Underground monitoring and mapping in conglomerate karst, a case study from "Castel Sotterra" Cave (Veneto, Italy)

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Abstract

The "Castel Sotterra" cave, with a length of ~7 km and a depth of ~125 m, is the largest cave on the Montello Hill and the fourth largest conglomerate cave in the world. The cave provides a unique environment for studying underground microclimatic patterns and their role in the ecology of a non-traditional multi-level cave system.

Speleological surveys and explorations coupled with temperature monitoring reveal the thermal dynamics and properties of a conglomerate cave, specifically how temperature variations correlate with cave levels, conduit intersections, and external climatic variations during precise temperature tracking. The goal is to reveal nuanced patterns of air movement that may be the same or different from traditional cave systems. Along with the monitoring, a three-dimensional cave map is being developed to provide spatial context for the temperature data and to identify potential connections between cave passages and the surface.

Temperature data are key to assessing the suitability of the cave for underground animal populations, such as Chiroptera, which are commonly found in Castel Sotterra Cave. These environmental parameters have wider implications for understanding the resilience of the cave ecosystem in the face of pressures from ongoing environmental issues such as habitat destruction, pollution and climate change.

1. Introduction

Caves represent a unique and fragile subterranean environment, where climatic characteristics reflect the complex interplay between external factors such as temperature and precipitation, cave morphology resulting from speleogenesis, and the physical properties of the substrate. The thermal properties of a cave depend primarily on heat conduction from the atmosphere and advection from water and air inflow (Badino, 1995). Monitoring temperature variations inside caves serves multiple purposes in modern speleological activities. Historically, tracking water flow along conduits and detecting slight variations in air movement have been the most common indicators of potential unexplored passages and entrances during exploration. However, a scientific approach using data loggers placed at key locations can reveal interactions within the underground environment, including the physical thermal state of a cave and its ecosystem (e.g., Luetscher et al., 2008; Dominguez-Villar et al., 2023). In this study, we explore how temperature variability is closely related to cave morphology in the unique environment of Montello Hill (Figure 1A), which is considered the "Classical Karst" of conglomerate (Ferrarese and Sauro, 2005). The Montello Karst has evolved rapidly over the last ~350 kyr, forming a well-developed multi-aquifer karst system influenced by substrate lithotypes and active tectonics.

In the Castel Sotterra Cave, temperature monitoring has been integrated with a new mapping project to provide modern visualizations of the cave, which are useful for scientific research. We observed how temperature variations influence the habitability of different cave sectors for bats, representing the archetype of cave-dwelling animals. The Castel Sotterra Cave is one of the most important hibernacula for bats in the Veneto Region, and sight counting can provide valuable information on the status of *Rhinolophus* species.

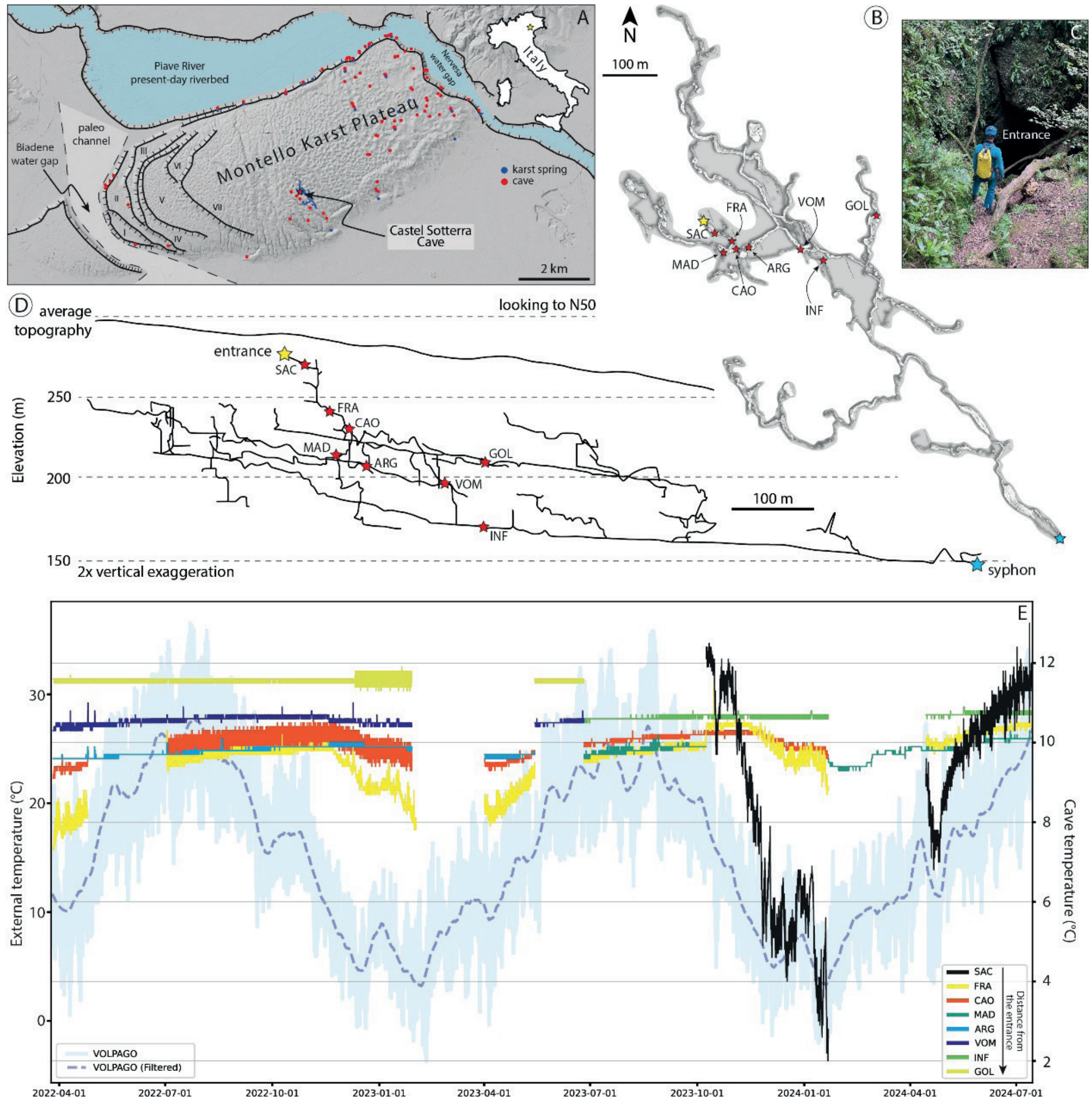

Figure 1: *(A) Map of Montello Hill showing caves entrances and Castel Sotterra Cave. (B) Planimetric map of Castel Sotterra Cave showing temperature datalogger positioning. (C) Picture of the entrance of Castel Sotterra Cave. (D) Vertical cross-section of the cave with datalogger positions. (E) Temperature monitoring of the last three years. The y-axis on the left shows temperature measured at the nearest ARPAV station (Volpago del Montello), the y-axis on the right shows temperature measured by dataloggers. Abbreviations: SAC, Saccardo Room; FRA, Frana Room; CAO, Caos Room; MAD, Madonna Room; ARG, Argilloni; VOM, Vomito Pit; INF, Inferiori Canyon; GOL, Golem Room.*

Following the precursor study by Badino (2004), we aim to initiate a long-term project in the Montello Hill conglomerate karst to better understand the effects of Climate Change, which are already evident in this ephemeral underground environment (e.g., Obleitner et al., 2024). Extended climate data series will be invaluable in predicting the adaptations that ecosystem actors will need to make in response to rising temperatures and extreme weather events.

2. Materials and methods

The temperature monitoring program inside the Castel Sotterra cave was carried out using Elitech RC-5+ loggers, stationed in different sectors of the cave and suspended from the ceiling at human eye level. The loggers have an internal NTC thermal resistor with a precision of 0.5°C. Temperature was recorded every 5 minutes between 2022 and February 2023, every 10 minutes in Spring 2023, and every 30 minutes from Summer 2023 onwards. The external temperature is monitored by open-access data from the ARPA Veneto agency, which provides the temperature every 1 hour at Volpago del Montello, the nearest meteorological station (~ 2.5 km from the cave entrance).

An initial analysis of the dataset was performed using a private online repository designed by the authors to manage temperatures from multiple caves, divided into cave sectors based on available surveys. Each temperature series is visualized on a timeline graph to control the spatial and temporal distribution of the records. Simple tools such as outlier removal and calibration factor are available, and the data can be exported in .xlsx or .csv format, showing metadata about the loggers. The online platform is currently under development but will be released for public use in the near future to contribute to open data science, possibly according to the FAIR data criteria.

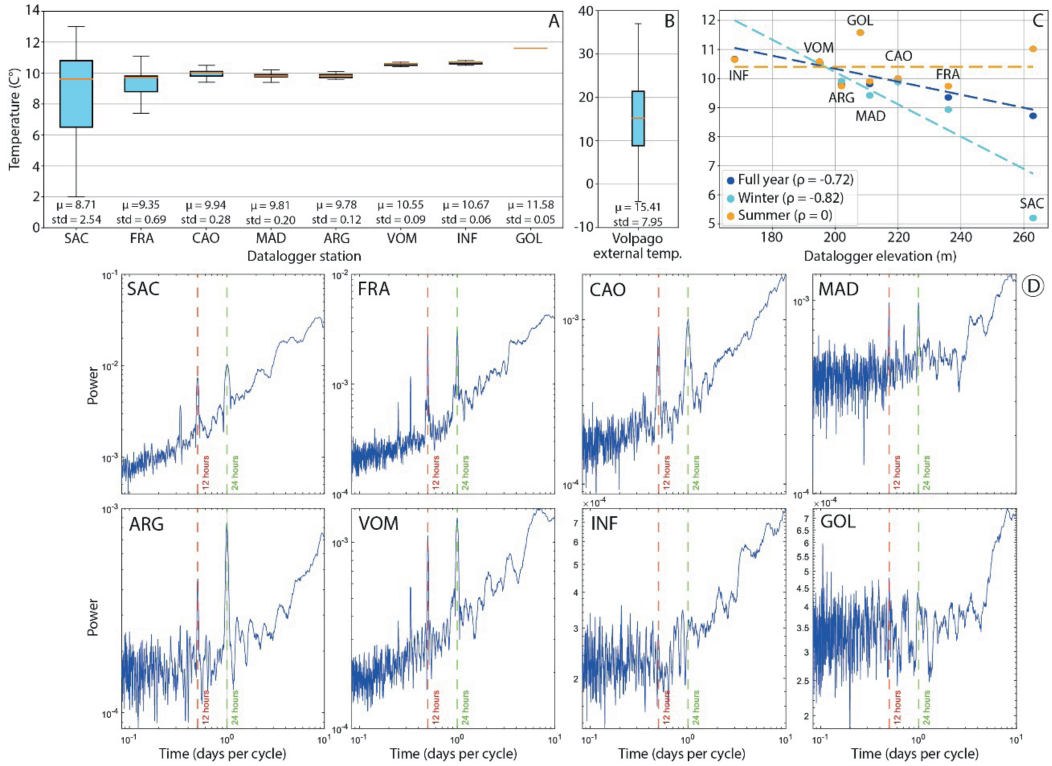

Figure 2: *(A) Boxplot showing temperature ranges measured by dataloggers. Light-blue boxes indicate temperature values between the second and the third quartiles, red lines represent the median value. At the bottom of boxes arithmetic means and standard deviations are shown. (B) Boxplot for temperature recorded at Volpago del Montello ARPAV station. (C) Mean values plotted against datalogger elevations (relative to the sea level). Means are calculated over three different time intervals. The inverse linear relationship between temperature and elevation is shown by dashed lines and Pearson's coefficients. (D) To highlight the high-frequency daily temperature oscillation a spectral analysis in the time domain shows peaks at 12 and 24 hours.*

Secondly, the time-temperature series were analyzed in the Python environment for statistical analysis using the scipy.stats and scipy.signal packages, and in MATLAB for spectral analysis using the Fast Fourier Transform function and filtering curves using a function from the Signal Processing Toolbox.

Topographic mapping of the cave was performed using a modified Leica Disto-X laser telemeter and the mobile application Topodroid. Data were measured relative to the first survey station at the entrance of the cave and to fixed points at the beginning of each cave branch. In addition, the previous map of the cave, made in the 90's by polygonal lines measured with an analog compass and clinometer, was computerized on C-Survey software and reprojected in a three-dimensional visualization in the Loch package. In the GIS environment, each station of the old survey was associated with X, Y, Z coordinates and plotted against the 2m resolution LiDAR-based digital elevation model (provided by the Veneto Region online repository).

Monitoring of bats was done by visual counting, differentiating between the two species found in the cave, and by bat acoustic detectors placed in locations similar to the temperature dataloggers.

3. Results

The Castel Sotterra cave is a hydrologically active multi-level cave carved in clastic sequences composed mainly of carbonatic conglomerate beds alternating with sandstone-siltstone intervals. The characteristic speleogenesis in Quaternary fluvial deposits is characterized by the interconnection of the cave levels, closely related to the landscape evolution of the Montello hill, large collapses and vadose pits or canyons. The cave is located on the southeastern side of the Montello Hill (Figure 1A), the mapped groundwater flow pattern is southeastward (see syphon location in Figure 1B), following the declining topography and conglomerate bedding. The entrance is at the bottom of a steephead valley (Figure 1C). Three major cave levels are found (Figure 1D), which are nearly parallel to each other along their entire length. It is noted that low angle cave conduits occur along fine-grained horizons in the substrate and are often vertically connected by steep and narrow vadose canyons.

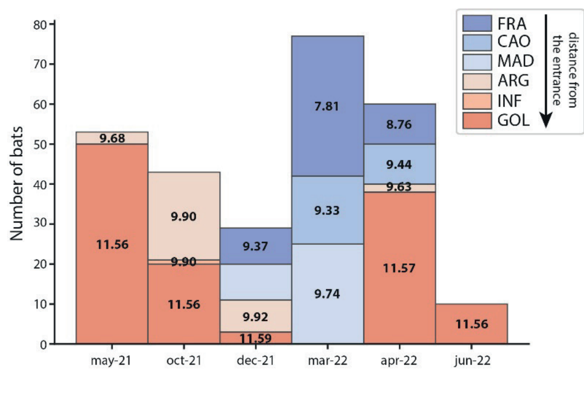

Figure 3 : Bat counting histogram between Spring 2021 and Summer 2022. Values inside boxes refer to monthly-averaged temperature calculated on out dataset between Spring 2022 and Summer 2024.

Eight stations were selected for temperature measurements with dataloggers (Figure 1B, D) along the entire cave between the entrance and the bottom of the active vadose canyon. The current dataset presented here reports time series between April 2022 and July 2024 (Figure 1E). Periods of missing data were due to systematic errors in data collection (e.g. February-March 2023) or intentional to account for logistical issues related to datalogger placement and data download. In general, the lowest and highest temperatures recorded in the cave are ~ 2 °C and ~ 12 °C, respectively, near the entrance in the first station in the Saccardo Room (SAC), but at ~ 40 m depth in the Frana Room (FRA) the amplitude of the annual temperature oscillation is reduced between ~ 7.5 °C and ~ 10.5 °C. The temperature generally increases on average towards the deeper (Inferiori Canyon, INF) and more distant (Golem Room, GOL) stations from the entrance, reaching a stable temperature of ~ 11.6 °C.

A positive correlation between cave temperature and external temperature measured at Volpago del Montello is highlighted by our data. The first three stations from the entrance (SAC, FRA, CAO) recorded low amplitude temperature variations forced by external thermal events, contrary to seasonal trends, such as in January 2023 and April 2024. It is also noted that the maximum temperature reached by the stations due to seasonal variations is not centered in August, as for the external record, but it has reached in November (Figure 1E).

Median values and arithmetic means of temperatures are gradually increasing going far from the entrance (Figure 2A), while the distribution of collected data show a decreasing trend (Figure 2A). The amplitude of the variability ranges is also different in different periods of the year. Considering the elevation of each station with respect to sea level as a reference, in summer the temperature has small variations in relation to station elevation (Figure 2C). Conversely, in winter, the inverse linear relationship between elevation and temperature is stronger (Figure 2C).

The spectral analysis in the time domain performed on the recorded data highlights the presence of two peaks at 12 and 24 h, reflecting the daily temperature variability (Figure 2D). This variability is present at all stations except at INF and GOL, and the relative power of the peaks decreases as one moves away from the entrance. The spectral analysis does not reveal other notable peaks that recur in more than one station on longer cycles, such as the seasonal cycle, due to the lack of a time series longer than one year without interruption.

Considering the monitoring of bats in the most visited areas of the cave, the number of specimens ranges between 10 and 80 (Figure 3). During the hibernation period, it cannot be excluded that more than 100 individuals may also be present, as bats have been reported to inhabit other cave conduits that are difficult to access during routine monitoring visits. Only two species commonly found in caves in the Veneto region have been documented: almost all individuals belong to *Rhinolophus hipposideros* (Bechstein, 1800), while no more than three individuals of *Rhinolophus ferrumequinum* (Schreber, 1774) have been reported at the same time, although more might inhabit unchecked branches. Other species frequenting the cave have been found only as subfossils. Bones of adult and juvenile *Myotis myotis/blythii* have been found in the mid level of the cave, while *Miniopterus schreibersii* remains have been identified in the upper levels.

During the hibernation period, from late October to late March, bats are mainly found in cooler areas (~ 8-10 °C), whereas during the summer months, they prefer warmer zones (~ 10-12 °C) (Figure 3). Bat guano is commonly present as accumulated deposits, varying in thickness from a few centimeters to several meters, observed in wide conduits in the upper, middle, and lower levels of the cave. Some guano mounds can be considered subfossils due to the absence of active colonies. Additionally, some bell-shaped cavities feature a darker alteration layer on the ceiling of large conduits, formed due to bat-induced corrosion of carbonatic conglomerate.

The current presence of other species in the cave, aside from the two mentioned above, is sporadic and has only been documented through prolonged recordings with automatic bat detectors placed inside the cave.

4. Discussion

The Castel Sotterra cave acts as a cave dominated by processes of thermal conduction and advection between the airflow coming from the only entrance, the water coming from the precipitation occurring on the top of the karst plateau, and the substrate. The thermal gradients calculated by linear regression (Figure 2C) are: (1) ~ 2.2 °C/100 m for annual averaged data sets, (2) ~ 5.6 °C/100 m for winter, (3) a stable gradient for summer. Between the entrance and 200 m elevation, the cave volume can be considered as belonging to the heterothermic zone (see Luetscher and Jeannin, 2004). Below, the homothermic vadose zone shows thermal stability throughout the year, so that only small variations are detected at the two deeper stations. The role of air advection is well recognized in the first ~ 80-100 m of depth of the cave, corresponding to the stations where spectral analysis highlights small temperature variations on a daily basis. The Castel Sotterra cave can be considered as a shallow network of karst conduits where the underground microclimate is strongly conditioned by external seasonal variability and the occurrence of extreme meteorological events. In addition, the huge influx of water caused by extreme precipitation is able to locally modify the temperature exchange heat by advection. Water is uniformly distributed along the pervasive fracture network and then concentrated along active canyons in the lower levels of the cave. The presence of long horizontal conduits favors thermal stratification in sectors of the cave in the uppermost levels, but far from the entrance. For example, at the station in Golem Room (GOL), which is at the same level as Madonna Room (see Figure 1D), the temperatures recorded are interestingly higher and almost stable and identical within the measured time series. The Golem Room can only be reached by descending to the Vomito Pit station (middle cave level) and then ascending to the upper level. The thermal stability of the upper level suggests that the cave has only one entrance. Nevertheless, the remains of *Myotis myotis* and *Miniopterus schreibersii* have contributed to new hypotheses on the morphological evolution of the cave, such as the presence of other openings in the past. The decreasing trend in the amplitude of seasonal variability along the cave profile is justified by the distance of the entrance, which provides air circulation (Figure 2A). The time shift observed between the peak of temperature outside the cave and the peak recorded at shallower stations from August to the first half of November is a period when the cave accumulates heat until the day when the outside and inside temperatures are equal. For three months, the temperature is constantly increasing due to the inflow of air that exchanges heat by advection.

5. Conclusion

Castel Sotterra Cave, the largest cave in the Montello Hill conglomerate karst plateau, provides a unique opportunity to reveal climatic patterns in a multi-level structured cave. Temperature monitoring and topographic mapping help to correlate the response of cave thermal dynamics, controlled by cave morphology, to external climatic variations. Initial results show that temperature variations are related to cave levels and intersections between horizontal and vertical vadose morphologies. Most of the cave belongs to the heterothermic zone, where the thermal gradient varies within the year following seasonal fluctuations. The observed thermal pattern suggests that the air circulation is mainly controlled by external temperature variations, whose influence decreases with depth and distance from the entrance until thermal stability is reached.

The temperature has a critical impact on the ecology of the cave, especially for bat populations such as *Rhinolophus hipposideros* and *Rhinolophus ferrumequinum*, which require specific conditions for hibernation. In Castel Sotterra, the sectors that are more sensitive to external environmental pressures are also among the most important for the cave ecology.

This study highlights the importance of temperature monitoring in understanding the resilience of subterranean ecosystems and the data collected will provide a baseline to have information on future changes and guide conservation efforts in the fragile karst environment.

Acknowledgments

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The digital elevation model is taken from the Veneto repository (https://idt2.regione.veneto.it/idt/downloader/download). Meteorological dataset are available at ARPAV website (https://www.arpa.veneto.it). The software used in this work are: C-Survey (https://csurvey.it/site), TopoDroid (https://sites.google.com/site/speleoapps/home/topodroid), QGIS Desktop 3.34.3, Adobe Illustrator 2023, Python 3.11.4, MATLAB R2022b.

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