealed correlations with fumarolic tremors and fault micro-displacements, allowing interpretations of Earth movements and seismic events, even at remote distances (Ambrosino et al. 2020c).

In Postojnska Jama, radon concentration has been linked to micro-tectonic movements along the NW–SE Dinaric fault zone. Horizontal fault motion partly closed radon pathways, reducing concentrations, whereas compression opened new routes, facilitating radon migration and increasing air concentrations (Šebela et al. 2010).

The aim of this study was to establish long-term radon monitoring at two show caves in Slovenia, Postojnska Jama and Županova Jama, located ~ 50 km apart in the northern and northwestern External Dinarides. We focused on detecting diurnal and seasonal variations, correlating radon concentrations with cave microclimate and external climate (temperature and pressure), and estimating allowable exposure times for guides and visitors based on annual radon averages.

Sources of radon in Slovene caves

Understanding the geological and environmental sources of radon is essential for interpreting the concentration levels measured in caves. As mentioned by Vukotić et al. (2025), the isotope ^{222}Rn is a daughter product of ^{226}Ra, which itself is a decay product of ^{238}U. Radon and its short-lived progeny make the largest contribution to the effective dose received by humans from natural sources of radiation. Geogenic ^{222}Rn released to the atmosphere comes mostly from basalt and limestone bedrock (Vukotić et al. 2025). Extensive karstification of limestone, with networks of cavities, fissures, faults, dolines, caves, and underground water systems, together with absorption of radium by residual clay coatings in fractures and solution cavities, enhances radon concentrations. This is also due to the greater mobility of radium in the environment compared to uranium (Vukotić et al. 2025).

Measurements of radon in soil gas in Slovenia show good correlation with equivalent uranium concentrations, with some exceptions in karst regions (Andjelov and Brajnik 1996), where radon concentrations belong among the highest in the country.

Although uranium concentrations in limestone are generally low, high radon emissions may still occur because of the large specific surface area of uranium minerals and the high permeability of limestone and overlying soils (Scheib et al. 2013). For example, radon emanating from low-uranium (0.5 ppm) but intensively karstified limestone is transported by biogenic CO_2 as a carrier gas into the relatively shallow and horizontal Modrič Cave in Croatia (Lončarić et al. 2023).

In Slovenia, radon represents the largest contributor to the annual effective dose from natural background radiation. The total average annual dose is estimated at 5.98 mSv, of which radon makes the dominant share (Žohar et al. 2024).

However, radon variations related to geological activity can be masked by external parameters such as atmospheric pressure, air and soil temperature, soil moisture, rainfall, and wind speed (Viñas et al. 2004).

Postojnska Jama is formed in Upper Cretaceous limestones that are at least 1200 m thick (Šebela 1998), while Županova Jama is developed in at least 550 m of Lower Jurassic limestones (Buser 1968, 1974). More broadly, the carbonate rock sequence below both caves is even thicker, strongly karstified, and dissected by numerous fissures and faults, providing conditions highly favorable for radon emanation.

Sites description

Monitoring of radon concentration in cave air was carried out at two locations in two show caves in Slovenia (Fig. 1). Postojnska Jama is a 24 km long and 115 m deep cave system. Radon monitoring is organized in the Lepe Jame passage (Postojna 2 site), located about 15 m west of the tourist trail in a short side passage, at 520 m a.s.l. and about 60 m below the surface. In Županova Jama (710 m long, 77 m deep), the monitoring site is in the remote Matjaževa Dvorana chamber, ~100 m from the vertical entrance, ~90 m below the surface, and at 468 m a.s.l. (Fig. 1). The Radim instrument is situated 2–3 m west of the tourist trail.

Although, in previous studies radon monitoring was organized at more locations in Postojnska Jama (Vaupotič 2010; Gregorič et al. 2014) particularly to understand radon concentrations in different cave parts, for this study only one monitoring site was established, because our first intention was to compare fault micro-displacement monitoring in Lepe Jame passage (Šebela et al. 2021) with radon emanations (Šebela et al. 2010). And similarly, in Županova Jama the radon monitoring site was primarily established near micro-displacement monitoring site to understand relations between radon concentrations and seismically active faults (Šebela et al. 2021; Ambrosino et al. 2020a). But for this study with the most recent radon data sets from two show caves, the principal aim was to compare radon concentrations with microclimatic parameters.

Geologically, Postojnska Jama is developed in the NW part of the External Dinarides, at the contact between impermeable Eocene flysch ($E_{1,2}$) and Upper Cretaceous limestones (K_2^2, K_2^3). Paleocene–Eocene (Pc_2, E_1) and Upper Cretaceous carbonates are partly thrusted over non-karst Eocene flysch (Fig. 2). The Upper Cretaceous limestones are folded into the Postojna anticline and Studeno syncline (Šebela 1998). Along the Dinaric-oriented (NW–SE) Predjama Fault, earthquake activity is still present (Šebela et al. 2023).

Županova Jama is developed in Lower Jurassic limestones (J_1 – Lower and Middle Lias) and belongs to the northern External Dinarides (Poljak 2000; Placer 2008). About 500 m west of the cave entrance lies the Dobrepolje Fault, along which the SW block, built of Triassic rocks, is uplifted, and the NE block (containing the cave) is downthrown (Buser 1968). Evidence also indicates dextral strike-slip movement along this Dinaric-oriented (NW–SE) fault, which remains tectonically active.

The oldest rocks in the studied area are Triassic bedded dolomites with interlayers of sandy shale with mica (T_1), and Middle Triassic Anisian (T_2^1) dolomite, partly bedded white to grey and partly massive. White, granulated massive dolomite with some bedded limestone belongs to the Middle Triassic (${}_2T_2^2$, Upper Ladinian), while dolomite and dolomitic shale represent the Upper Triassic (T_3^1). Additional Upper Triassic formations (T_3^{2+3}, Norian and Rhaetian) are composed of grey to dark, bedded, fine-grained dolomites (Buser 1968, 1974).

East of Županova Jama, on the eastern side of a N–S fault (Fig. 3), Jurassic dark-grey oolitic limestones occur ($J_{1,2}$ - Upper Lias and Dogger), followed by Malm (J_3 - dense white to grey-brown oolitic limestones, sometimes altered to white granulated dolomite). Lower Cretaceous and Cenomanian rocks (K_1; $K_{1,2}$) consist of bedded limestones with dolomite layers. The Grosuplje Valley is infilled with Pliocene to Quaternary deposits composed of clays, loams, and gravels.

Methods

Radon concentrations were measured in the air of both caves (Fig. 4) with RADIM instruments. In Postojnska Jama, a RADIM 3AT (produced by TESLA, Czech Republic) was used, while in Županova Jama a RADIM 3 A (originally

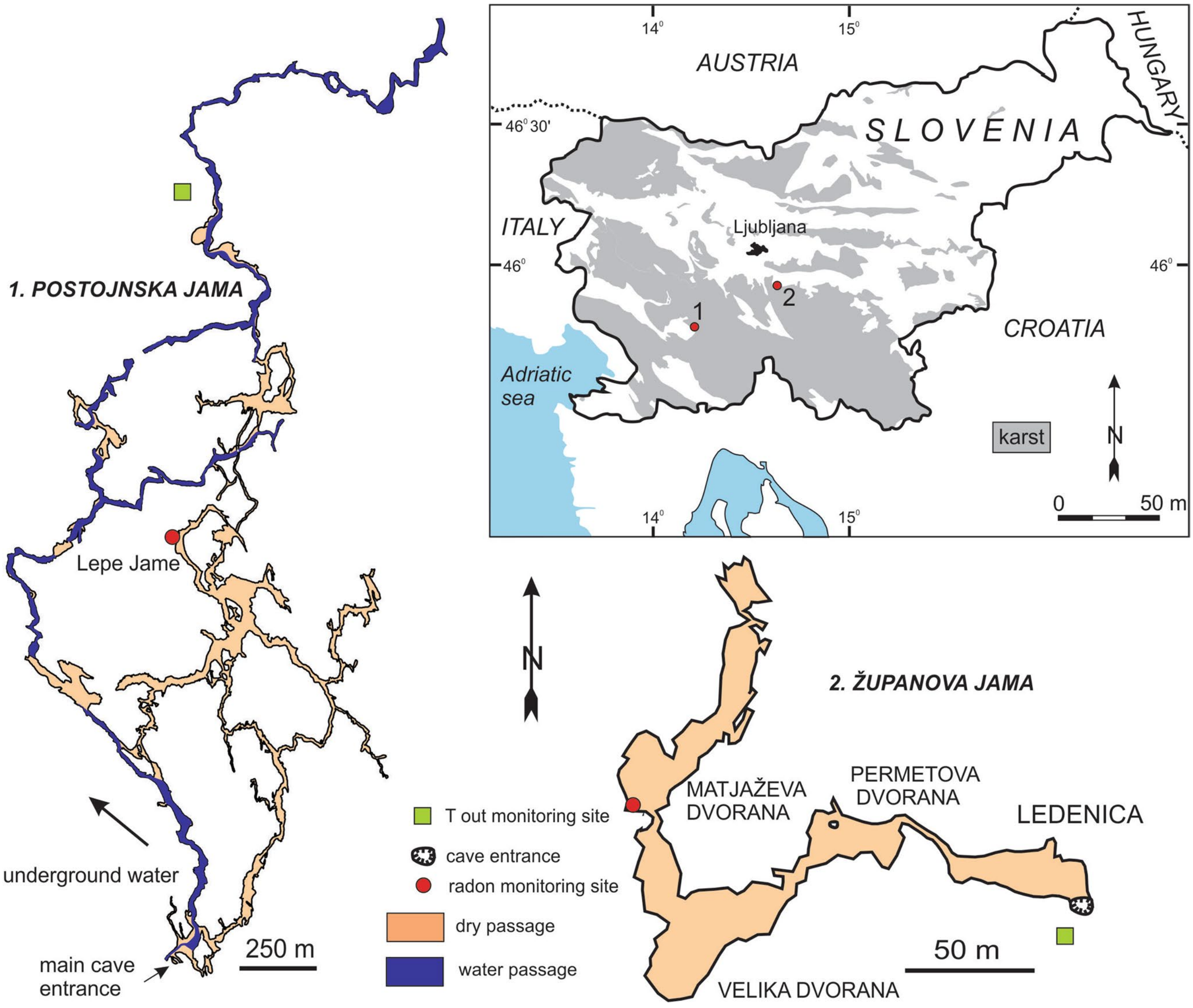

Fig. 1 Locations of Postojnska Jama (Lepe Jame–Postojna 2) and Županova Jama (Matjaževa Dvorana) with positions of monitoring sites

developed by Ing. Jiří Plch (SMM) and produced in Prague) was employed. The measurement sensitivity is 0.8 counts h^{-1} per (Bq/m^3), with a sampling interval of 30 min. Measurement uncertainty for a 1-hour integration is <2% at 3000 Bq/m^3 and <7% at 300 Bq/m^3. RADIM instruments have inner corrections for relative humidity and in such a way are suitable for radon concentration measurements in cave environments where relative humidity can be very high (>90%). Nevertheless, to maintain the air humidity within the required range, the detection system is protected from the typically near-saturated cave environment by a dedicated arrangement consisting of a plastic enclosure and a calcium chloride ($CaCl_2$) desiccant (Ambrosino et al. 2020c).

Air temperature and atmospheric pressure in Postojnska Jama (Lepe Jame passage) were measured at 1 h intervals using Baro-Diver® dataloggers for long-term, real-time monitoring (Van Essen Instruments B.V., The Netherlands). The devices have a temperature range of -20 to +80 °C (accuracy ± 0.1 °C, resolution 0.01 °C) and a pressure range equivalent to 1.5 m water column (accuracy ± 0.5 cm H_2O). Additional Baro-Diver® instruments were installed outside Postojnska Jama, in the forest above Pivka Jama, for comparative monitoring (Šebela et al. 2025).

In Županova Jama, meteorological parameters (air temperature and pressure) were recorded every 30 min with the same instrument as radon (RADIM 3 A). Outside the cave, near the main entrance, air temperature was measured at 30-minute intervals using a Comet Logger R0110E, which does not measure atmospheric pressure (Fig. 1).

The radon monitoring period in Postojnska Jama lasted from 14 June 2022 to 27 July 2024, and in Županova Jama

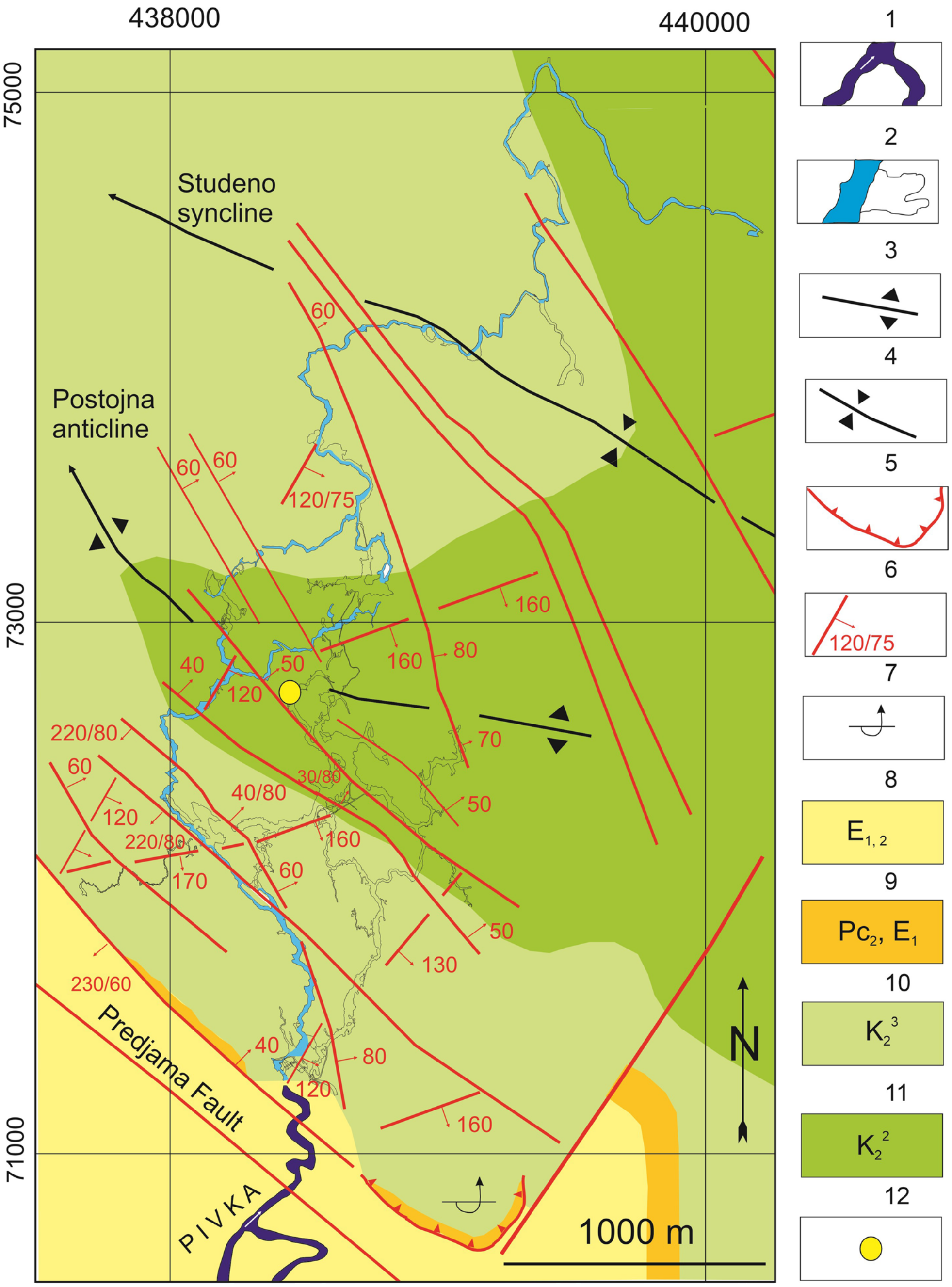

Fig. 2 Geological map of Postojnska Jama cave system. 1 – surface river, 2 – underground water flow, 3 – anticline, 4 – syncline, 5 – thrust, 6 – fault with strike and dip direction, 7 – overturned beds, 8 – Eocene flysch, 9 – limestone breccia and conglomerate (Pc_2, E_1), 10 – Upper Cretaceous limestone (K_2^3), 11 – Upper Cretaceous limestone (K_2^2). Modified after Gospodarič (1976), Čar and Gospodarič (1984), and Šebela (1998, 2019), 12 – radon monitoring site

from 22 March 2017 to 22 April 2025. Correlation analyses were carried out between radon concentrations in both caves. Radon data were compared with outside temperature and pressure. The difference between external and cave temperatures was used to evaluate seasonal ventilation regimes (summer vs. winter) in both caves. Based on studies in other caves, where ^{222}Rn was employed as a tracer of seasonal, diurnal, and hourly-scale cave air flow (Fijałkowska–Lichwa et al. 2025), similar outlines were applied for our study sites. Diurnal and seasonal radon variations were analyzed. Based on average annual radon concentrations, the permissible time that visitors, researchers, and guides can spend in the caves without exceeding harmful effective doses was calculated, and annual effective doses (mSv) were determined for these groups.

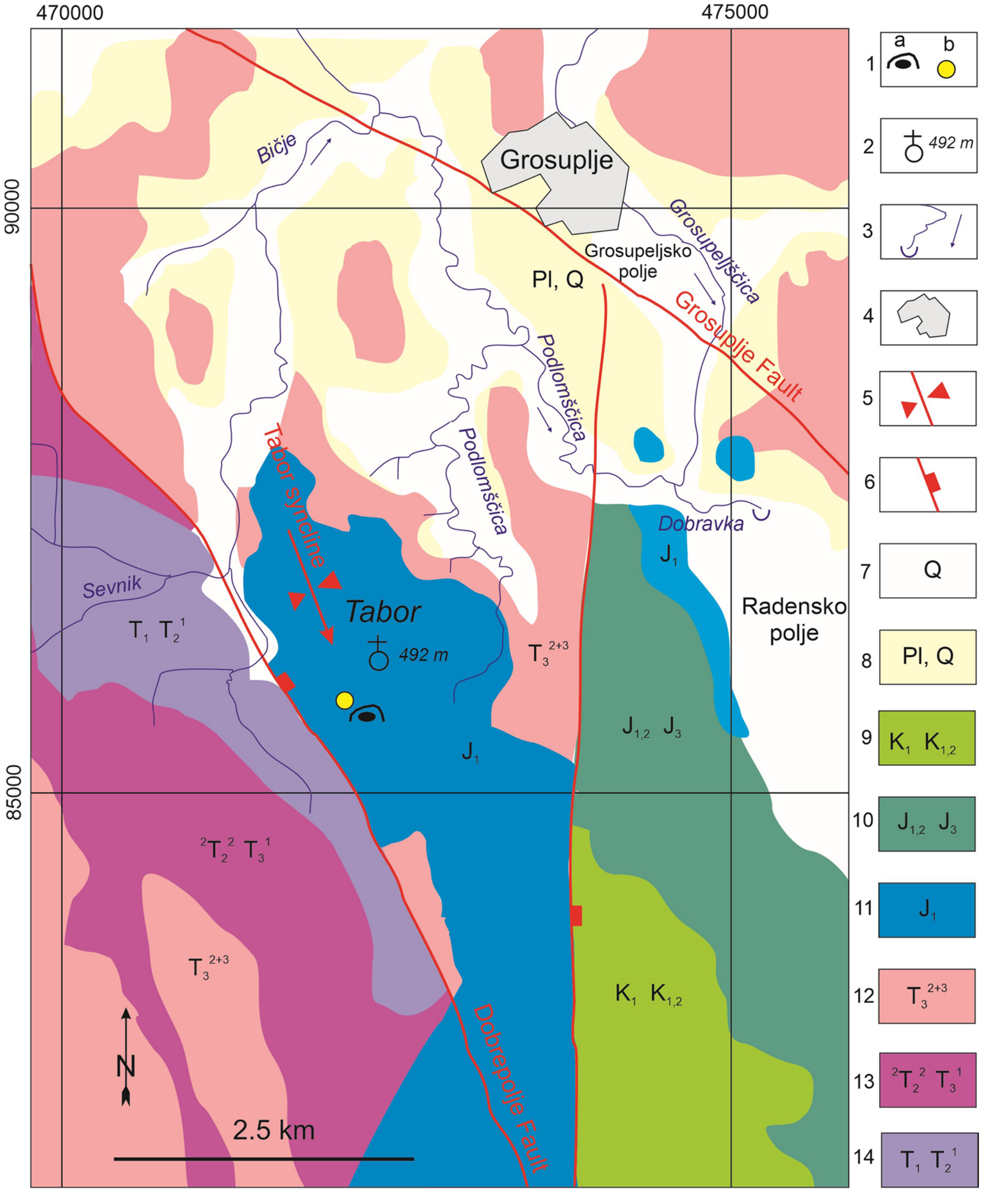

Fig. 3 Geological map of the area around Županova Jama. 1a – cave entrance, 1b – radon monitoring site, 2 – hill Tabor with elevation, 3 – surface water stream and flow direction, 4 – town, 5 – syncline, 6 – fault with vertical displacement (NE block downthrown), 7 – Quaternary (Q), 8 – Pliocene and Quaternary (Pl, Q), 9 – Lower Cretaceous and Cenomanian (K$_1$; K $_{1,2}$), 10 – Jurassic (J $_{1,2}$ - Upper Lias and Dogger; J$_3$ - Malm), 11 – Jurassic (J$_1$ - Lower and Middle Lias), 12 – Triassic (T$_3^{2+3}$ - Norian and Rhaetian), 13 – Triassic ($_2$T$_2^2$ - Middle Triassic, upper Ladinian; T$_3^1$ - Upper Triassic, Carnian), 14 – Triassic (T$_1$, T$_2^1$). Modified after Buser (1968, 1974) and Poljak (2000)

Results and discussions

Diurnal changes of ^{222}Rn

To better understand short-term radon variability, diurnal changes were analyzed by comparing midday (12:00) and midnight (00:00) radon concentrations in both caves. The diurnal cave temperature changes have already been discussed in previous studies (Šebela and Turk 2011) in relation to closed cave without visitors during night and the highest visitor numbers during midday. In this way (Fig. 5A), we see that the oscillation between day and night is slightly larger in Postojnska Jama than in Županova Jama what is related to higher visitor numbers in Postojnska jama and thus ventilation alterations. However, radon concentrations are generally higher in Županova Jama than in Postojnska Jama.

The difference between midday and midnight concentrations (Fig. 5B) shows prevailing negative values for Županova Jama, meaning that radon levels are generally higher at midnight than at midday for the period 14 June 2022 to 26 July 2024. For example, on 20 October 2023, midnight values were up to 750 Bq/m³ higher than midday values, while on 15 October they were 1285 Bq/m³ higher. In contrast, on 16 October 2023, midday concentrations were 980 Bq/m³ higher than those at midnight.

In Postojnska Jama, the highest diurnal difference was detected on 18 October 2023, when midday values exceeded

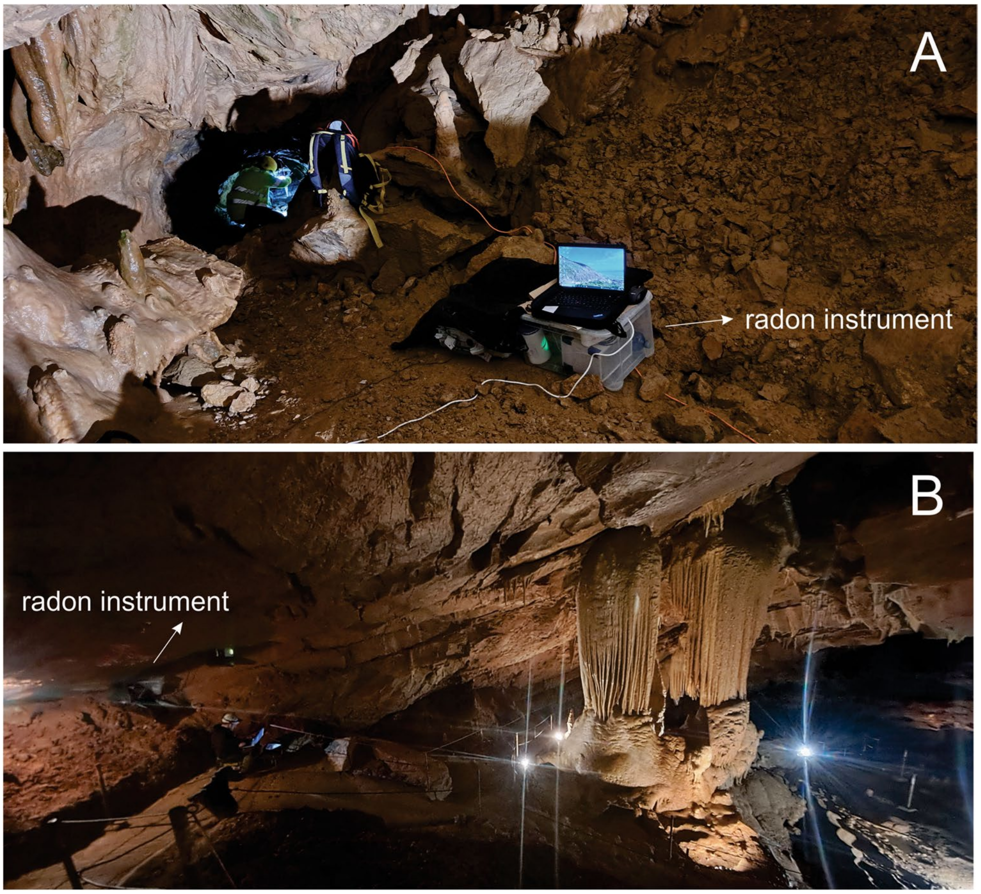

Fig. 4 Radon monitoring sites in Postojnska Jama (A) and Županova Jama (B). Photo: S. Šebela

midnight values by 3380 Bq/m³. Conversely, during 11–16 November 2022, midnight values were significantly higher than daytime ones. On 16 November 2022, midnight concentrations were 3460 Bq/m³ higher than those recorded at midday. The anomalies observed between 15 and 20 October 2023 in both caves suggest unusual short-term changes in radon dynamics. During 15–20 October 2023, precipitation was very low: only 7.7 mm of rain fell near Postojna on 15 October, and even less near Županova Jama. Therefore, rainfall cannot explain the observed anomalies. No strong local or regional earthquakes occurred during this period either. So, the exact cause for this short-term radon concentration changes remains unclear.

In summary, comparing midday (12:00) and midnight (00:00) radon values demonstrates that small day–night variations exist in both studied caves, but in Županova Jama midnight radon values are generally higher than midday values, while in Postojnska Jama midday and midnight concentrations are more balanced.

Postojnska Jama – radon and air temperature diurnal changes

To investigate the relationship between radon dynamics and external climate, radon concentrations in Postojnska Jama were compared with outside air temperature at diurnal timescales. In Postojnska Jama, during the warm part of the year (14–18 June 2022, Fig. 6A), the daily maximum of outside air temperature was followed by the daily radon concentration maximum after about 17–18 h. On 16 June 2022, the maximum concentration of 4330 Bq/m³ was measured at 7:00 am, while the outside temperature maximum occurred the day before at 2:00 pm (arrows on Fig. 6A).

In August 2023, the daily radon maximum in Postojnska Jama occurred 4–8 h before the outside temperature maximum, meaning that the outside temperature peaked 12–14 h before the radon maximum (Fig. 6B). Daily radon maxima in August 2023 occurred around 2–5 am. This contrasts with earlier studies, which reported radon concentrations in

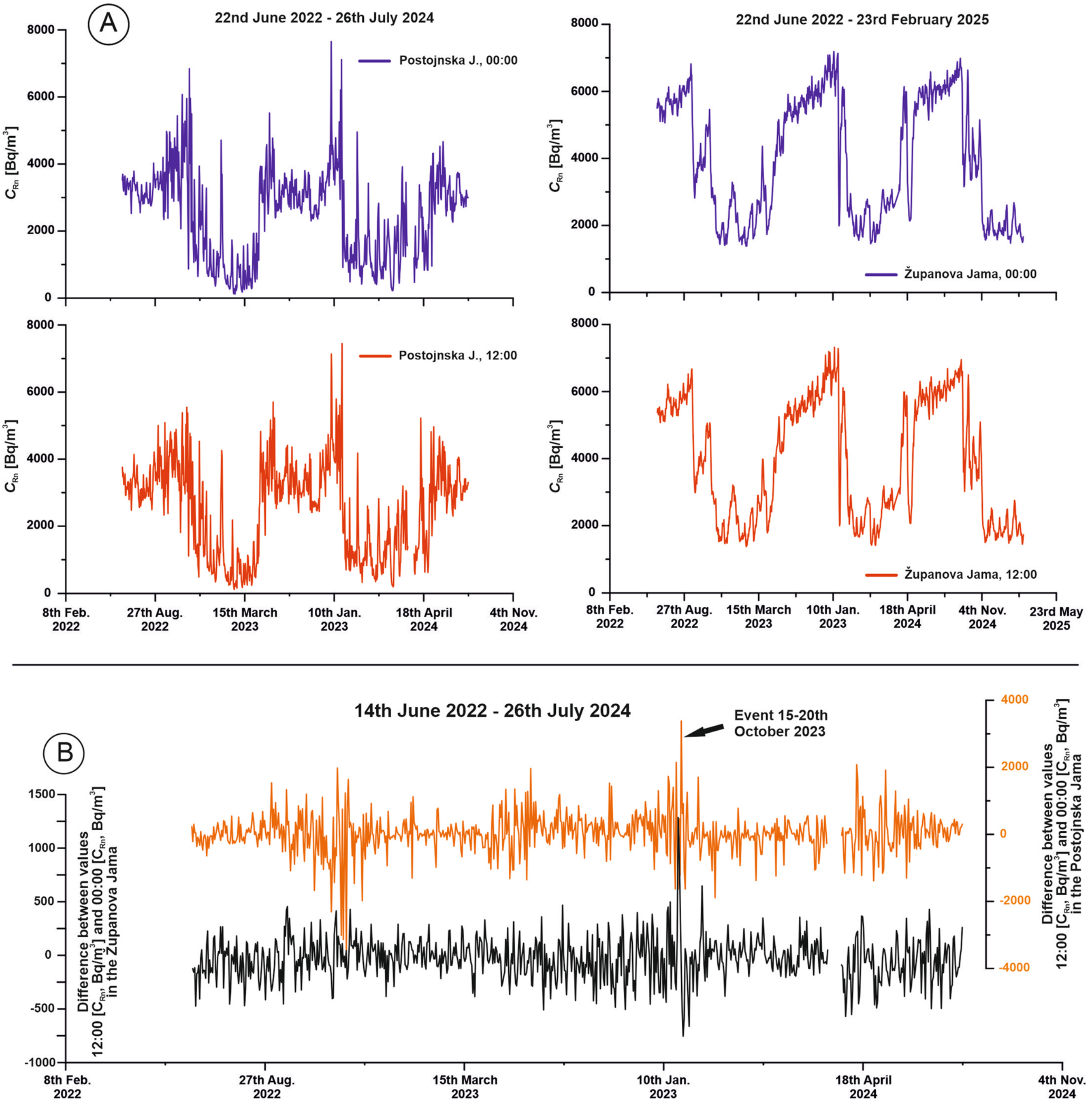

Fig. 5 **A**. Comparison between midday (12:00) and midnight (00:00) radon concentrations (Bq/m³) in Postojnska Jama and Županova Jama at a 12 h interval. **B**. Difference between midday radon concentration values (Bq/m³) and midnight values (12 h interval) for Postojnska Jama and Županova Jama

Postojnska Jama being higher in the afternoon when outside air temperature was also higher (Kobal et al. 1988). It should be noted, however, that the measurement location might not have been exactly the same as in Kobal's study. For example, in Driny Cave (Slovakia), two radon meters placed at different sites recorded significantly different results (Ambrosino et al. 2020b), indicating that each location in a cave can show its own radon dynamics.

During winter (Fig. 6C), when outside temperature (*T*out) was higher than 8–9 °C (6 January 2024) radon concentration increased (8 January 2024, arrow on Fig. 6C) due to reduced cave ventilation. For example, values rose from 660 Bq/m³ on 6 January 2024 at 7:00 am to 3200 Bq/m³ on 8 January 2024 at 9:00 pm. From previous studies we know that winter cave air temperature in Postojnska Jama is about 10 °C (Šebela 2023). When ventilation was active (*T*out<*T*cave), outside

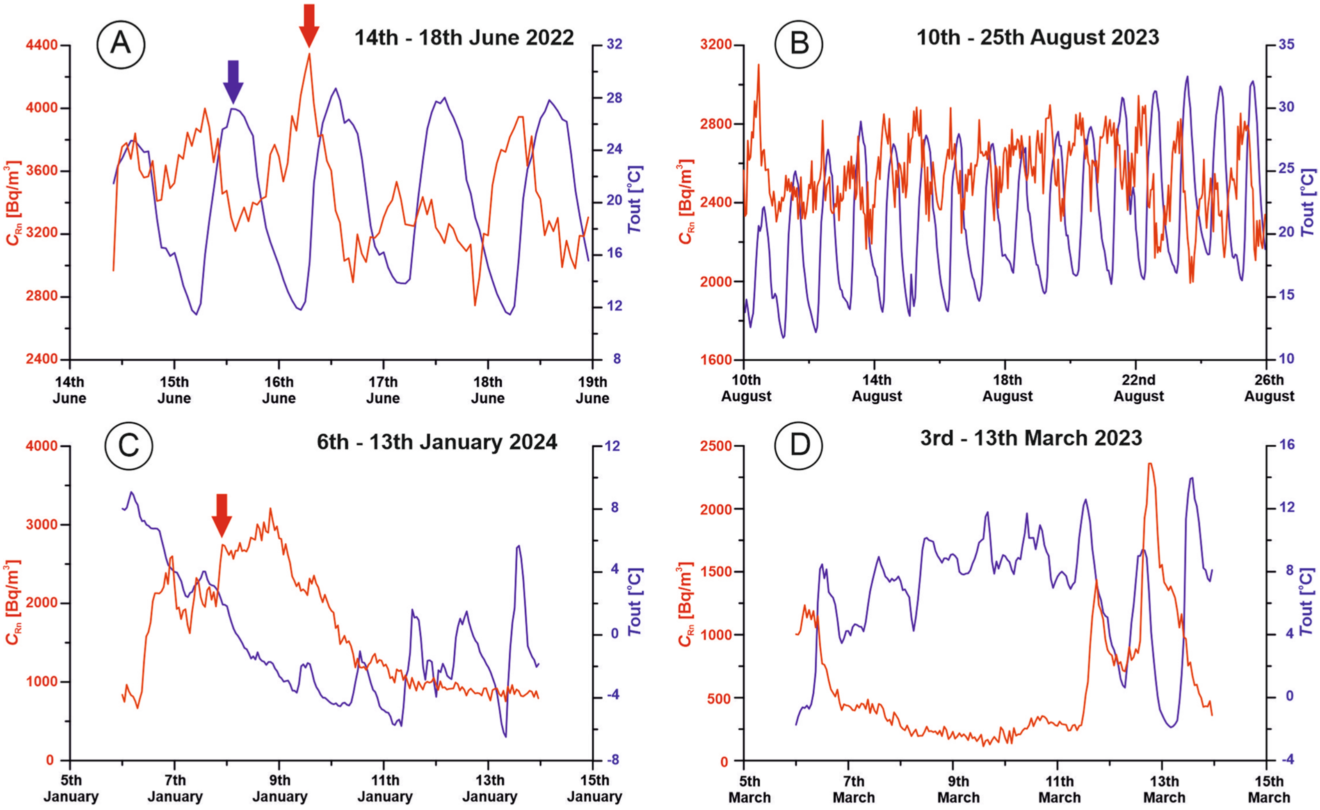

Fig. 6 Postojnska Jama: radon concentrations (Bq/m³) compared with outside air temperature (°C) (1 h interval). **A.** 14–18 June 2022, **B.** 10–25 August 2023, **C.** 6–13 January 2024, **D**. 3–13 March 2023

temperature began to decrease while radon initially increased (6 January, 5:00 am to 8 January 2024, 9:00 pm). Later, however, radon concentration decreased (when *T*out dropped below zero or remained lower than *T*cave) due to winter ventilation and no longer showed daily oscillations. Concentrations fell from 3000 Bq/m³ to 1000 Bq/m³ between 8 and 11 January 2024.

In March 2023 (Fig. 6D), radon concentration in Postojnska Jama started to increase when the daily outside temperature oscillation reached up to 16 °C. Daily radon maxima lagged 3–5 h behind outside temperature maxima. This delay is attributed to ventilation processes.

Past measurements on Velika Gora in Postojnska Jama indicated that the effect of the difference between outside and cave air temperature on radon concentration can be delayed by up to 4 days, presumably due to the distance between the monitoring site and the lower cave entrance (~2 km) (Gregorič et al. 2011). When daily outside temperature drops below −6 °C, radon concentrations increase, possibly because ice and snow above the cave block natural air exchange (Gregorič et al. 2011). Maximum radon concentrations at the Velika Gora site (Postojna 1) reached up to 3500 Bq/m³ (June–July 2007), while at the Lepe Jame site (Postojna 2) they reached up to 10,000 Bq/m³ (October–November 2007) (Šebela et al. 2010).

Negative correlation between radon concentrations and outside air temperature, which was strong only for the winter period 3–13 March 2023 (Fig. 6D) and moderate correlation for the summer period 14–18 June 2022 (Fig. 6A) was determined by Pearson Correlation coefficients (PCC, Table 1). For the periods 10–25 August 2023 (Fig. 6B) and 6–13 January 2024 (Fig. 6C) PPC was weak, showing that correlation between radon concentration and outside temperature can be strong or/and weak during summer and also during winter months in Postojnska Jama related to air exchange between cave and outside environment.

Županova Jama – radon and air temperature diurnal changes

To assess the relationship between cave radon and external climate, radon concentrations in Županova Jama were compared with outside air temperature (*T*out) at 1 h intervals for different seasons (Fig. 7A–D).

In Županova Jama, daily maxima of radon concentration during the warm part of the year are not as distinct as in Postojnska Jama. On 16 June 2022, the *T*out maximum occurred at 13:00, while the radon maximum was reached

Table 1 Pearson Correlation coefficients (PCC) between radon concentration (CRn) and outside temperature for Postojnska Jama and Županova jama for selected periods represented on Figs. 6 and 7

PCC	C_{Rn} (PJ) Fig. 6A	C_{Rn} (PJ) Fig. 6B	C_{Rn} (PJ) Fig. 6C	C_{Rn} (PJ) Fig. 6D
Tout Postojna Fig. 6A	-0.41			
Tout Postojna Fig. 6B		-0.27		
Tout Postojna Fig. 6C			0.02	
Tout Postojna Fig. 6D				-0.54
	C_{Rn} (ŽJ) Fig. 7A	C_{Rn} (ŽJ) Fig. 7B	C_{Rn} (ŽJ) Fig. 7C	C_{Rn} (ŽJ) Fig. 7D
Tout Županova Fig. 7A	-0.07			
Tout Županova Fig. 7B		-0.79		
Tout Županova Fig. 7C		-0.02		
Tout Županova Fig. 7D				0.04

PJ-Postojnska Jama

ŽJ-Županova Jama

PCC>0.5 - strong correlation

PCC=0.3-0.5 - moderate correlation

PCC=0-0.3 weak correlation

PCC=0 - none correlation

at 20:00, i.e., 7 h later (Fig. 7A, red arrow). This is seen also with Pearson Correlation coefficient (PCC), which is negative and weak (Table 1).

A similar situation to Postojnska Jama is observed during winter. When *T*out dropped below 0 °C, radon concentrations decreased from 2800 Bq/m³ to 1400 Bq/m³ between 8 and 10 January 2024 (Fig. 7B, black horizontal line), probably due to enhanced ventilation. Pearson Correlation coefficient (PCC) for this period between radon and outside temperature was negative and strong (Table 1).

During the high summer season (10–25 August 2023), daily oscillations of radon concentration in Županova Jama are not as evident as in Postojnska Jama (Fig. 7C), what is seen also with Pearson Correlation coefficient (PCC), which is negative and weak (Table 1).

In 2023 (6–13 March), Županova Jama does not show clear daily oscillations of radon, but rather a gradual increase from 1900 to 2900 Bq/m³ (Fig. 7D). Although daily *T*out oscillations are similar to those in Postojnja, radon does not exhibit the same response, possibly indicating a lack of effective ventilation. Also, the Pearson Correlation coefficient (PCC) is positive and weak (Table 1).

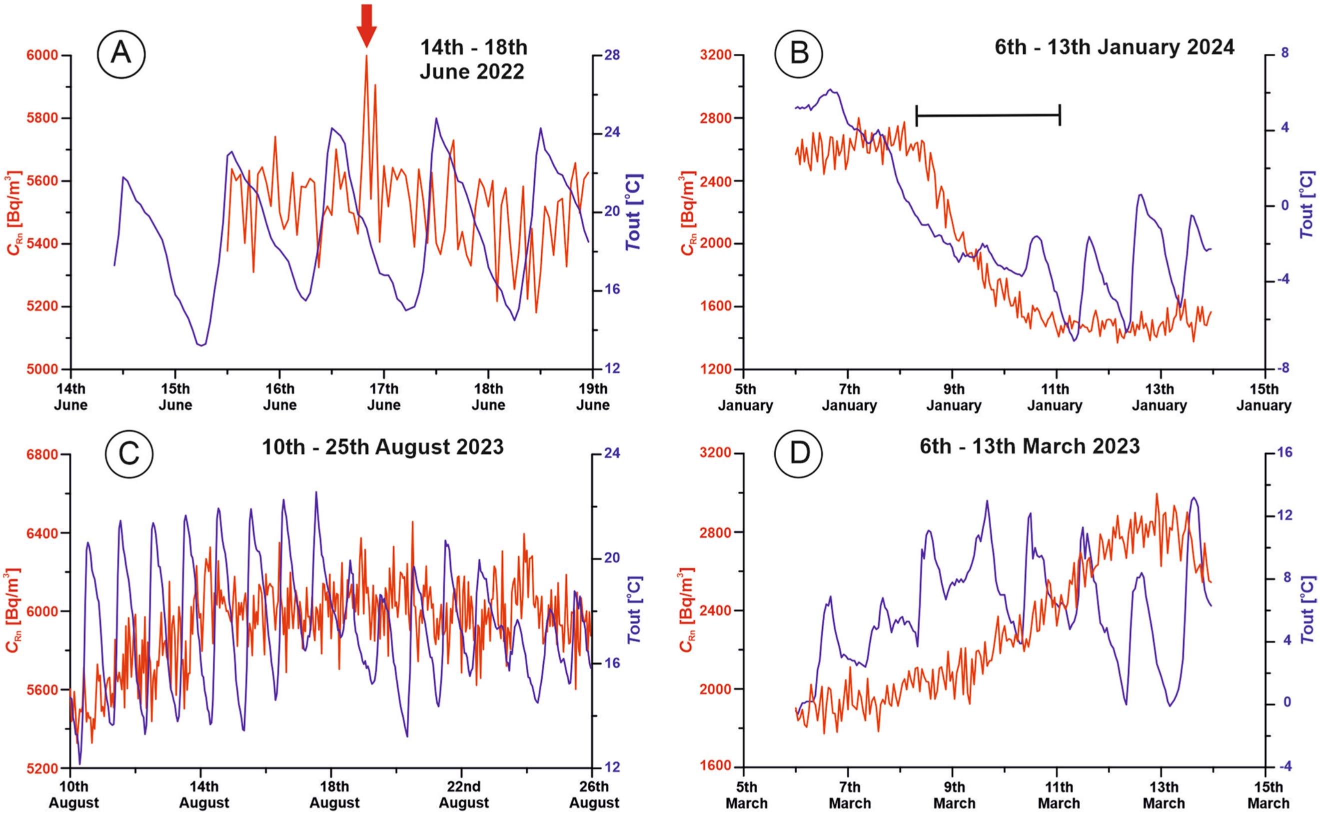

Fig. 7 Županova Jama, radon concentrations (Bq/m³) compared with outside cave *T* (°C) (1 h interval). **A.** 14–18 June 2022, **B**. 6–13 January 2024, **C**. 10–25 August 2023, **D**. 6–13 March 2023

Seasonal ^{222}Rn changes and temperature

To better understand the seasonal dynamics of radon in relation to external and cave air temperature, long-term radon monitoring data were analyzed for both caves.

A seasonal radon fluctuation is evident, with maxima in summer and minima in winter (Cigna 2005), which is also typical for both of our studied caves (summer represents June-September and winter represents December-March periods). Radon concentrations are generally higher throughout the year in Županova Jama (mean radon concentration in 2023 was 4030 Bq/m³, maximum 7726 Bq/m³, minimum 1253 Bq/m³) than in Postojnska Jama (mean 2278 Bq/m³, maximum 8110 Bq/m³, minimum 99 Bq/m³) (Table 1).

In 2022 and 2024, the summer outside temperature (*T*out) maximum around 15 August preceded the radon maximum in both caves by ~ 15–20 days. In 2023, however, the radon maximum occurred later, on 15 October in both caves, lagging by about two months compared with the *T*out maximum. Spatial and seasonal radon concentration changes in two Polish caves and mines were also explained by ventilation driven by atmospheric temperature changes, with locations farther from the entrance showing poorer ventilation and higher radon concentrations (Przylibski 1999; Fijałkowska–Lichwa and Przylibski 2023; Fijałkowska–Lichwa et al. 2024).

In Županova Jama, after the initial decrease from the highest radon values following 15 September 2022 and 5 October 2023, another radon increase was noted around 9 October and 1 November 2022 (red arrows on Fig. 8). This pattern was not as obvious in Postojnska Jama (Fig. 8). After 6 November 2022, radon dropped in Županova Jama and did not significantly rise again until April 2023, except for three short-term increases on 5 January, 26 February, and 29 March 2023.

During summer in Postojnska Jama (August 2022, 2023, and 2024), there were periods of ~ 20 days with lower radon concentrations (3000 Bq/m³ in 2022, 2500 Bq/m³ in 2023, and 3000 Bq/m³ in 2024), with smaller daily oscillations compared to the elevated summer values after 20 September 2023 (5000–8000 Bq/m³, black arrow on Fig. 8). This could indicate periods of reduced ventilation.

When comparing hourly outside air temperature between the two caves, Postojna shows larger daily oscillations than Županova Jama. This is explained by site setting: the Postojna monitoring station is located in a forest above the cave, while the Županova Jama station is positioned near the cold-air trap cave entrance but again in the forest. The closer location of this outside monitoring site to the cave entrance results in lower annual *T* values and smaller daily oscillations. However, general seasonal oscillations are very similar outside both caves.

Cave ventilation is governed by the difference between *T*out and *T*cave. When *T*out – *T*cave exceeds ~ 10 °C, the highest radon peaks are reached in Postojnska Jama (summer ventilation), such as 24 September 2023 (arrow on Fig. 9A) when radon reached 8100 Bq/m³. In contrast, when *T*out – *T*cave is around or below 0 °C (*T*out < *T*cave), typical of winter ventilation, radon concentrations are lowest, between 100 and 2000 Bq/m³ (Fig. 9A).

A similar pattern is seen in Županova Jama (Fig. 9B). During winter ventilation, when *T*out – *T*cave is below

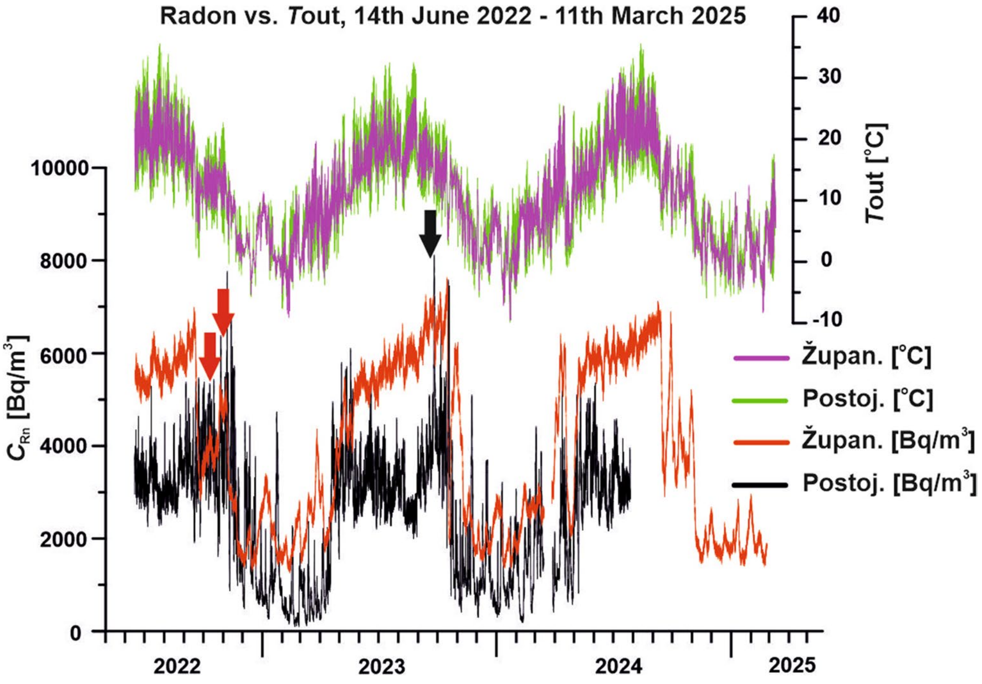

Fig. 8 Radon concentrations (Bq/m³) in Postojnska Jama and Županova Jama, together with outside air temperature (°C) measured near the cave entrances (data for Postojna area are from Šebela et al. 2025). Data were recorded at 1-hour intervals

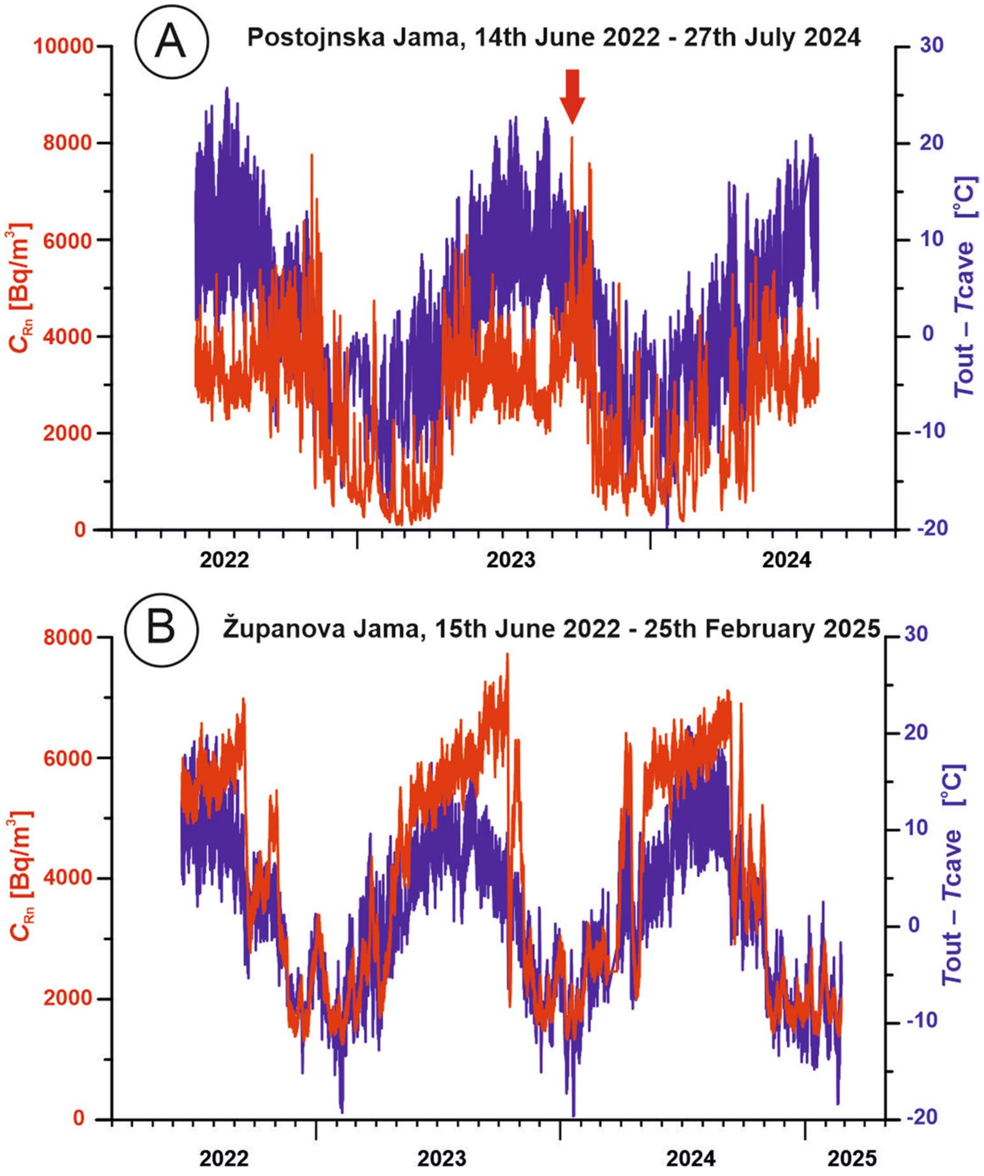

Fig. 9 **A**. Postojnska Jama, radon concentrations (Bq/m³) compared to *T*out – *T*cave difference (1 h interval), 14 June 2022–27 July 2024. **B**. Županova Jama, radon concentrations (Bq/m³) compared to *T*out – *T*cave difference (30 min interval), 15 June 2022–25 February 2025

10 °C, a strong relation between temperature difference and radon values is evident, with radon consistently lower than in summer. During summer ventilation, when *T*out – *T*cave exceeds 10 °C, extreme radon concentrations occur, typically lagging about 20 days after the temperature difference peak.

Županova Jama has been characterized as a dead-end cave with no significant ventilation, and was compared with five similar caves in Europe (January 2017 to January 2020). In such caves the difference in temperature and air density between the cave interior and outside atmosphere is the main driving force for radon transport. In Županova Jama, radon concentrations between 743 and 6769 Bq/m³ were recorded (Briestensky et al. 2022). Radon anomalies occurring within ±30 days of nearby earthquakes (M>4) have also been documented in five European caves, including Županova Jama (Ambrosino et al. 2020a).

In Županova Jama (older name: Taborska Jama), radon concentrations were first determined by α-scintillation method without preconcentration on 13 October 1985. During one hour of measurements, values up to 6000 Bq/m³ were recorded, ranking among the highest in Slovene show caves (Kobal et al. 1986). Air temperature in isolated parts of Županova Jama is relatively stable. In Velika Dvorana (a remote collapse chamber comparable to our Matjaževa Dvorana site), cave air *T* remains stable throughout the year and is generally unaffected by the outside atmosphere, ranging between 9.4 and 9.9 °C, a few tenths of a degree lower than the mean annual outside temperature (Ravbar and Košutnik 2014).

At Lepe Jame (Postojnska Jama), radon concentrations displayed two different annual cycles (Gregorič et al. 2014), with a change observed after flooding in September 2010. Radon ranged between 500 and 9000 Bq/m³ in 2010, and 500–5500 Bq/m³ in 2011 and 2012. Two ventilation regimes were identified in 2010, whereas after the 2010 flood, three ventilation regimes were distinguished. Moreover, as claimed by Gregorič et al. (2014), rainfall has an important influence on gas transfer between the cave and the outside atmosphere. Narrow fissures and cracks in bedrock, as well as pores in the overlying soil, act as a semi-permeable membrane, which can reduce ventilation when saturated. Rainfall can thus decrease ventilation and correlate with elevated radon concentrations in cave air. High groundwater levels can also cause permanent changes in airflow by blocking cracks and fissures with sediment.

Long-term ^{222}Rn monitoring in Županova jama (2017–2025)

Long-term monitoring of radon concentrations in Županova Jama provides an opportunity to evaluate multi-annual trends and their relationship to cave and outside air temperature. Here we present results from nearly eight years of continuous radon measurements, compared with cave and external temperature records.

In Županova Jama we have almost eight years (2017–2025) of radon concentration data with a 30-minute interval (Fig. 10). Outside air temperature was recorded for almost seven years (2018–2025), while cave air temperature monitoring in Matjaževa Dvorana site in Županova Jama began on 10 November 2021 and is still ongoing.

In 2019 the maximum outside air temperature (26 July) occurred three months before the maximum cave radon concentration (22 October). In 2020 the maximum outside air temperature (29 August) preceded the radon maximum (25 September) by one month. In 2022 the maximum outside temperature (8 August) was also about one month before the maximum cave radon concentration (15 September). In 2023 the outside maximum (25 August) was one to two months before the radon maximum (14 October). In 2024 the maximum outside temperature (25 August) again preceded the maximum radon concentration (12 September) by about one month.

When outside air temperature significantly decreases (probably also below the cave temperature) during the late summer–autumn period, cave radon values also drop.

Descriptive statistics (Table 1) show a rise in mean annual outside air temperature of + 0.86 °C in the six-year period from 2019 to 2024, which corresponds to an average increase of + 0.14 °C per year. The rise in mean annual (and also maximum and minimum) radon values was especially pronounced in 2023–2024 (Fig. 11).

Additionally, mean annual cave air temperature (Matjaževa Dvorana chamber in Županova jama) increased slightly, by + 0.114 °C in the three-year period 2022–2024. For comparison, in the remote chamber of Kostanjevica Cave (SE Slovenia), an increase of + 0.24 °C was observed during the five-year period 2020–2024 (Šebela, 2025, in review). This suggests that in Županova Jama the cave temperature increase is slightly lower than in Kostanjevica Cave, by ~ 0.05 °C over five years. The coefficient of determination (R^2) is similar for radon (0.419) and outside air temperature (0.468) (Fig. 11).

Outside Županova Jama, mean annual air temperature is consistently higher than mean annual cave air temperature. In 2022 mean annual outside air temperature was 0.59 °C higher than inside the cave, in 2023 it was 0.40 °C higher, and in 2024 it was 0.89 °C higher (Fig. 11; Table 2).

In 2023 the mean annual outside air temperature at Postojnska Jama was 0.51 °C higher than the cave air temperature

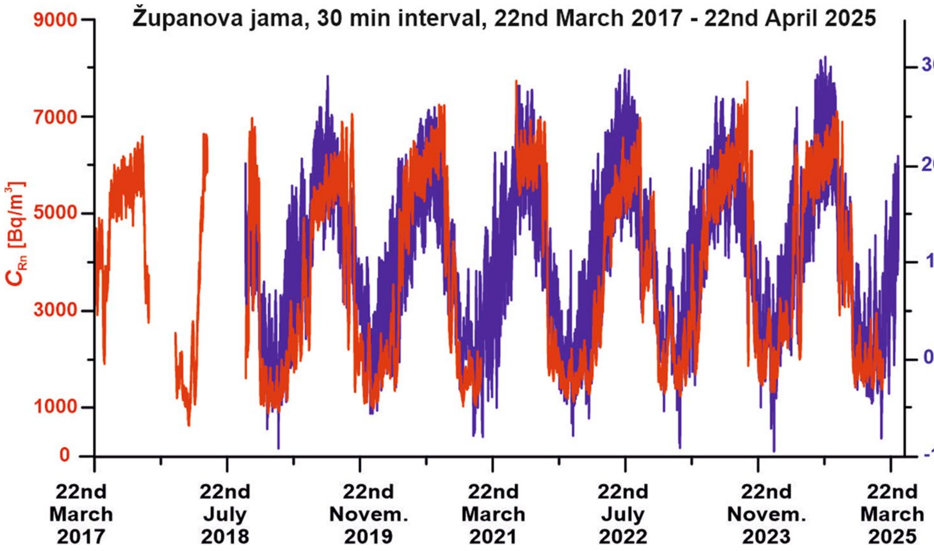

Fig. 10 Županova Jama, radon concentrations (Bq/m³) compared to outside air temperature (°C), 30-minute interval

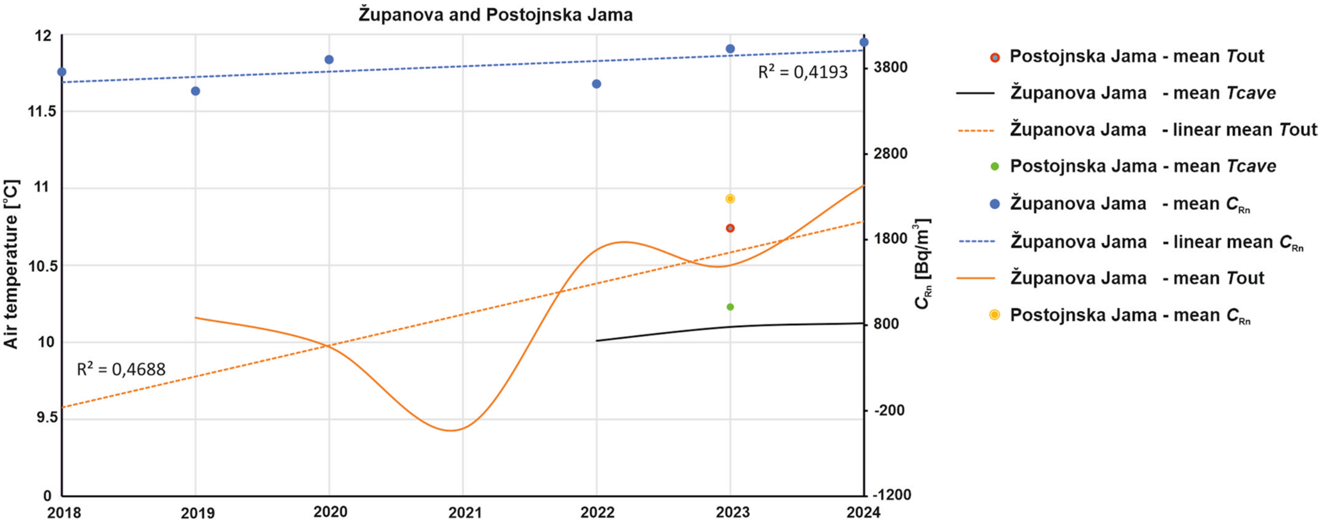

Fig. 11 Županova Jama and Postojnska Jama, mean annual radon concentrations (Bq/m³), outside air temperature (°C) and cave air temperature (°C)

Table 2 Županova Jama and Postojnska Jama, descriptive statistics for radon concentrations-C_{Rn} (Bq/m³), cave air temperature (°C) and outside air temperature (°C)

	C_{Rn} -mean Bq/m^3	Tout - mean	Tcave - mean	C_{Rn} max (Bq/m^3)	C_{Rn} min (Bq/m^3)	Tout max	Tout min	Tcave max	Tcave min
Županova Jama									
2018	3761			6977	641				
2019	3537	10.16		7059	925	29.2	-9.2		
2020	3904	9.97		7252	991	26	-5.6		
2021		9.44				28.2	-8		
2022	3619	10.6	10.01	6983	1130	29.9	-7.9	10.5	9.8
2023	4030	10.5	10.1	7726	1253	27.07	-9.14	10.5	9.9
2024	4106	11.02	10.124	7118	1333	31.19	-9.5	10.5	9.9
Postojnska Jama									
2023	2278	10.74	10.23	8110	99	32.53	-7.72	10.6	10.08

at Postojna 2 site. For Postojnska Jama, we have only one complete calendar year of radon data (2023). In that year, mean annual cave air temperature at Postojna 2 was 0.5 °C higher than in Županova Jama (Matjaževa Dvorana). The mean annual outside air temperature at Postojnska Jama was also higher (+0.24 °C) compared to Županova Jama. Importantly, mean annual radon concentration in Županova Jama in 2023 (4030 Bq/m³) was almost twice as high as in Postojnska Jama (2278 Bq/m³).

Radon concentration and atmospheric pressure

To investigate the influence of barometric changes on cave microclimate, radon concentrations were analyzed in relation to atmospheric pressure in both Postojnska Jama and Županova Jama. Summer air pressure (outside of Postojnska Jama) shows lower oscillations compared to winter. This corresponds with higher radon values in the cave during summer. In contrast, during colder parts of the year, when outside air pressure has stronger oscillations, radon values are generally lower. On an annual scale, outside air pressure and cave radon values appear to show some dependency (Fig. 12A). The same situation was observed in Županova Jama (Fig. 12B). Overall, seasonal radon changes in both studied caves are closely related to oscillations in atmospheric pressure.

Similar relationships between atmospheric pressure and cave radon have been reported in other European caves. In Candamo Cave (Spain), an inverse correlation was observed, particularly during periods when the temperature difference (ΔT) between the cave and the surface was close to zero, such as in December and March (Hoyos et al. 1998). In Jenolan Caves (Australia), radon concentrations varied in strong anti-correlation with surface air pressure during dry periods, indicating that most radon originated from remote rock voids of limited permeability. The negative correlation was most significant in autumn, while in summer the relationship was weaker or insignificant (Whittlestone et

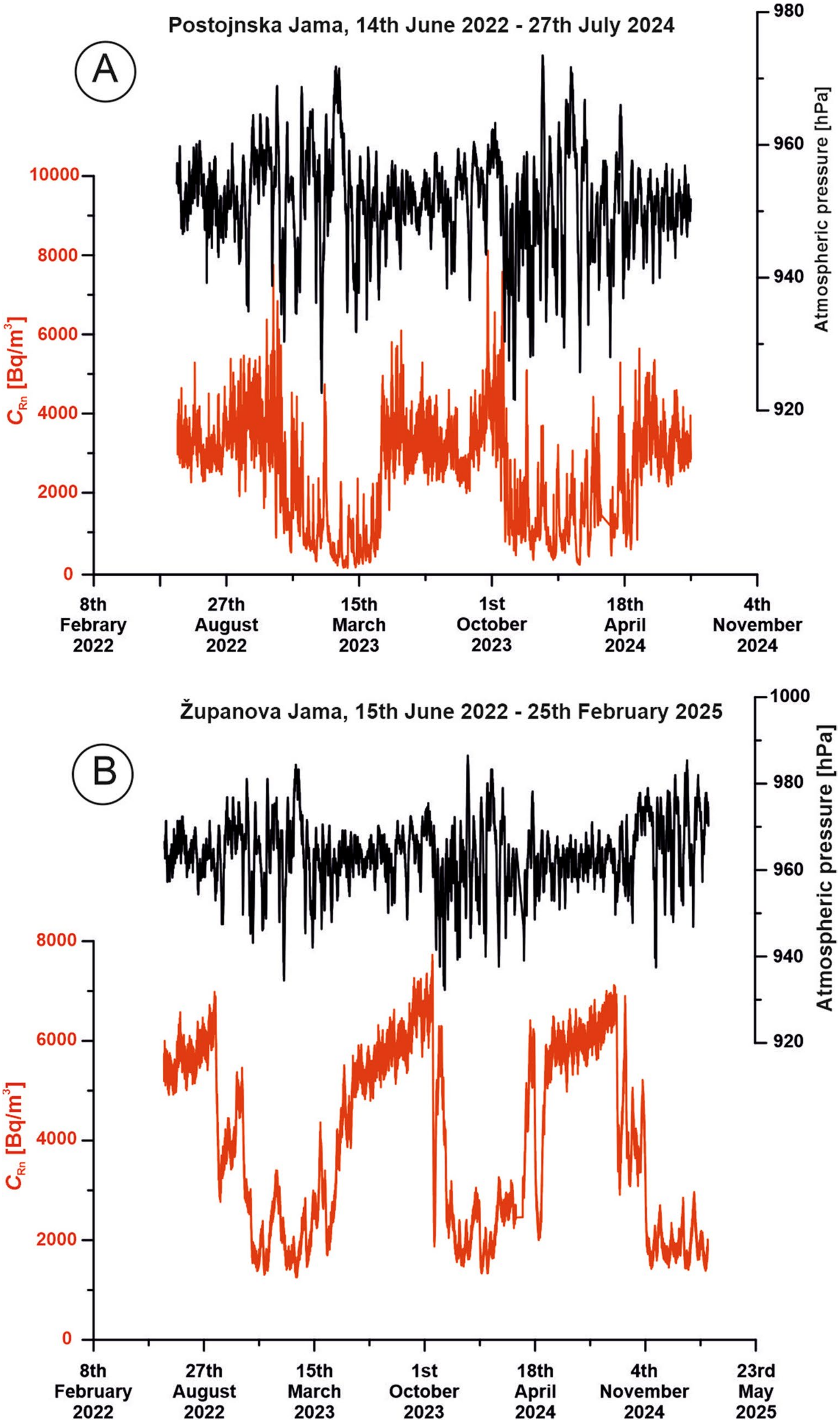

Fig. 12 **A** Comparison of radon concentrations (Bq/m^3) with outside cave atmospheric pressure (hPa), 1 h interval, Postojnska Jama (after Šebela et al. 2025). **B** Comparison of radon concentrations (Bq/m^3) with cave atmospheric pressure (hPa), 30 min interval, Županova Jama

al. 2003). At Villanova Cave in NE Italy, the influence of atmospheric pressure on radon was strongest during summer months, whereas in winter radon appeared independent of pressure fluctuations. Additionally, intense rainfall events (~30 mm/day) produced rapid radon increases, followed by gradual decreases (Garavaglia et al. 1998).

Radiation dose assessment and permissible exposure time in Slovene show caves

Assessment of radiation exposure in caves is essential, since high radon concentrations directly affect the permissible time workers and visitors can safely remain underground. For this reason, regulations in many countries have established dose limits and calculation approaches for radon exposure (Cigna 2005).

The time which can be spent in a cave during one year, based on the average radon concentration, can be estimated using the equation provided by Cigna (2005):

$$t = 10^6 \times E/7.784 \times F \times C_{Rn} \tag{1}$$

Where:

t = hours/year.

E = annual dose limit (mSv) (The average effective dose of 5 mSv was used by Vaupotič (2010).)

F = equilibrium factor (Generally $F = 0.40$ has been used, as recommended for radon dosimetry, but for Slovene show caves the value of $F = 0.55$ was used by Vaupotič (2010).)

C_{Rn} = average radon concentration (Bq/m^3) per year.

Two calculation scenarios were adopted regarding annual dose limit (E) values (Table 3). The lower E value of 5 mSv/year was adopted after Vaupotič (2010) who used this value in previous studies for Postojnska Jama, where ventilation is much smaller comparing to outside wind effects. Additionally, higher E value of 20 mSv/year was taken for calculation as general limit in Slovenia (Uradni list RS 2017).

Table 3 Calculated time (t) that can be spent in the caves (hours per year) according to Eq. (1)

	Postojnska Jama (2023)	Županova Jama (2023)	Županova Jama (2023)
E = annual dose limit (mSv)	5 mSv	5 mSv	5 mSv
F = equilibrium factor	0.55	0.55	0.55
C_{Rn} = average radon concentration (Bq/m^3)	2278 Bq/m^3	4030 Bq/m^3	4106 Bq/m^3
t = hours/year	**512**	**289**	**284**
E = annual dose limit (mSv)	20 mSv	20 mSv	20 mSv
F = equilibrium factor	0.55	0.55	0.55
C_{Rn} = average radon concentration (Bq/m^3)	2278 Bq/m^3	4030 Bq/m^3	4106 Bq/m^3
t = hours/year	**2050**	**1159**	**1137**

The calculated permissible time is 512 h/year for Postojnska Jama and 284–289 h/year for Županova Jama, based on an annual dose limit of 5 mSv. It should be noted that the studied monitoring sites are located in dead-end passages, which tend to accumulate higher radon concentrations compared to well-ventilated passages.

If we take higher annual dose limit values (20 mSv), which are suggested (Uradni list RS 2017) in Slovenia we have longer permissible time in h/year for both studied caves (Table 3).

The effective dose (E) in mSv can also be calculated by using the equation from Dueñas et al. (2011):

$$E = 7.78 \times 10^{-9} F \times t \times C_{Rn} \tag{2}$$

Where:

t = time spent in the cave in hours in 1 year.

F = equilibrium factor between radon and its decay products (the value of 0.60 was used after Dueñas et al. (2011)

C_{Rn} = mean annual radon concentration (Bq/m^3).

Dose calculations (Table 4) show that visitors and scientists do not exceed the effective dose limit for Slovenia (20 mSv/year). However, cave guides are more affected. In Županova Jama, guides working once every two weeks (~20 h/year) already exceed the proposed dose limit, receiving ~19 mSv/year, almost twice the recommended value. Guides here are occasional workers, so cumulative exposure is limited. In contrast, in Postojnska Jama, guides are full-time employees (~1800 h/year). Under such conditions, the calculated annual effective dose reaches 191 mSv/year,

Table 4 Annual effective doses (E, mSv) for Postojnska Jama and Županova Jama based on Eq. (2)

	Postojnska Jama (2023)	Županova Jama (2023)	Županova Jama (2024)
F	0.6	0.6	0.6
C_{Rn} (Bq/m^3)	2278	4030	4106
t (h) cave guides	1800	208	208
t (h) scientists	170	20	20
t (h) visitors	3	2	2
E (mSv) cave guides	191.4 mSv/year	39 mSv/year	39 mSv/year
E (mSv) scientists	18 mSv/year	3.7 mSv/year	3.8 mSv/year
E (mSv) visitors	0.31 mSv/year	0.37 mSv/year	0.38 mSv/year

about nine times the recommended occupational dose limit. Therefore, regulations concerning radon protection in Slovene show caves must be followed strictly (Uradni list RS 2017). Previous studies estimated annual doses of 10–50 mSv for employees in Slovene caves (Jovanovič 1996).

The reference level of mean annual radon concentration in residential buildings in Slovenia is 300 Bq/m³ (Uredba 2018). Compared to this, Postojnska Jama has ~7 times higher average concentrations, and Županova Jama ~ 13 times higher.

Historical measurements confirm the health implications. On 8 March 1978, radon in Postojnska Jama ranged from 780 to 2410 Bq/m³, with an inhaled ^{222}Rn dose of 2500 Bq and a bronchial dose of 135 µSv (Kobal et al. 1986). On 13 October 1985, radon in Županova Jama ranged from 650 to 5920 Bq/m³, with an inhaled dose of 10,000 Bq and a bronchial dose of 540 µSv, the highest recorded among 12 Slovene show caves. Postojnska Jama showed the second highest inhaled dose (Kobal et al. 1986).

For tourists, exposure is generally low. A visitor to Postojna Cave receives < 2% of the worldwide average annual effective dose of 1.2 mSv from radon progeny (Vaupotič et al. 2001). However, in poorly ventilated passages such as Pisani Rov, a speleologist could receive up to 15 mSv in a single hour (Kobal et al. 1988).

Similar risks are reported worldwide. In Montenegro, the highest radon levels in dwellings and schools were found in high-karst regions (Vukotić et al. 2025). In Kungur Ice Cave (Ural), radon exceeded permissible limits by a factor of seven during summer due to poor ventilation (Krasikov and Kazantseva 2024). In Županova Jama, Ambrosino et al. (2020b) showed that annual effective doses for workers could reach several tens of mSv. In Magura Cave (Bulgaria), large fluctuations were found between entrance and interior radon levels, with exposures assessed according to ICRP recommendations (Kunovska et al. 2023).

The only effective protection measure is limiting time spent underground, as it is neither feasible nor advisable to alter cave air (Cigna 2005). This is reinforced by urgent calls to manage radon exposure in indoor environments, given its established role in lung cancer risk (Ambrosino et al. 2024).

Comparable studies show high exposures for cave guides: in Modrič Cave (Croatia), annual effective doses reached 19.0 ± 5.2 mSv in tourist sections and 34.1 ± 9.2 mSv in non-tourist parts (Lončarić et al. 2023). In Nerja Cave (Spain), worker and visitor exposures were only a small percentage of general population limits (Dueñas et al. 2011). In Candamo Cave (Spain), the June–September period was identified as the safest season for visits due to optimal ventilation (Hoyos et al. 1998). In volcanic caves of the Canary Islands, special radon hazard guidelines were recently developed (Hernández-Gutiérrez et al. 2024).

Conclusions

Continuous radon monitoring in two Slovene show caves, Postojnska Jama and Županova Jama, revealed distinct patterns of radon variability linked to microclimate and geological setting. By comparing radon concentrations with outside and cave air temperature as well as atmospheric pressure, we were able to evaluate diurnal and seasonal changes and identify the principal mechanisms driving cave ventilation.

The results show that Županova Jama generally maintains higher radon concentrations throughout the year compared to Postojnska Jama. This is consistent with its morphology, location of the monitoring site in a remote chamber, and weaker ventilation capacity. Postojnska Jama, although more ventilated, still displays strong radon fluctuations, particularly in dead-end passages. Diurnal changes are evident in both caves but differ in expression: in Županova Jama, midnight radon levels are usually higher than midday values, whereas in Postojnska Jama midday and midnight concentrations are more balanced, with occasional reversals driven by short-term shifts in airflow.

Seasonal variability follows the established global patterns for karst caves, with higher concentrations in summer when outside air is warmer than the cave atmosphere, and lower values in winter when cooler outside air enhances ventilation. Short-term anomalies, such as the October 2023 events, underline the complexity of cave air exchange processes, which cannot always be explained by rainfall or seismic activity alone. Long-term monitoring in Županova Jama further highlighted rising trends in both outside air temperature (+ 0.86 °C between 2018 and 2024) and mean radon levels, suggesting a connection between broader climatic shifts and cave microclimate dynamics.

The comparison of radon with external climate parameters confirmed that temperature differences between cave and exterior air represent the main control on ventilation, while pressure variations play a secondary but still detectable role. These findings agree with previous studies in Slovenia and abroad, where convective air exchange and stratigraphy of the host rock have been shown as dominant controls on radon levels. The geological context of both caves, developed in thick and strongly karstified carbonate sequences cut by fissures and faults, provides highly favorable conditions for radon emanation.

Exposure assessments based on average annual concentrations demonstrated that occasional visitors remain well within safe radiation limits. However, cave guides and long-term staff may exceed the recommended occupational dose, particularly in Postojnska Jama where daily exposure is prolonged. This highlights the necessity of applying radiation safety regulations, limiting working hours, and maintaining continuous radon monitoring in show caves.

Overall, this study confirms that radon is not only a radiation hazard in tourist caves but also a valuable natural tracer of ventilation regimes and climatic influence in karst environments. By combining long-term radon datasets with cave microclimate parameters, it is possible to identify patterns at diurnal, seasonal, and interannual scales and to better understand interactions between geology, climate, and human exposure. These results contribute to the broader field of karst research, where radon serves as an integrative indicator of microclimatic, hydrological, and tectonic processes.

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Data availability Data are available from the authors by request.

Declarations

Competing interests The authors declare no competing interests.

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