Seasonal variations of water condensation in cave environment: A case study from the Výpustek Cave (Moravian Karst)

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Abstract
Seasonal variations of water condensation were studied in the Výpustek Cave (Moravian Karst). Microclimatic data such as cave/external air temperatures and visitor numbers were monitored in the Škrapový Dome and exterior of the cave with one-hour step during an almost season-long monitoring campaign. Water condensation data were recorded at monthly intervals using a polished limestone tablet located in a dome near the thermometers. Long-term monitoring showed that the temperature of the cave air was controlled by cave airflow driven by the temperature difference between the exterior and the cave, ΔT_{AF}. Anthropogenic temperature influence appeared as peaks superimposed onto natural cave air temperatures curves and corresponded to the number of visitors. Seasonality of water condensation based on cave airflow was identified: no condensation during the UAF mode and drops of condensed water on the tablet surface in the DAF mode. Traces of calcite recrystallization were found on the tablet surface as a consequence of dissolution by the condensed water.

Abstrakt
Sezónní variace kondenzace vody byly studovány v jeskyni Výpustek (Moravský kras). Mikroklimatická data, jako teplota jeskynního/externího vzduchu a počty návštěvníků, byla monitorována ve Škrapovém dómu a exteriéru s hodinovým krokem během téměř sezónní monitorovací kampaně. Data kondenzace vody byla zaznamenávána v měsíčních intervalech pomocí leštěného vápencového etalonu umístěného v monitorovaném dómu blízko teploměrů. Dlouhodobý monitoring ukázal, že teplota jeskynního vzduchu byla určována prouděním vzduchu jeskyní, které bylo řízeno teplotním rozdílem mezi exteriérem a jeskyní, ΔT_{AF}. Antropogenní teplotní příspěvek představovaly píky nasuperponované na přírodní křivce teploty jeskynního vzduchu, které odpovídaly počtu návštěvníků. Na základě proudění vzduchu jeskyní byla identifikována sezonalita kondenzace vody: kompletně suchý povrch vápencového etalonu během UAF módu a kapky zkondenzované vody na povrchu etalonu v DAF módu. Jako následek rozpouštění zkondenzovanou vodou byly na povrchu etalonu nalezeny stopy rekrystalizace kalcitu.

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Introduction

Protection of cave environment has represented a problem in karst areas for some decades. Caves open to public are often discussed as the most affected sites due to their (1) tourist (e.g., Lobo 2015), (2) cultural (e.g., Lang et al. 2017), and/or (3) therapeutic (e.g., Gerjevič 2002; Licbinsky et al. 2020) utilization. One of the most discussed questions in this context is the speleothem destruction via condensation corrosion (Sarbu and Lascu 1997; Tarhule-Lips and Ford 1998; de Freitas and Schmekal 2006; Ford and Williams 2007). Water vapor in the cave atmosphere condenses on the walls and speleothems and creates water drops/film

(i) in equilibrium with the actual cave CO_2 partial pressure, but (ii) unsaturated with respect to the carbonates and, therefore, corroding calcite forming the cave walls. Generally, the process of water condensation/evaporation is conditioned by the temperature difference

$$\Delta T_c = T_{DP} - T_{wall} \quad (1)$$

where T_{DP} is the dew point temperature (temperature of air at water vapor condensation point) and T_{wall} is the wall temperature. Whereas positive ΔT_c corresponds to water condensation, negative ΔT_c leads to water evaporation from the cave wall. Since the relative humidity of cave air is close to 100% throughout the entire season, the relation (1) could be expressed as

$$\Delta T_c = T_{cave} - T_{wall} \quad (2)$$

where T_{cave} is the cave air temperature. T_{cave} distribution is produced by cave airflow controlled by pressure differences resulting from distinct air densities (de Freitas et al. 1982). Since density is a function of temperature, cave airflow is mostly related to the temperature difference

$$\Delta T_{AF} = T_{exterior} - T_{cave} \quad (3)$$

where $T_{exterior}$ is the external air temperature (Pflitsch and Piasecki 2003; Russell and MacLean 2008; Kowalczk and Froelich 2010). Based on cave geometry, static caves with one entrance and dynamic caves with two or more entrances at different altitudes can be distinguished (Bögli 1978). In contrast to static caves, dynamic caves ventilate throughout the year by a so-called chimney effect, and according to the sign of the ΔT_{AF} values, two ventilation regimes are distinguished. Whereas the downward airflow, corresponding to the DAF ventilation mode, occurs during the summer season, when $T_{exterior}$ exceeds T_{cave} ($\Delta T_{AF} > 0$), upward airflow, representing the UAF ventilation mode, is typical for the winter season, when T_{cave} exceeds $T_{exterior}$ ($\Delta T_{AF} < 0$) (Faimon et al. 2012). In addition to natural factors, the T_{cave} distribution is also influenced by anthropogenic factors associated with large visitor numbers (Lang et al. 2017; Lang et al. 2024). This work was conducted in the Výpustek Cave, a cave open to the public all year round, and represents part of the water condensation research in the Moravian Karst (MK) caves opened to the public, that should contribute to a better understanding of water condensation in the cave environment.

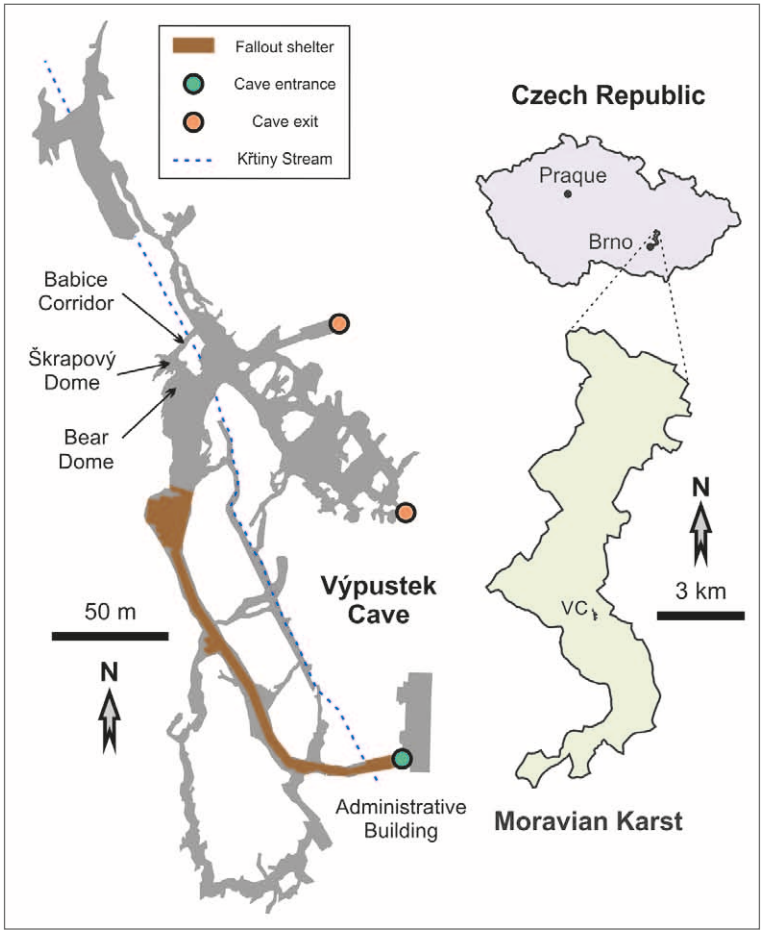

Fig. 1: The Výpustek Cave location and the cave sketch map with the monitoring site.

Site of study

The site of study, the Výpustek Cave, is situated in the central part of the MK in the Křtiny valley about 2 km from the village of Křtiny (Fig. 1). The cave represents a complex of relatively narrow corridors and large domes with a total length of about 2 km formed by the Křtiny Stream in the Middle/Upper Devonian limestone (Lms.) of (i) the Macocha Formation (Lažánky and Vilémovice Lms.) and (ii) the Líšeň Formation (Křtiny Lms.). A complex morphology of the cave (two levels and three entrances) ensures a typical dynamic air circulation. Between 1961 and 2001, an underground fallout shelter and a secret command post of the Czechoslovak army operated in the cave. Since 2008 has the cave been open to tourists with a total attendance of 16,000 to 30,000 people per year. The Škrapový Dome, situated about 50 m from the cave exit, was chosen as the monitoring site. It represents a multientranced cave dome with about 3900 m^3 of total volume. Its input passage is a narrow corridor with descending staircase from the Bear Dome and the output passage is a narrow corridor leading to the Babice Corridor (Fig. 1).

Methods

Presented data were collected during (1) a long-term monitoring campaign and (2) regular individual campaigns during period from February 2024 to January 2025. The long-term campaign was focused on air temperature monitoring for ΔT_{AF} calculation. Temperatures were logged (i) outside the cave, between administrative buildings, and (ii) in the Škrapový Dome 1 m above the cave floor. Temperatures were recorded with 1-hour time steps by Termio-2 dataloggers with a precision of ±0.07 °C in the range from –10 to 100 °C. In addition to air temperature, daily cave attendance was registered.

Tab. 1: The scale for evaluation of water condensation intensity on the polished limestone tablets in the cave environment.

Degree	Limestone tablet description
1	A completely dry surface of the limestone tablet.
2	A slightly wet surface of the limestone tablet.
3	Water droplets on the surface of the limestone tablet.
4	A completely wet surface of the limestone tablet.

Individual campaigns were focused on water condensation measurements. Based on White et al. (2021), the water condensation effect was studied on a polished limestone tablet (6 × 4 × 0.5 cm) placed in the Škrapový Dome near the temperature datalogger in February 2024. The tablet was cut from the Vilémovice Lms. from the cave itself. The intensity of the water condensation was quantified using the four-stage scale (dry tablet to completely wet surface; Table 1) used by Fajkošová (2011) or Hrdý (2021). The surface of the limestone tablet was examined in roughly monthly intervals, except for the campaigns in July and September, covering the periods from June to July and August to September, respectively.

Surface of the limestone tablets was analyzed in March 2024 (the period of exposure ~ 11 months) by a scanning electron microscope JEOL 6490LV equipped with an EDX microanalyzer (Oxford Instruments) in the Laboratory of Electron Microscopy and Microanalysis of the Institute of Geological Sciences (Faculty of Science, Masaryk University in Brno).

Results

Microclimatic data

During the long-term monitoring campaign that ran from February 2024 to January 2025, $T_{exterior}$ values varying in a wide range from –7.1 to 33.5 °C showed strong annual oscillations with maxima in the summer season (July) and minima in the winter season (December) (Fig. 2a). However, the $T_{exterior}$ curve shows several multiday periods with unusual behaviour in the form of sharp temperature decreases. Such a phenomenon was observed for ~ 10 days in the second half of April, where a decrease of $T_{exterior}$ values of almost 20 °C was recorded. A similar $T_{exterior}$ decrease for the same period was also found in the first half of September. In contrast to the $T_{exterior}$ evolution, the T_{cave} values showed no seasonality and varied in a relatively narrow range from 7.3 to 9.4 °C (Fig. 2b). However, two sections with different trends were distinguished on the T_{cave} curve. The first section, February to October, was characterized by a systematic increase from the initial value of 7.7 °C up to 8.4 °C. The second section, representing the period between December and January, shows a relatively sharp decrease from 8.1 to 7.6 °C. In the period from October to November, the data logging was interrupted due to technical problems with the thermometer. It is important to note that the "natural" curve of T_{cave} contained sharp peaks corresponding very well with the attendance numbers, representing the anthropogenic impact on the air temperature in the monitored dome. Heights of individual peaks corresponded to the number of visitors in individual tours and the maximal attendance of 1296 visitors resulted in a peak height of 1.4 °C. Similarly to the $T_{exterior}$ evolution, significant seasonality was also identified in daily attendance including 13,663 persons in the summer season and 2910–4147 persons in the remaining seasons (Fig. 2c). Two

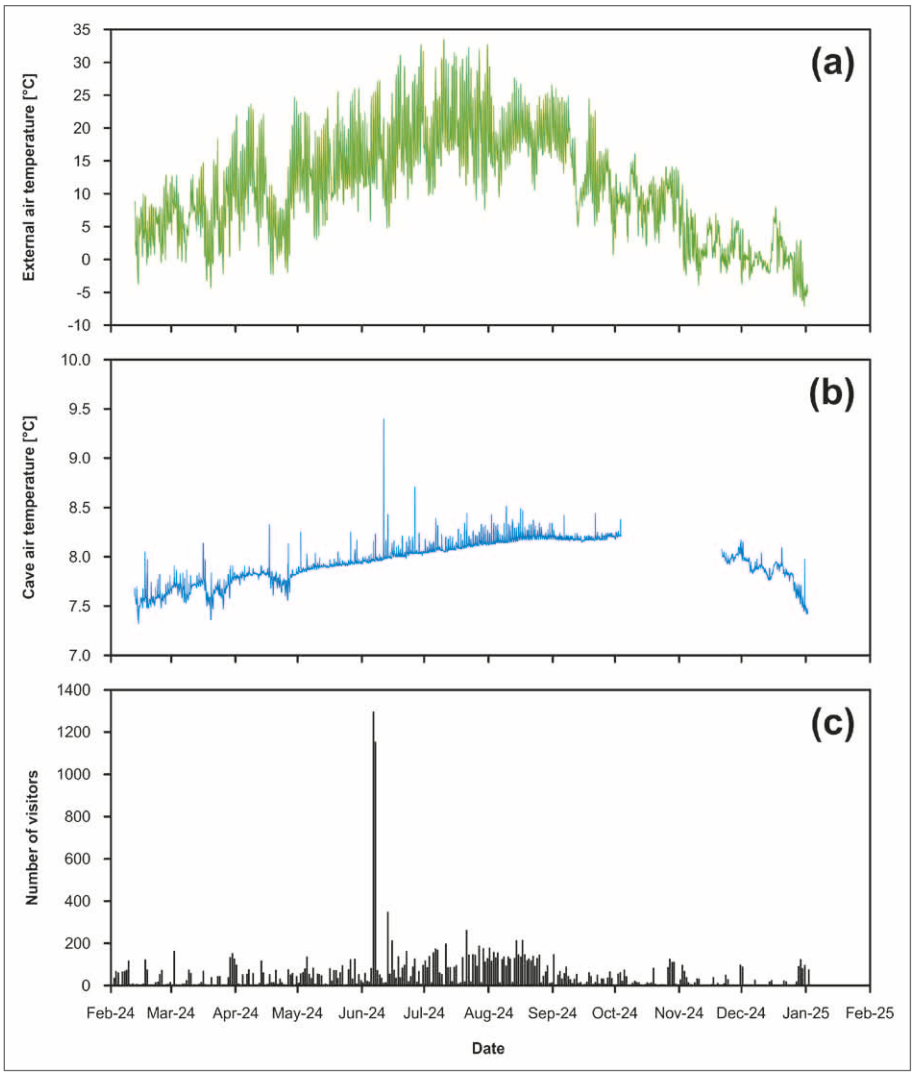

Fig. 2: The seasonal evolution of external air temperature (a) and cave air temperature within the Škrapový Dome (Výpustek Cave) (b) in dependence on the daily cave attendance (c).

types of cave visits connected with walking through the monitored dome occurred during the monitoring campaign: (i) standard cave tours and (ii) occasional cultural events connected with a significantly enhanced and prolonged attendance. Examples of these events are clearly visible on 6 and 7 June, when 1296 and 1153 persons passed through the dome (Fig 2c).

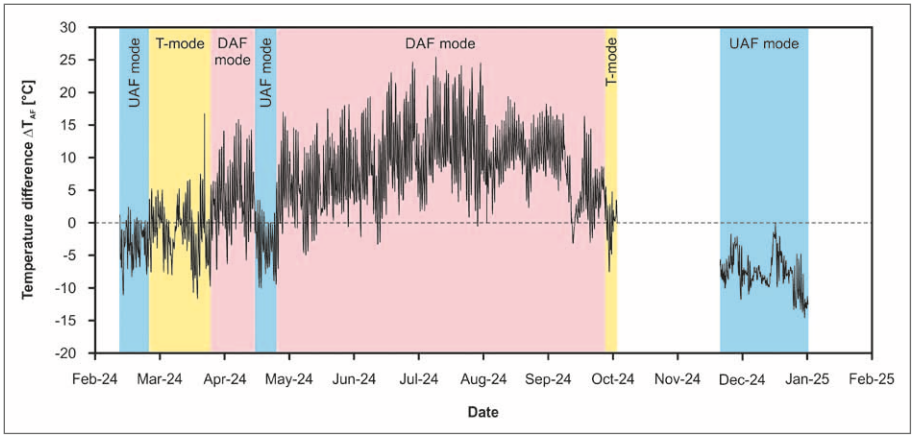

Fig. 3: The seasonal evolution of temperature difference $\Delta T_{AF} = T_{exterior} - T_{cave}$ within the Škrapový Dome (Výpustek Cave). The colored columns represent periods with predominant DAF mode (red columns), UAF mode (blue columns) and transitional mode (yellow columns).

The intensity and direction of cave airflow during the long-term monitoring campaign were estimated from the temperature difference, $\Delta T_{AF} = T_{exterior} - T_{cave}$, calculated using Eq. (3), and its evolution is depicted in Figure 3. Based on $T_{exterior}/T_{cave}$ variations, the resulting ΔT_{AF} values inside the monitored dome ranged between –14.6 and 25.4 °C. Positive ΔT_{AF} values, corresponding to the downward airflow (DAF) ventilation mode, operated in the period from April to September. In contrast, negative ΔT_{AF} values, representing the upward airflow (UAF) ventilation mode, occurred in February, November, and December, but this mode was also briefly recorded during April. During the remaining periods, March and October, the cave persisted in the transitional ventilation mode, with switching between the DAF mode and the UAF mode at ΔT_{AF} values oscillating around zero.

Water condensation data

The intensity of water condensation in the monitored dome during the individual campaigns was estimated from the presence of condensation on the surface of the polished limestone tablet using criteria in Table 1. During the whole monitored campaign, three periods characterized by different intensity of water condensation were distinguished (Fig. 4). The first period covered the spring season (March, April) and the winter season (December, January), during which was the surface of the tablet completely dry (condensation degree 1). The second period, May and November, was characterized by the presence of water droplets on the surface of the tablet (condensation degree 2). The third period, the summer season, was associated with the most intensive condensation. While large water drops (condensation degree 3) were found on the tablet surface in September and October, a completely wet surface (condensation degree 4) was registered on the tablet surface in July.

The intensity of water condensation on the tablet surface during individual campaigns was documented by photographs (Fig. 5). Four images in Figure 5 represent (i) different seasons and (ii) the highest condensation degree of the relevant season. The spring season is represented by an image from May showing slight water condensation (condensation degree 2) (Fig. 5a). The summer season image from July shows the highest water condensation (condensation degree 4) (Fig. 5b). The fall season is documented by image from October showing moderate water condensation (condensation degree 3) (Fig. 5c). The winter season (December) had no signs of water condensation (condensation degree 1) (Fig. 5d).

SEM images of the limestone tablet

The presence of corrosion on the surface of the limestone tablet was studied using SEM images, and the results are given in Figure 6. Despite the relatively homogeneous surface (see the overall view in Figure 6a), some distinct objects were identified (see details in Figure 6b, c). These objects have darker and lighter areas representing various intensities of influence of condensed water on

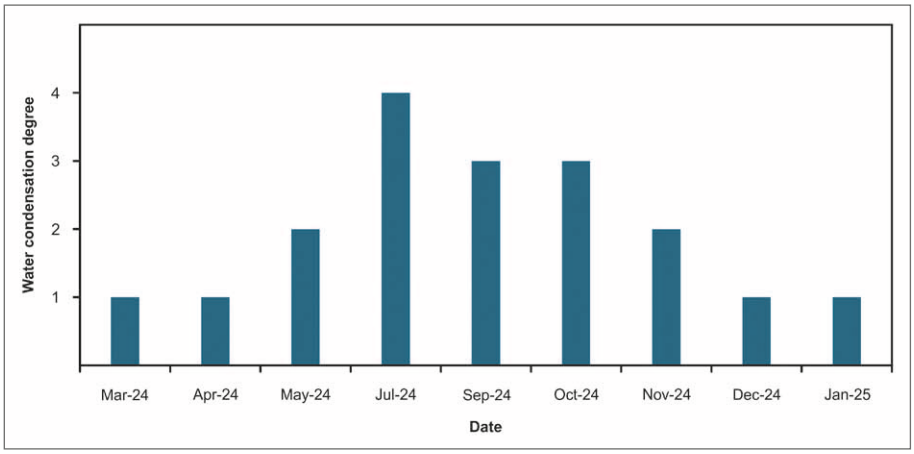

Fig. 4: The seasonal evolution of water condensation on polished limestone tablet situated within the Škrapový Dome (Výpustek Cave).

the limestone tablet surface. Even traces of calcite recrystallization were found: some objects were overlain by cave aerosol products (Fig. 6d).

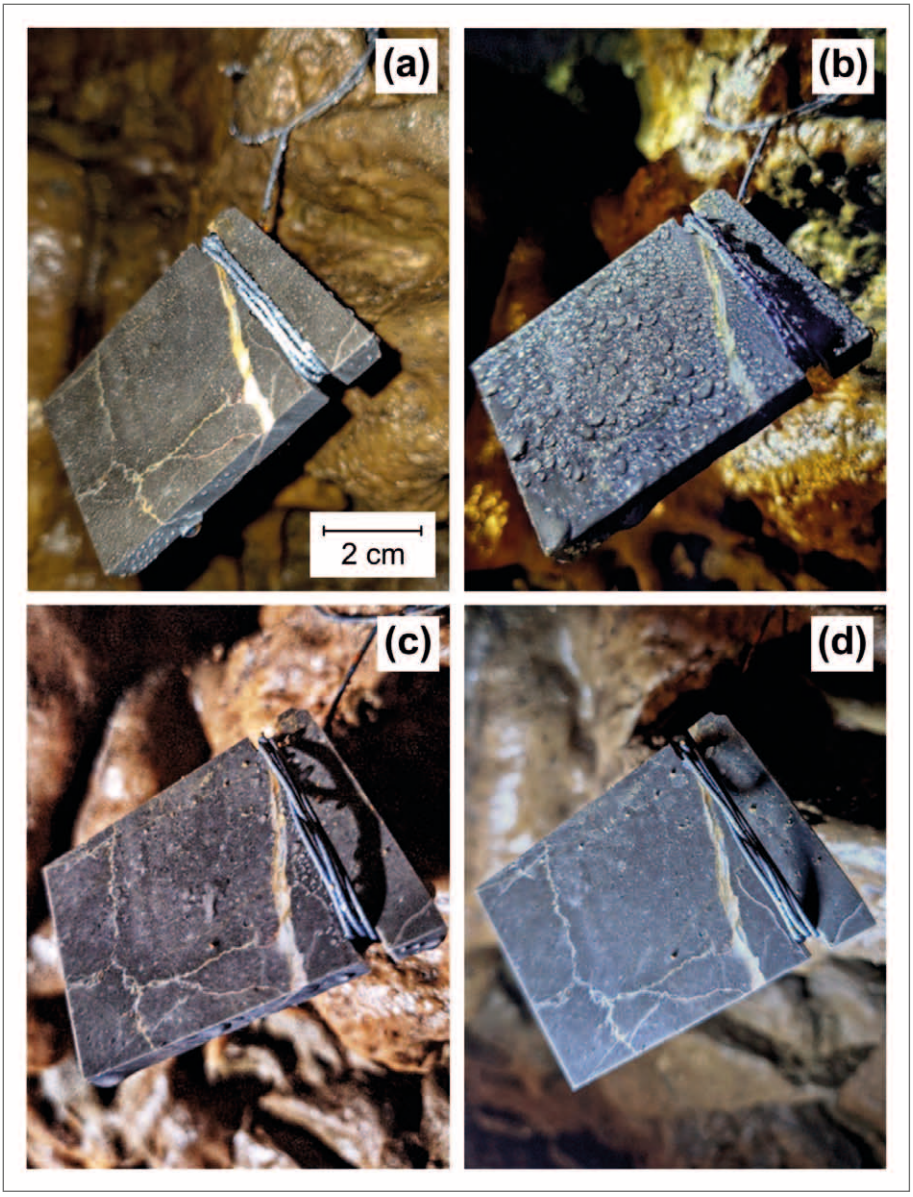

Fig. 5: Examples of water condensation on polished limestone tablet situated within the Škrapový Dome (Výpustek Cave) from different seasons: May (a), June/July (b), October (c), December (d).

Discussion

Narrow range of T_{cave} values (2.1 °C) documented in the monitored dome indicates relatively stable temperature conditions throughout the seasons corresponding to the passages of the homothermic zone Luetscher and Jeannin 2004). However, some hints of seasonal trends, represented by spring systematic increase or winter sharp decrease of the natural T_{cave} values, are clearly visible (Fig. 2b). Similar patterns of T_{cave} and ΔT_{AF} evolution show that the seasonal character of T_{cave} values could be associated with ΔT_{AF} changes that control the cave airflow (Pflitsch and Piasecki 2003; Faimon et al. 2012). ΔT_{AF} values varied in a wide range of 40.6 °C, which allowed identification of periods with different airflow directions: periods with positive ΔT_{AF} values corresponding to the DAF ventilation mode, periods with negative ΔT_{AF} values corresponding to the UAF ventilation mode, and periods with quick switching between DAF/UAF modes corresponding to a transitional ventilation mode (Fig. 3). Ventilation modes were controlled by the summer (DAF) and the winter (UAF) seasons, however, data showed their dependence especially on the ΔT_{AF} values. This behaviour is evident in April, where the decrease in $T_{exterior}$ values of up to 20 °C led to the switch of cave ventilation to UAF mode for ~ 10 days. Furthermore, some authors (Faimon et al. 2012; Lang et al. 2015) reported that the mode switching could be achieved at nonzero ΔT_{AF} and estimated the switching ΔT_{AF} in the range from 0.4 to 3.2 °C. In addition to natural influence, air temperature of the monitored dome was also anthropogenically affected by cave attendance, as shown by the temperature peaks whose heights were controlled by visitor numbers in individual tours. Similarly to the T_{ext} evolution, a significant seasonality was also identified in the case of water condensation, where both periods with completely dry and wet surface of limestone tablet were recorded (Fig. 4). Completely dry tablet surface was found only in the winter and early spring seasons and the remaining seasons were characterized by water condensation on the tablet surface with the peak in July. This is consistent with data from karst massifs of the Crimea Mountains (Dublyansky and Dublyansky 1998). Since condensation occurred especially during DAF ventilation mode (Fig. 3), it could be deduced that condensation was controlled by airflow that transported warm external air into the dome (de Freitas and Schmekal 2005).

Despite relatively short exposure time, the limestone tablet showed some signs of influence by condensed water (Fig. 6). These signs were represented by objects differing in lighter color from the dark tablet (Fig. 6b, c). The mechanism of their origin was described by Lang et al. (2024), when drops of condensed water remain on the calcite/limestone surface until cave conditions change and then evaporate. Detailed analysis of the lighter parts of the drops showed traces of recrystallization of the calcite/limestone surface (Fig. 6d) as a result of new calcite

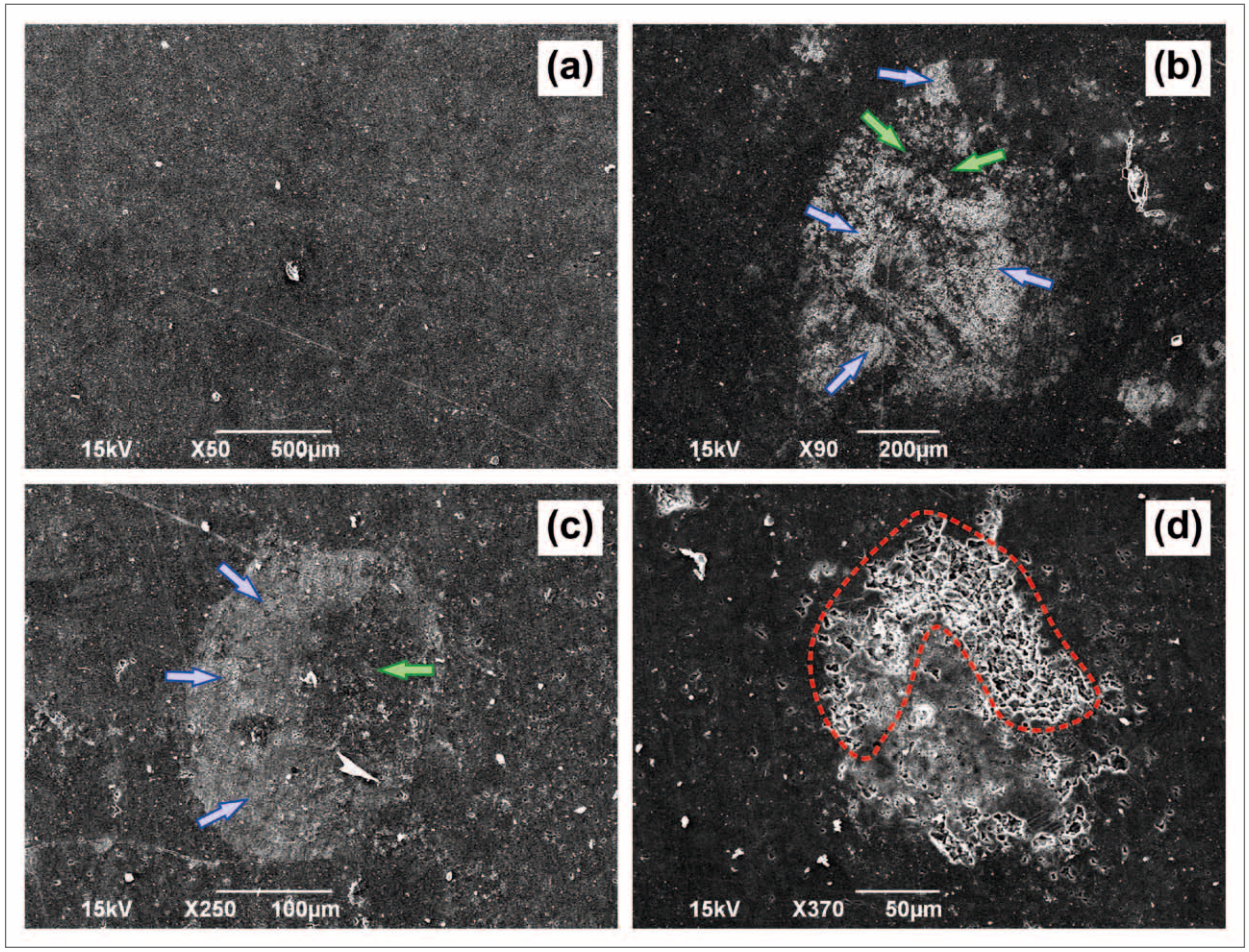

Fig. 6: The SEM images of the limestone tablet placed in the Škrapový Dome (Výpustek Cave) in the period from February 2024 to January 2025: natural tablet surface (a), regular objects (b, c), and traces of calcite recrystallization (d).

growth from supersaturated solution during evaporation. This process could be a potential risk for the conservation of prehistoric paintings in caves in the Moravian Karst (Golec et al. 2021) and in the world (Sánchez-Moral et al. 1999). Similar drop relics on the limestone tablet surface were also observed by Hrdý (2021) in the Amatérská Cave, already after four months of exposure. It indicates more intense condensation and subsequent influence of condensed water on the tablet surface. However, SEM analysis of the tablet after almost a year of exposure in the cave environment did not show direct evidence of condensation corrosion. Therefore, a greater effect of condensation corrosion requires a longer period of exposure (years) to the cave environment. It was demonstrated by Fajkošová (2011) in the Amatérská Cave, where corrosion of limestone tablets was documented after 17 months after their placement in the cave.

Conclusions

Seasonal variations of water condensation were studied in the Škrapový Dome in the Výpustek Cave (a cave open to the public in the Moravian Karst). Research was carried out during regular individual campaigns and long-term monitoring of the cave/external air temperature. Intensity of the water condensation was quantified by evaluating a polished limestone tablet placed in the monitored dome. Long-term temperature data showed the dynamic character of cave airflow comprising UAF/DAF ventilation modes. This resulted in seasonality of cave air temperature, where maxima corresponded to the summer season and minima were found during the winter season. Presence of visitors led to short-term increase of the cave air temperature and subsequently to a decrease of driving force of water condensation. Monitoring of the limestone tablet showed a seasonal presence of water condensation based on cave airflow. During the UAF mode (winter and early spring seasons), the tablet was completely dry. During the DAF mode (late spring, summer and fall seasons), drops of condensed water were registered on the tablet surface as a result of warm air transported to the studied dome from cave passages close to the cave entrances. Traces of recrystallization on the calcite/limestone surface were found as a consequence of prolonged interaction between the tablet and condensed water. The results of this study could be of interest to karstologists and environmentalists for a better understanding of the dynamics of water condensation in caves open to public to improve the visitor regime management.

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