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Measurement of spatio-temporal changes of cave ice using geodetic and geophysical methods: Dobšiná Ice Cave, Slovakia

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Abstract: Dobšiná Ice Cave has attracted the attention of many researchers since its discovery more than 150 years ago. Although the cave is located outside the high-mountain area, it hosts one of the largest blocks of underground perennial ice. The topographic mapping of this unique UNESCO Natural Heritage site has led to several historical surveys. In the last decades of rapid climate change, this natural formation has been subject to rapid changes that are dynamically affecting the shape of the ice body. Not only increased precipitation, the rise in year-round surface temperatures, but also the gravity cause significant shape changes in the ice filling. This paper describes modern technological tools to comprehensively survey and evaluate interannual changes in both the floor and wall of the underground ice block. Technologies such as digital photogrammetry, in conjunction with precise digital tacheometry, make it possible to detect ice accumulation and loss, including the effect of sublimation due to airflow, as well as sliding movements of the ice block to the lower part of the cave. In the last two years, geophysical methods (microgravimetry and ground penetrating radar) have been added to determine the thickness of the floor ice in the upper parts of the cave due to the complexity of the measurements. The paper not only highlights the current technological possibilities but also points out the limitations of these technologies and then sets out solutions with a proposal of technological procedures for obtaining accurate geodetic and geophysical data.

Key words: Ice cave, cryomorphological topography, tacheometry, photogrammetry, laser scanning, SLAM, microgravimetry, ground penetrating radar.

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1 Introduction

The dynamics of the evolution of the ice filling of caves is a long-standing scientific problem. The world of fragile underground ice caves offers its beauty in many countries around the world. Their uniqueness attracts the attention of many researchers as well as the general public (Perşoiu and Lauritzen, 2018). Since the first discoveries of these unique natural beauties, researchers have noticed that the ice fill is subject to change over time. Their research focuses primarily on the morphology and the dynamics of the glacier's shape changes depending on the climatic conditions prevailing underground, but also on their age dating, genesis, and geographic location. Awareness of the world's ice caves was relatively small until the 19th century and narrowly geographically confined to Central Europe and Russia. Ice caves in Jura and the Western Alps (now France and Switzerland) have been known for a long time, but Dobšiná Ice Cave, together with Demänovská Cave (Slovakia) and Pestera Scărisoara Cave (Romania), are among the first caves discovered in the 19th century in Central Europe outside the Alpine regions (Meyer, 2018). As stated by Meyer (2018), the history of ice cave exploration in the more distant past (19th-20th century) was devoted to the unification of heterogeneous nomenclature, to the description of phenomena influencing the formation of ice in caves - depending on the airflow pattern, climatic conditions (defining the relationship between internal and external climatic conditions, microclimate, climate in front of the cave, as well as regional macroclimate), cave shapes. Many of these theories have been contradicted and disproved over time.

In the past, ice level was typically measured as the distance from a fixed point (monitoring datum) on the cave wall or ceiling above the ice floor (marked by a screw or nail permanently inserted into the rock) to the surface of the ice floor (Smith, 2014). When multiple observations from a cave were available for a given year, the data offered the opportunity to model inter-annual variation in ice height. However, modern geodetic and geophysical tools after 2010 provide quite different qualitative results for surveying ice-fill dynamics (Behm, 2008; Podsushin, 2008; Hausmann, 2011; Gómez-Lende, 2014). Digital tacheometry and, more recently, terrestrial laser scanners, or digital photogrammetry tools, allow the collection of data with high temporal and spatial resolution. These technologies have been highly proven in many research works (for instance, Pukanská et al., 2018; Šupinský et al., 2019; Pukanská et al., 2020; Bella et al., 2021). The measurements have been used to detect bulk masses or to trace some ice blocks but mainly to survey the geomorphological features of cave spaces - cartographic and topographic representation or the creation of geological maps (Petters, 2011; Berenguer-Semper, 2014; Milius, 2012).

Over time, as the technology and methodologies of topographic research have evolved, so have the knowledge and refinement of scientific results. From the early historical geodetic measurements with optical instruments, and analog photogrammetry, we are now moving to technologies such as digital tacheometry and photogrammetry, terrestrial laser scanning (TLS), or modern geophysical methods such as microgravimetry, ground penetrating radar (GPR), and seismometry.

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2 Study area

The Dobšiná Ice Cave ("Dobšinská ľadová jaskyňa" in Slovak) belongs to the well-known ice cave in the world. It is located in the southern part of Slovenský raj (Slovak Paradise) National Park in the Spiš-Gemer Karst (north of the town of Dobšiná) (Fig.1). Its entrance lies at 969 m a.s.l., on the right side of the Hnilec River valley, on the west slope of the Duča Plateau, 130 m above the valley bottom. The length of the cave is 1483 m with a vertical span of 112 m. It is an inflow part of the larger genetic system of the Stratenská Cave, which is longer than 23.6 km. The whole system was formed by two underground streams - the Hnilec River and the Tiesňava Stream in the Late Pliocene (Tulis and Novotný, 1989; Novotný, 1993; Novotný and Tulis, 1996, 2005; Bella et al., 2014). The conditions for the formation of the ice fill were probably created in the Middle Pleistocene after the collapse of the ceilings (Duča sinkhole) and the breaking of the passage between Dobšinská Ice Cave and Stratenská Cave (Novotný and Tulis, 1996). At present, it is mostly filled with ice that reaches the ceiling in some places, and that divides the cavity into several parts: Small Hall, Great Hall, Collapsed Chamber, Ruffíny' Corridor, Ice tunnel, Ground Floor, and Hell. The ice filling of the cave is mainly made of floor and wall ice, ice stalagmites, and icefalls (Fig. 2). In 1995, a joint geodetic and geophysical survey of the ice volume and area was carried out, which revealed the ice volume was 110,132 m^3, the surface of ice fill was 9772 m^2, the maximal thickness of floor ice reached 26.5 m, and the average thickness of floor ice was 13 m (Novotný and Tulis, 1996; see also Bella, 2006, 2018; Bella and Zelinka, 2018; Bella et al., 2020). The surface area (in the vicinity of the cave) is in the moderately cool (mean annual air temperature 4,7 °C; mean air temperature in January -5,4 °C, in July 14,2 °C) and very humid subregion (mean annual precipitation total 900–1000 mm) (according to Lapin et al., 2002; Faško and Šťastný, 2002; Šťastný et al., 2002).

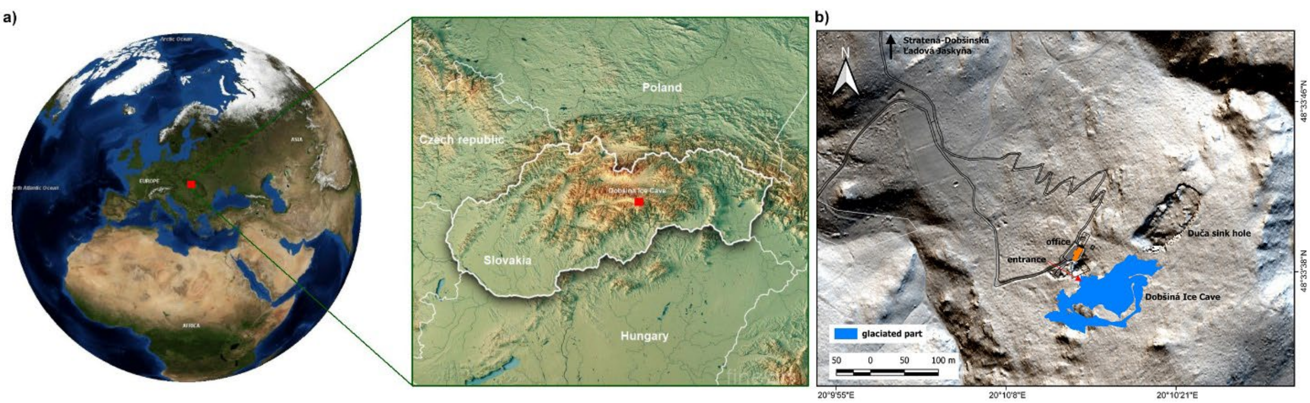

Figure 1 a) Dobšiná Ice Cave, Slovakia (Ramspott, 2017); b) projection of the glaciated part of the cave on the surrounding digital terrain model (source of the DTM - LiDAR data: ÚGKK SR).

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Figure 2 Great Hall and ice tunnel (source: authors).

3 Material and methods

Although the "ice hole" under the Duča had been known to shepherds and loggers for a long time, it was discovered only on 15 June 1870 by Eugene Ruffini and Co. (Lalkovič, 2000; Kudla 2020). The cave was opened to the public on 8 March 1871. The first map of the Dobšiná Ice Cave was made by its discoverer Eugen Ruffiny in 1871; later, new drawings were added. The first stereophotogrammetric surveys of the cave spaces were carried out in 1936. Another measurement was the research of spatial changes of the ice fill by geodetic and photogrammetric methods in the years 1976-1990, in which the Department of Mine Surveying and Geophysics of the Technical University of Košice (VŠT Košice) was also involved.

3.2 Methodology of ice cave mapping

Dobšiná Ice Cave is a significant geomorphological and geological object of world importance. Research of changes in the ice surface due amount and composition of surface precipitation, the temperature of the internal environment, speed and direction of airflow, as well as anthropogenic factors (number of visitors, human interference), must be carried out by precise geodetic and geophysical measurements, which use detailed measurements of small surface changes and can also capture the dynamics of change over time. Geodetic methods such as digital tacheometry, but also modern non-contact technologies (digital photogrammetry and laser scanning), as well as geophysical methods such as microgravimetry and ground penetrating radar, provide an innovative way for the study of surface and volume changes of the underground ice. The systematic measurement of surface ice changes started in 2011, with the first step being the monumentation of the geodetic point field and its survey as a closed traverse, followed by its adjustment and connection to the national spatial network by GNSS measurements. Since 2011, the survey methodology has been gradually complemented by newly available technologies (Figs. 3 and 4).

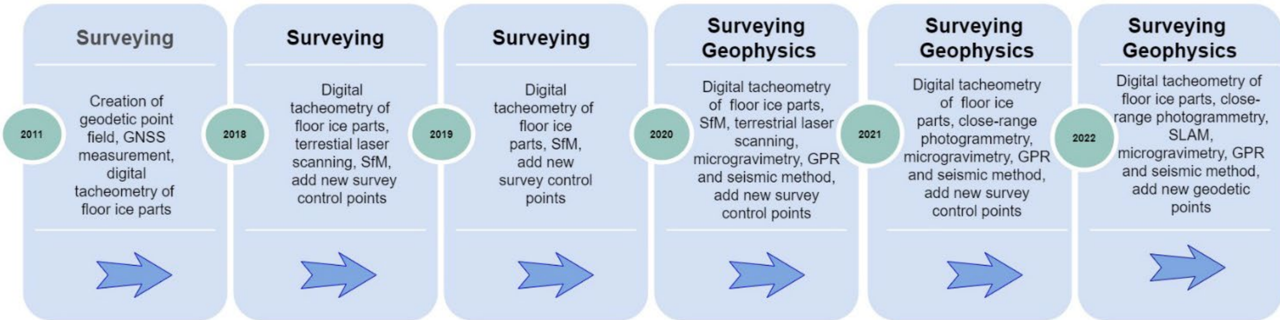

Figure 3 The timeline of geodetic and geophysical surveys.

The acquisition of spatial data on the ice surface of horizontal and vertical parts of the ice-filling and the subsequent analysis of its changes is fundamentally affected by the fact that the ice surface has a variable structure and electromagnetic radiation can penetrate it. This has influenced the way in which the survey and the choice of appropriate technologies were made. Using our established methodology, we propose methodological procedures that eliminate the influence of factors negatively affecting the results of measurement and spatial model building (Fig. 4).

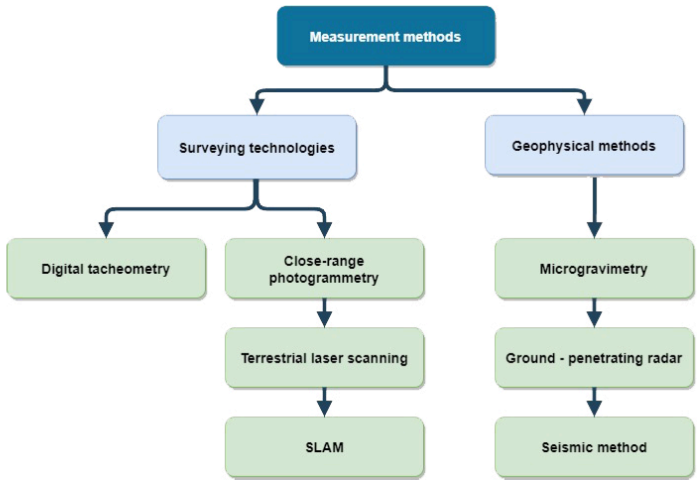

Figure 4 Overview of surveying and geophysical methods.

When EMR passes from one environment to another, there is absorption, refraction, reflection, and transmission as the speed of propagation of EMR changes, as well as the humidity and temperature, in the different environments. The refractive index of water as a liquid is 1.333. In the solid state, it can be determined to be around 1.309. Materials with a higher refractive index are more sensitive to temperature change. The interaction of electromagnetic radiation with ice and media containing ice, but also snow, is described by the refractive index and absorption coefficient, which are functions of the wavelength. Volume reflectivity, absorption, and transmittance are further influenced by the grain size of snow, ice, and bubbles (Warren, 2019).

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As a crystalline form of water, ice in a cave has a variable structure that depends both on the surface and ambient temperature and on the admixture of overlaying rock material. In Dobšiná Ice Cave, we can observe various structural forms of ice: large ice crystals in the ice mass, which have a coarse, granular texture, smooth clear ice, ice containing dust or impurities of overlaying rock, as well as various forms of frost on the walls (Fig. 5). It can be clearly stated that the ice surface is variable depending on the position of the ice mass relative to the surface (floor ice and wall ice) as well as the ambient temperature.

Figure 5 Various types of ice surfaces in the cave (source: authors).

Electromagnetic radiation has the ability to penetrate transparent materials - such as water and ice. The choice of surveying methodology must be considered in this context (Warren, 2019). Since the optical properties of ice influence the interpretation of measured data, the choice of an appropriate methodology for geodetic and geophysical mapping of ground ice in the cave certainly does not have a clear answer.

Figure 6 Penetration of the laser beam into the ice structure.

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Figure 6 shows the penetration of the laser beam (TLS and digital tacheometry) through the ice structure, which can reach up to 0.5 m into the ice structure. Methods such as laser scanning and digital tacheometry are not suitable for very accurate measurements of ice surface topography, much less for detecting changes in ice-fill dynamics. Nevertheless, their use is in mapping the irregular shape of a cave's rock surface and other geodetic activities.

3.3 Establishment of the geodetic network

The geodetic survey started in 2011 on the initiative of the Slovak Caves Administration, and the measurements were carried out in several stages. The planimetric and altimetric measurements are carried out in the Slovak national coordinate system of the Uniform Trigonometric Cadastral Network (S-JTSK) and vertical datum Baltic Vertical Datum - After Adjustment (Bpv) from fixed points of the surveying net monumented in the ceiling parts of the cave. The basic prerequisite for the accurate evaluation of temporal and spatial changes in the ice fill of the cave (Fig. 7) is the existence of an underground geodetic control with the required density and accuracy.

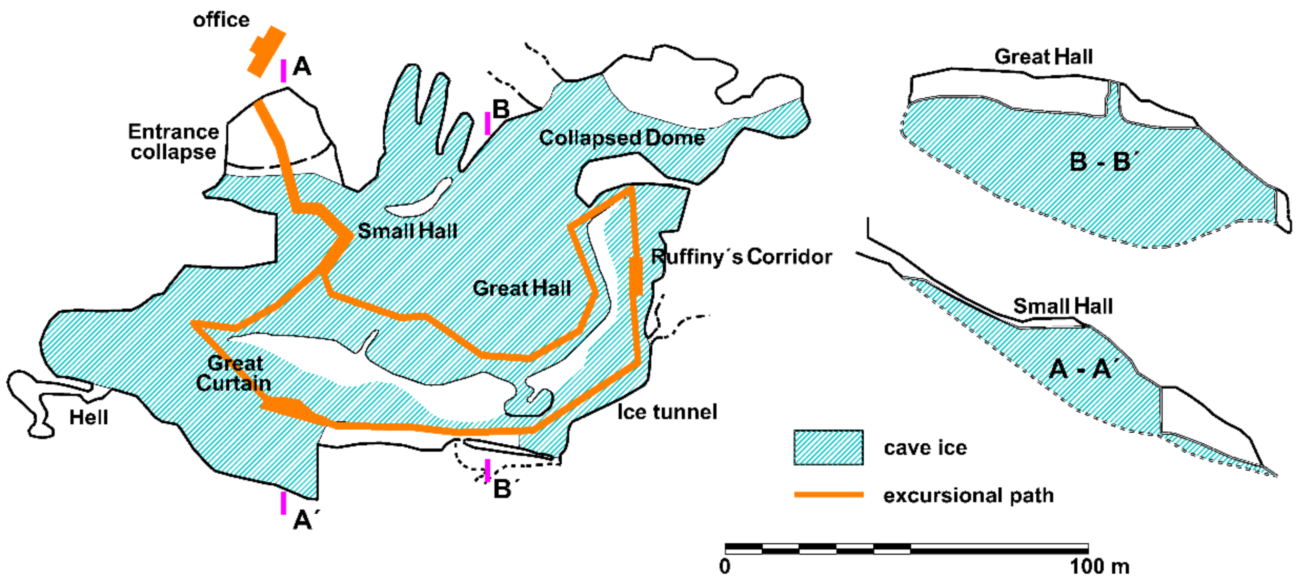

Figure 7 Cave floorplan and cross sections with ice filling in the cave (after Tulis et al., 1999).

The connection of the surface points of the Dobšinská Ice Cave network to the National Spatial Network was carried out through the Slovak Real-Time Positioning Service (SKPOS), using signals from Global Navigation Satellite Systems (GNSS) by a static method for a duration of 3 hours, whereby the points of the orientation line 5001-5002, approximately 1047 m apart, were determined. Underground points 5004 to 5012, monumented in the solid, unweathered parts of the cave rock ceiling by

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surveyor's nails, as well as points monumented by retro-reflective targets, were determined in 2011 from the orientation line. Since 2018, the point field has been complemented in several stages (Fig. 9), taking advantage of the drilled mine monumentation with reflective targets, with new survey marks monumented in the side walls and cave ceiling.

The point monumentation and marking were realized by the following methods (Fig. 8):

a) surveying nail in the cave ceilings,
b) drilled nail in the cave ceilings/wall,
c) surveying prism with reflective foil,
d) Leica retro-reflective target (2cm x 2cm) on an invar strip glued to the cave wall,
e) ice screw with leica retro-reflective target (2cm x 2cm),
f) ice screw with 12-bit coded target (2cm x 2cm x 3mm) for photogrammetry,
g) A4 paper 12-bit coded target for photogrammetry,
h) 12-bit coded target (2cm x 2cm x 3mm) glued to the cave wall for photogrammetry.

Figure 8 Monumentation of points of the geodetic point field and photogrammetric points and their marking.

The geodetic network as a whole after the 2011 adjustment in the 2D cartographic plane can be characterized by a mean position error of 4.9 mm and a mean coordinate error of 3.5 mm. The mean error of the adjusted heights had a value of 1.7 mm for the height adjustment of the points. The standard error ellipses of the local geodetic network are represented by an estimate of the standard deviation of measured lengths of 1.4 mm and directions of 1.49 mgon for the Leica Viva TS15 motorized total station.

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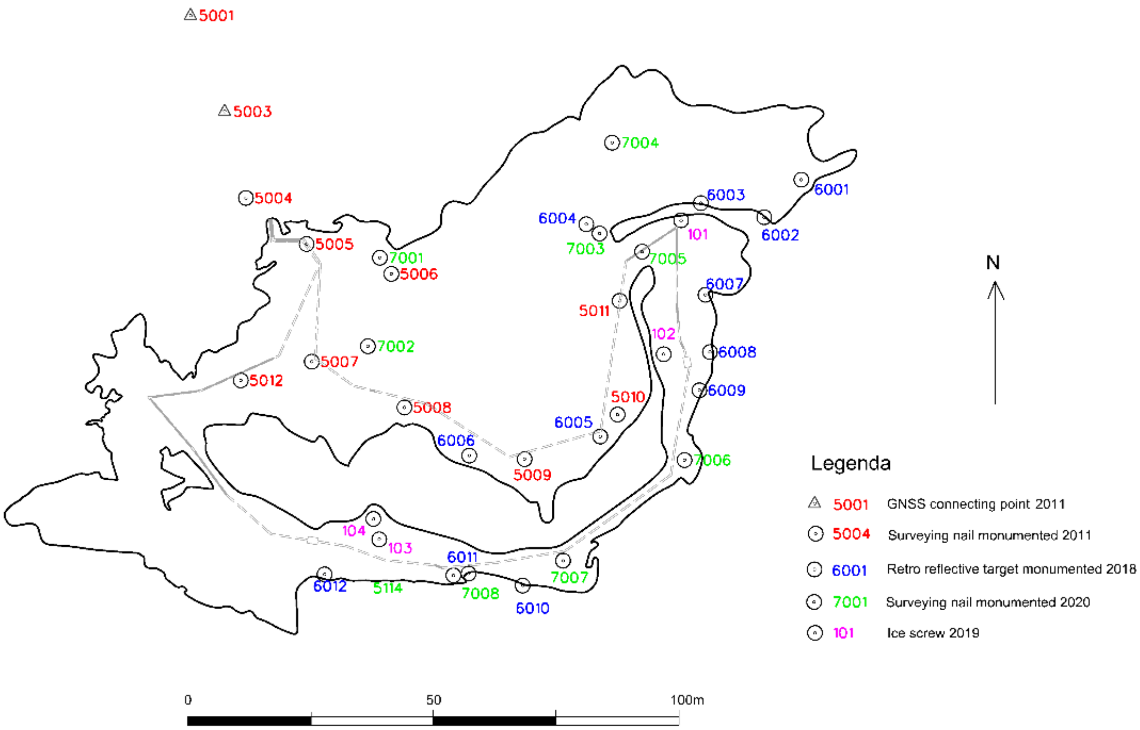

Figure 9 Geodetic point field in the cave.

3.4 Digital tacheometry

In order to provide original knowledge about speleoclimatic and glaciological patterns in Dobšiná Ice Cave, their seasonal and trend changes, the first two stages of detailed spatial surveying of its upper part, formed by the Small and Great halls, were carried out. A detailed 3D model of the cave entrance and its underground spaces is being built on the basis of tacheometry, terrestrial laser scanning, and digital photogrammetry and in synergy with the existing climate monitoring system of the cave managed by the Slovak Caves Administration in Liptovský Mikuláš. In the future, it will serve as a basis for detailed scientific analyses of the state and development of the glaciation of the cave system in the environment of geographic information systems. The first measurements of the ice fill were made in 2011. However, regular and accurate measurements have been carried out from 2018 to the present. Detailed spatial measurements of the Small Hall and the Great Hall in the cave are carried out semi-annually using a motorized total station Leica Viva TS15 and a Trimble®VX™ Spatial Station in the months of May (before the start of the tourist season / after winter) and October (after the end of the tourist season / before winter). The positional and vertical connection was realized to the original and complemented survey points of the underground geodetic point field in the binding national coordinate system and vertical datum. Complete inter-annual and inter-semi-annual (seasonal) measurements of the change in floor ice height will be analyzed in a separate paper.

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3.5 Terrestrial laser scanning and SLAM technology

The survey of the ice cave was realized by terrestrial laser scanning (TLS) in October 2018. More than 85 million points from 30 survey stations were measured with a compact all-in-one full panoramic pulse laser scanner Leica ScanStation C10 (Fig. 10 - left) and Leica HDS 6" targets with a laser beam in visible green EMR with wavelength 532 nm. The accuracy of a single measurement in position is 6 mm, in the distance 4 mm, and angle accuracy (horizontal/vertical) is 60 µrad / 60 µrad (12" / 12"). The precision of modeled surface is 2 mm. The spatial resolution of 30 × 30 mm of the final point cloud was achieved. Point clouds were processed in the computer-aided design software Leica Cyclone. We used a triangular mesh generation method by the Poisson Surface Reconstruction algorithm (Bolitho et al., 2007) to create the 3D MESH model, where surfaces are represented as a polygonal mesh.

In 2021, the Slovak Caves Administration (SCA) started monitoring the ice of the Dobšiná Ice Cave by monitoring its volume changes using a mobile 3D scanner Zeb Horizon from GeoSlam (Fig. 11 - right). The scanning is carried out on the trail of the guided tour and in its surroundings, with the circuit divided into two (approx. 20 min) scans. During the scanning of the first part, it is connected to 5 monumented survey points for georeferencing purposes (in post-processing), and to 6 points in the second part.

Figure 10 Leica Scanstation C10 (left) and GeoSLAM measuring (right).

Since the EMR penetrates the ice surface, the laser scanner survey was only used to model the overall shape of the cave itself, not to model changes in the ice surface accurately.

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3.6 Digital close-range photogrammetry

Due to the specific characteristics and shapes of the ice surface, or their location and accessibility, some parts of the cave have been mapped and monitored semi-annually by digital close-range photogrammetry - the Structure-from-Motion (SfM) method, since 2018. These parts are as follows (see Fig. 11):

1. *vertical ice wall in Ruffiny's Corridor* (digital tacheometry and TLS are not possible due to the size of the vertical surface, large height differences, and limited space for movement),
2. *an artificial tunnel through the ice massif* (digital tacheometry and TLS are not possible due to the specific ice surface in the tunnel characterized by a significant penetration of the laser beam under the ice surface),
3. *a site in the part of the Great Curtain below the ice massif* at the interface between the ice and the bedrock (TLS is not possible due to the site and the limited space; however, total station measurements are used to track the position of the observation points accurately).

Figure 11 Localities of the photogrammetric survey.

The Structure-from-Motion (SfM) photogrammetric method is used at all three sites. SfM is currently one of the most advanced photogrammetric processing techniques. It is originally based on computer vision and visual perception but has been gradually adapted to photogrammetry to derive three-dimensional structure from two-dimensional images of objects. The principle of

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SfM is to estimate the 3D structure of a spatial object from two-dimensional image sequences originating from a moving recording medium. The advantage of SfM is the simultaneous image matching, bundle adjustment, and reconstruction of a 3D structure on images. The principle itself, the sequence of individual processing steps, and the corresponding algorithms are generally well-known and frequently used (Seitz et al., 2006; Westoby et al., 2012; Remondino et al., 2014; Pavelka et al., 2018; Štroner et al., 2020; and others).

From the principle of SfM and image matching, it follows that the success of this method strongly depends on the structure and texture of the imaged surface. In the case of:

- flat and uniform texture,
- surfaces with high reflectivity,
- transparent surfaces,

the image matching may fail and result in too noisy data or no data at all. In ice caves, especially reflectivity and transparency of the ice surface can make the SfM unusable. This is also the case with the artificial tunnel in Dobšinská Ice Cave (Figs. 11 and 15a-b). In order to be able to suppress reflections and refractions of light from the ice surface and thus use the SfM photogrammetry, we proposed to apply a cross-polarized photogrammetry (Wells et al., 2005; Edwards, 2011; Conen et al., 2018; Marčiš et al., 2018). This encompasses a polarized light source (stronger than other sources or the only source of illumination in the cave), in our case, a polarizing sheet attached directly to a DSLR camera flash, and a second polarizing filter attached to the DSLR camera lens. A prerequisite for cross-polarisation is that the polarizer on the lens must be rotated at 90° with respect to the polarizer on the flash.

We use a digital camera DSLR Pentax K-5 with the lens Pentax SMC DA 15 mm f/4 ED AL Limited for all three parts surveyed by photogrammetry. All images are taken using a tripod, 12-sec self-timer, ISO 200, aperture f/10 - f/13, and RAW format with subsequent conversion to 12-bit TIFF. Acquired images are processed in Agisoft Metashape® Professional Edition, Version 1.6.0 software (Agisoft LLC, St. Petersburg, Russia, 2019) by standard photogrammetric processing.

3.7 Geophysical methods

Methods of applied geophysics are based on precise measurements of physical fields, which are caused or influenced by structures with anomalous physical properties in the underground. These methods are used to detect and identify various subsurface objects – from shallow to larger depths (meter to kilometer scales). Application areas come from a large interval: from geological and tectonic studies and exploration of mineral deposits to very shallow applications in the detection of archaeological objects (near surface geophysics). Based on the kind of the studied physical field, applied geophysics is divided into various methods: gravity methods (gravimetry), magnetic methods (magnetometry), geoelectrical and electromagnetic methods, seismic and seismological methods, radiometric methods, etc. (Telford et al., 1990; Milsom and Eriksen, 2011; Reynolds, 2011). Determination of the thickness of ice layers represents a quite well-posed problem formulation for several methods in near-surface geophysics because there exists a quite large contrast in selected physical properties between the ice and its rocky basement (for instance, density, electrical permittivity, and conductivity, velocity of mechanical waves). Based on the general knowledge from applied geophysics, a combination of several geophysical methods is often necessary – because various methods can support or debar outputs of them (each of the method is reacting to different physical properties of subsurface structures). From a great variety of near-surface geophysical methods, we have selected in this study the microgravity method (very precise gravimetry) and ground penetrating radar method (GPR), which is one of the most effective electromagnetic methods in near-surface geophysical applications.

3.7.1. Gravimetry

Gravimetry, or its specific detailed version - microgravimetry, is a geophysical method to measure and interpret very small changes in gravity acceleration. In microgravimetry, gravity changes (anomalies) that are caused by shallow subsurface objects with a significant density contrast to the surroundings are particularly interesting, for instance, crypts in archaeology (Pašteka et al., 2020), mines (Bishop et al., 1997) and caves (Butler, 1984). Due to its low density compared to the surrounding rocks, the ice filling of caves can also be a subject of interest for gravimetry. In the case of ice filling, we can basically talk about two possibilities for using gravimetry. The first method is mapping the thickness of the ice fill based on the complete Bouguer anomaly (CBA) calculation and subsequent density modeling. This methodology requires the necessary corrections for the topography, as well as corrections for the cave spaces themselves.

The second methodology is repeated monitoring of changes in gravity acceleration due to volume changes of the ice filling. For this purpose, test gravity measurements along the V-shaped profile were carried out at the site (Fig. 12 - right) in 2020 and 2022. A Scintrex CG-5 gravity meter was used for the measurements. A stable base point (on rocky ground) was located inside the cave, on which measurements were taken to check the drift of the gravity meter. The reference point was located outside the cave. Measuring on ice is not easy, as the ice is easily deformed under the measuring tripod due to the weight of the gravimeter, which makes measurement very problematic. That is why we also used a special steel pad for the measurement, which better distributes the pressure on the surface of the ice (Fig. 12 - left). Stabilization of the steel pad on the sloping surface of the ice filling is also problematic. The estimated error of the gravity measurement from the control measurements is at the level of approx. 5 μGal (5.10^{-8} m/s^2). Measured gravity changes between 2020-2022 reach one order higher values (up to approximately 50 μGal), so we can discuss a reliable measurement.

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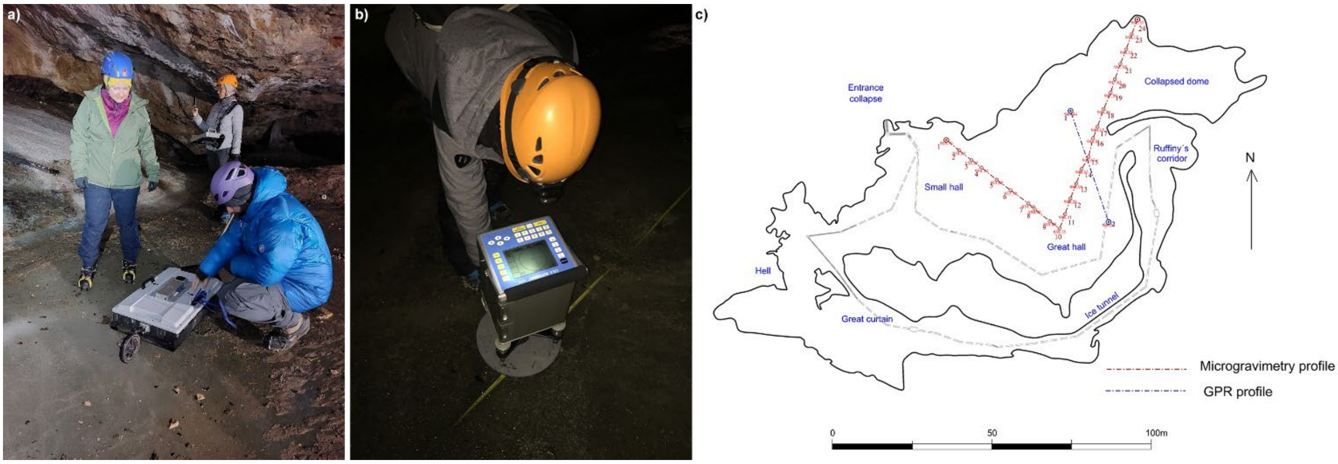

Figure 12 Example from GPR (a) and gravity (b) measurements along a selected line in the Dobšiná Ice Cave (c) (used instrument: MALA GroundExplorer GX with 160 MHz antenna (a) and Scintrex CG-5 gravity meter (b)).

3.8 Ground penetrating radar

As mentioned in the upper part of this contribution, electromagnetic emission (EM) can penetrate through lucent materials and environments – also through ice medium. In the case of the GPR method (familiarly georadar), electromagnetic emission is created by a transmitting antenna of the instrument to study the subsurface's structure (Fig. 12 - left). In the case of the GPR method, electromagnetic emission usually has frequencies that are outside the interval of visible light – these usually have a value of hundreds of MHz (typical values are from 100 to 500 MHz). Transmitted pulses of EM emission are reflected from subsurface objects, and after their return back to the surface, these are registered by a receiver antenna of the instrument. Registered reflections of EM emissions are then processed by means of special methods due to the wave character of the acquired data, and vertical time-sections (so-called radargrams) are usually the first outputs for geological or geotechnical interpretation (for instance, Milsom and Eriksen, 2011) (Fig. 17a). It is also important to mention that the recorded and displayed time in these sections is the so-called two-way-time (TWT) because this is the time, which the EM pulse has traveled from the emitting source to the reflecting object and then back to the registration in the instrument. In the process of recalculation of the TWT values, these must be then halved. Precise positions of the surface measurements are usually obtained through terrestrial geodetic methods and/or using GNSS technology. The local position of the instrument along measuring lines is determined by means of an odometer wheel.

During the processing and interpretation of acquired GPR data, a very important parameter is the velocity of EM radiation in the subsurface medium – this value is influenced by the electromagnetic physical properties of soils, rocks, and ice. There exist

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several methods for velocities estimation, and one of them is widely used: fitting the shape of a selected diffraction wave of hyperbolic shape in the vertical time section. Typical values of the velocities for various types of ice (from freshwater ice to permafrost environments) vary in quite large intervals from 0.15 to 0.3 m/ns (for instance, Reynolds, 2011). In the case of the ice in ice caves, it can be expected that these values will be closer to the lower limit of this interval. For example, we can mention typical values for the ice-sheet margin in East Antarctica, where the average value equals 0.18 m/ns (Guo et al., 2022). After using estimated velocity values to the TWT data, typical depths achieved by the GPR method are first meters; in the case of lower electrical permittivity, these can reach depths of 10 – 20 m (but this result depends strongly upon the used frequency of the GPR antenna). The GPR method was applied before with great success for the estimation of the thickness of ice in the case of continental or mountain glaciers (Singh et al., 2012; Navarro et al., 2018; Bello et al., 2020; Guo et al., 2022 and many others).

4 Results

4.1. Digital tacheometry

The ice fill is constantly changing its shape. Both external (precipitation, temperature) and internal factors (airflow velocity and direction, internal temperature, air pressure, humidity in the cave) influence the height of the floor ice in the cave during the year. The contour plots of both surfaces were made by processing the measured tacheometric data at two epochs in May 2018 and May 2023 (Fig. 13).

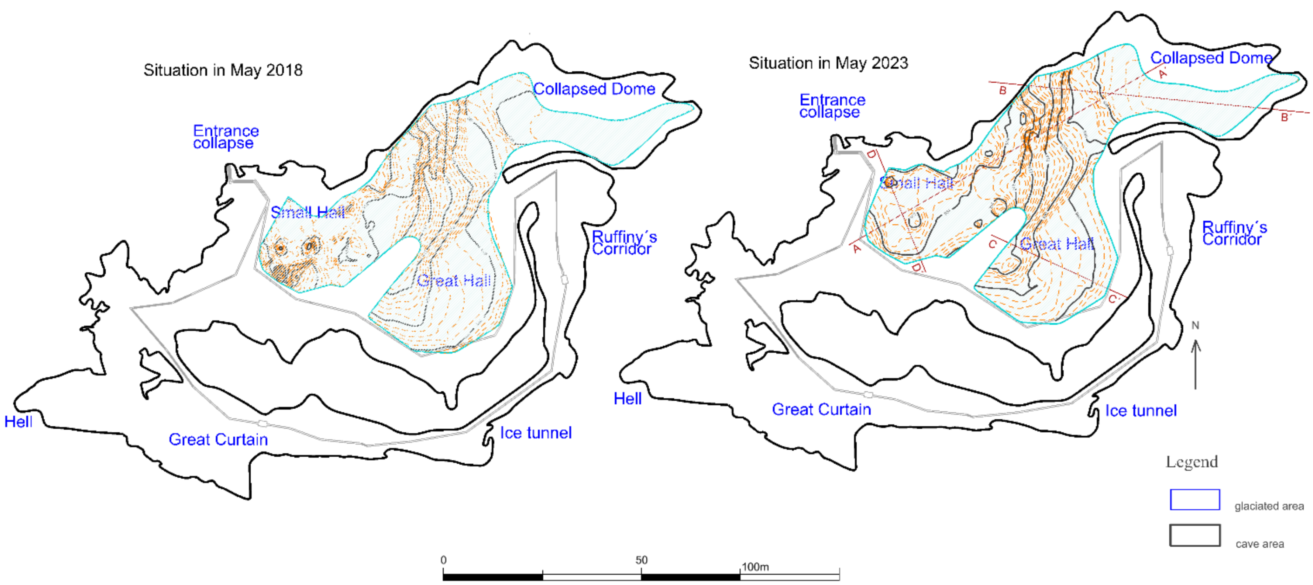

Figure 13 Height and extent of glaciation in the Small Hall, Great Hall, and Collapsed Dome

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4.2. Terrestrial Laser Scanning and SLAM technology

TLS survey allows us to obtain a complete general point cloud and, thus, a 3D model of the glaciated part of the Dobšiná Ice Cave. Due to the penetration of the laser beam into the ice (Fig. 6), not all parts of the TLS point cloud are suitable for detailed analysis. However, these data can be used for visualization and presentation to show a general overview of the cave. Processing the point clouds from both terrestrial laser scanning and SLAM produced the resulting visualization shown in Figure 14a. The point cloud can also be viewed as freely available data on the web at http://ugkagis.fberg.tuke.sk/potree/dobsinska_ladova_jaskyna/portal.html.

A longitudinal cross-section through the trail of the guided tour in the cave and corresponding surface (classified point cloud from aerial laser scanning; ÚGKK SR) is shown in Fig. 14c.

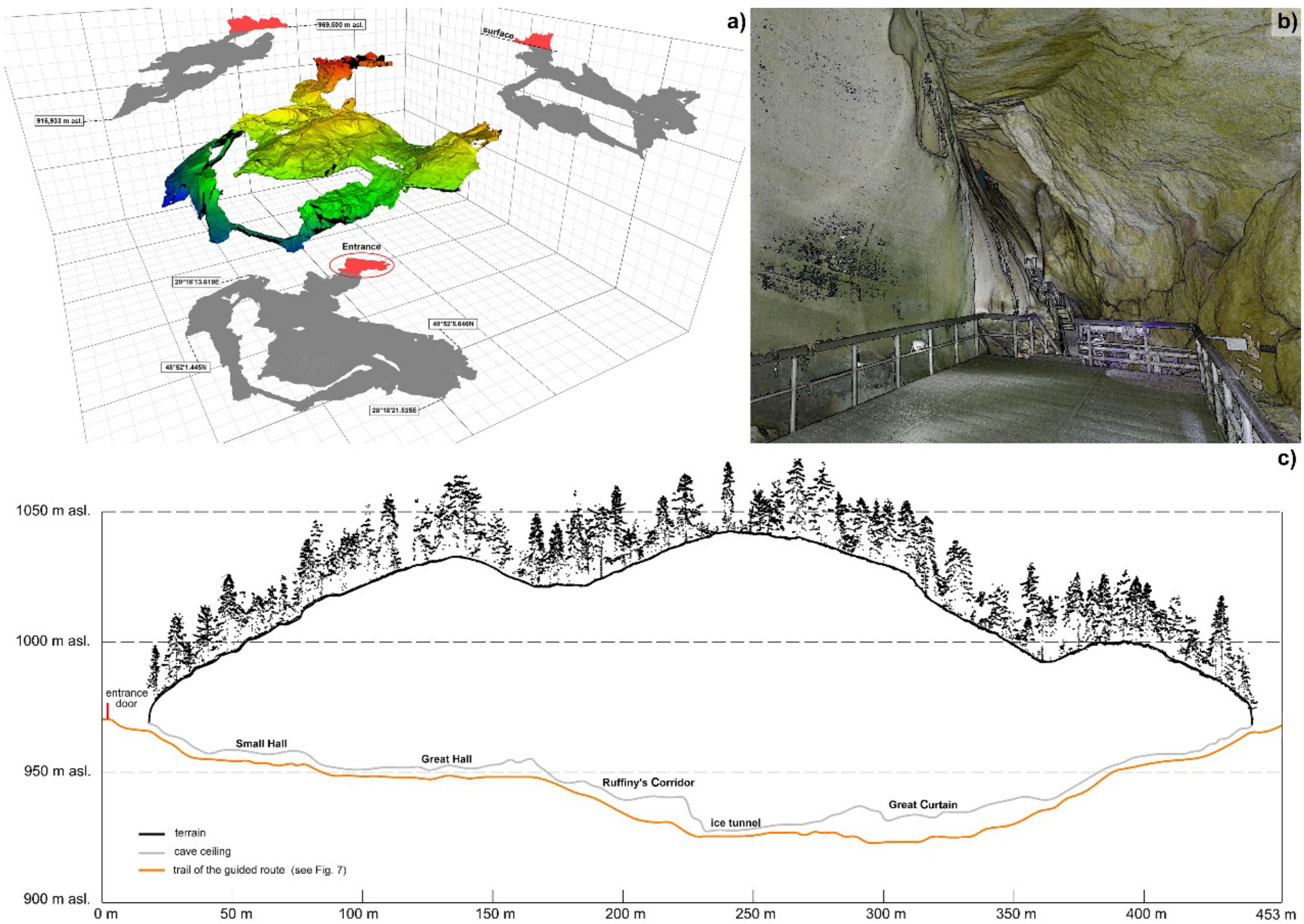

Figure 14 a) a general overview of the final 3D MESH model; b) detail of the point cloud from laser scanning; c) a longitudinal cross-section through the cave (source of the terrain - LiDAR data: ÚGKK SR).

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4.3. Digital close-range photogrammetry

The results of digital photogrammetry confirmed the usability of the SfM method for 3D reconstruction of the ice filling surfaces in the selected parts of the cave with sufficient accuracy. By using cross-polarized photogrammetry, we are able to suppress light reflections from the ice successfully (Fig. 15). The main results of the SfM processing are dense point clouds, MESH models (Fig. 15), and for the Ruffiny's corridor also an orthophotomosaic.

The following Figure (Fig. 15) shows the effect of cross-polarization (DSLR camera with a mounted flash and polarizing filter on the lens and the flash rotated at 90° with respect to each other) on the reflections caused by artificial illumination on the ice surface (a-b). Figure 15c shows the final textured 3D MESH model generated by the SfM photogrammetry from cross-polarized images, and Figure 15d shows the final dense point cloud of Ruffiny's corridor. Both of them, the MESH model and dense point cloud, are compact, smooth, and without significant noise or holes. The only part with lower quality is the railing of the guided tour trail in the tunnel, but this railing is not necessary to determine the tunnel's spatial changes.

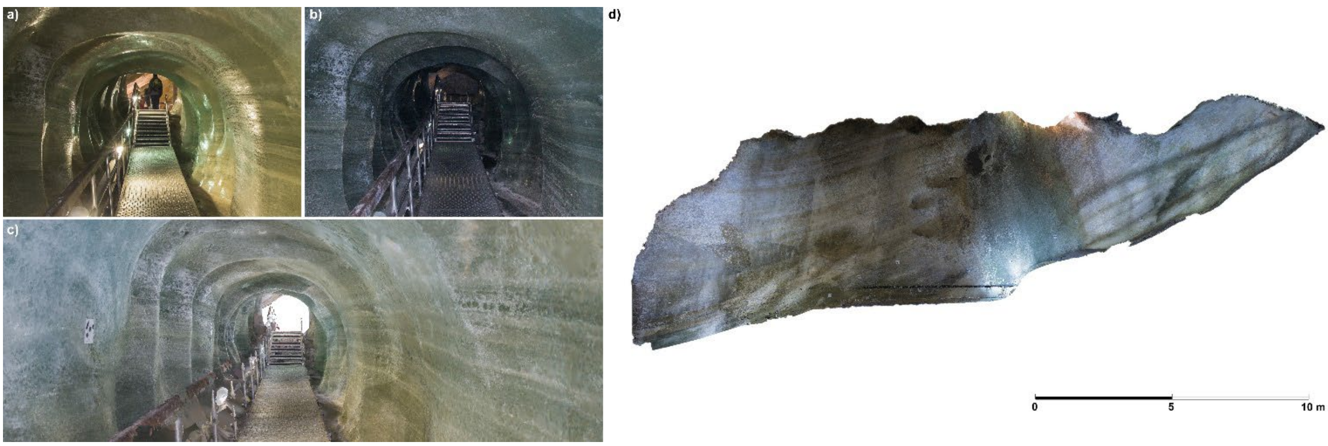

Figure 15 Results of the photogrammetric survey of the ice tunnel and Ruffiny's corridor; a) image without cross-polarisation, b) cross-polarized image; c) resulting 3D digital model of the tunnel; d) dense point cloud of the Ruffiny's corridor in 2018.

By comparing these results from individual epochs, we are able to determine changes in the ice filling over time. These results give us information about the direction and speed of the ice filling dynamics and also about changes in the volume of ice filling in these parts. Given the complexity of the issue and the amount of data, we provide a partial analysis of results for the 2018-2023 epochs only for the first two photogrammetric sites.

4.4. Microgravimetry measurements in Dobšiná Ice Cave

The results of repeated test gravity measurements between the years 2020 - 2022 (Fig. 16) confirmed that given volume changes of the ice filling, which manifest themselves in height changes at the level of at least a few cm (or more), are reliably

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detectable by gravimetric methods despite the difficult measurement conditions. Gravimetry can thus be used to monitor dynamic changes in the level of the ice fill.

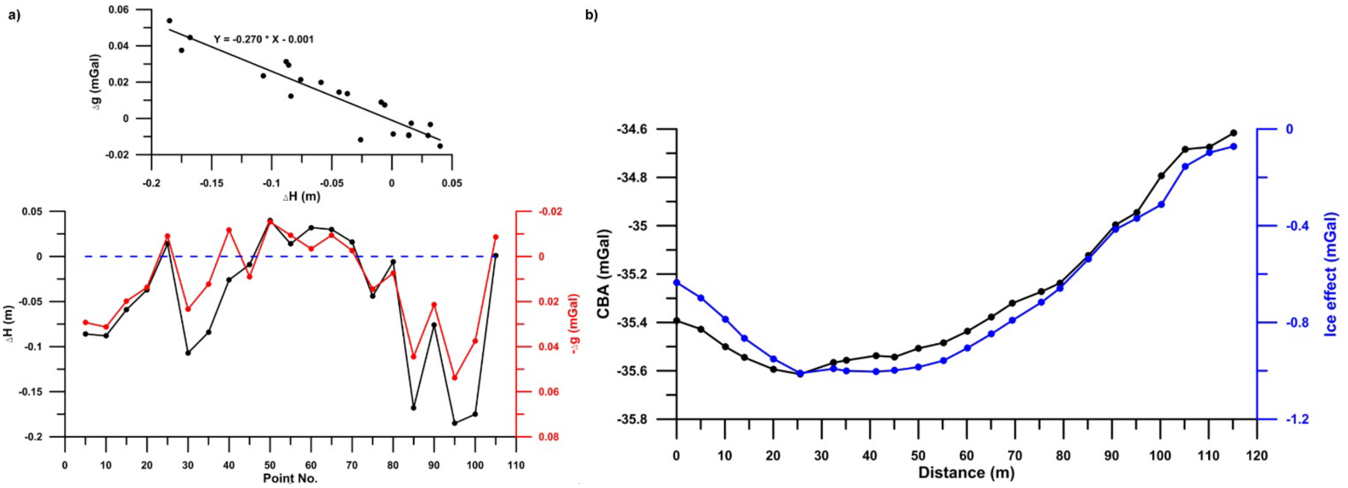

Figure 16 (a) Grav-1: Correlation of measured height and gravity differences between the years 2020 - 2022 at test profile points. For a better comparison, the gravity differences (in red) are shown with the opposite sign. The blue dashed line shows zero differences. (b) Grav-2: Approximate comparison of the CBA (correction density 2670 kg/m^3) and the gravitational effect of the ice fill (differential density -1750 kg/m^3) along the test gravimetric profile.

4.5. Ground penetrating radar

Tests of the GPR method during the years 2020-2022 in Dobšinská Ice Cave brought very interesting and promising results. Measurements have been performed by means of a MALA GroundExplorer GX instrument (with 160 MHz antenna) along the selected line in the cave. Basic processing steps have been performed with a focus on selecting the proper gain function (aiming to amplify reflection amplitudes from deeper positioned objects). As it can be seen in the processed vertical radargram from this site (Fig. 17a), the ice filling is characterized by a relatively homogeneous wave pattern – besides a relatively large amount of isolated diffraction waves (with the typical hyperbolic shape), coming with great probability from isolated stones and pieces of rocks in the ice. The average velocity, estimated from these diffraction waves (Fig. 17b), was set to 0.16 m/ns. In the selected vertical radargram (Fig. 17a), accepting the estimated velocity of 0.16 m/ns, the depth of the base of ice varies from 10 m to approx. 25 m below the ice surface (corresponding TWT values were 125 and 320 ns). The boundary between the ice and its basement is plotted with a thick red line in Fig. 17a.

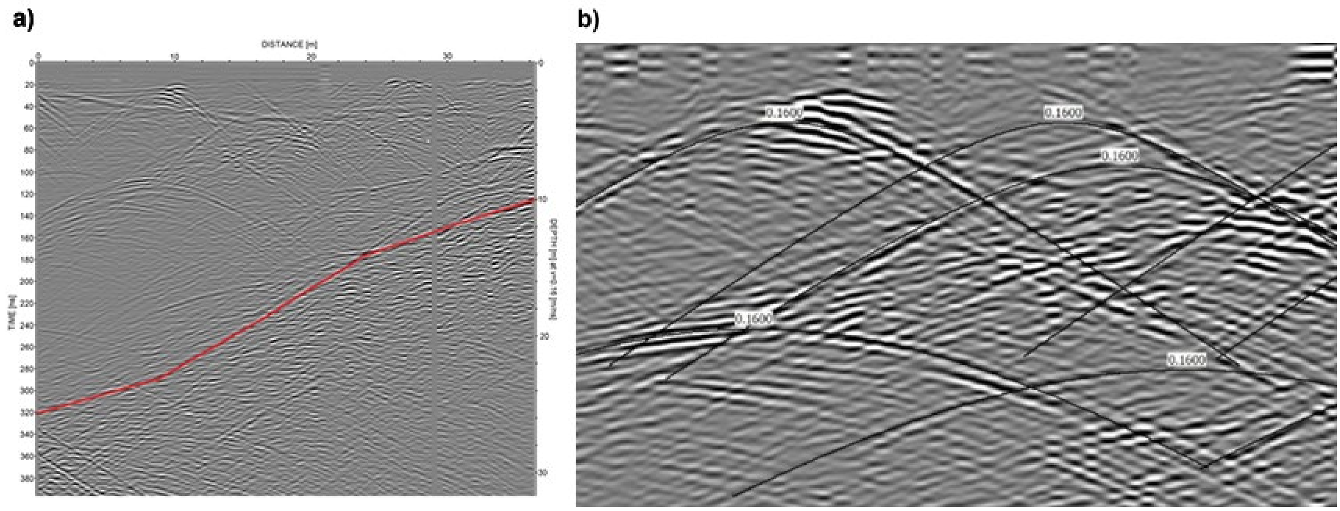

Figure 17 (a) Selected vertical radargram from the Dobšiná Ice Cave (left-hand vertical axis: two-way-time, right-hand axis: depth for the velocity 0.16 m/ns, the thick red line represents the boundary between the ice and the basement). (b) The selected part of a vertical radargram with plotted diffraction waves and estimated values of the EM wave velocity (0.16 in this case).

5 Discussion

Different surveys of the cryosphere, and especially of ice caves, have been part of their documentation for many years. There are measurements of ice extent, ice surface characteristics, the volume of ice filling in caves, spatio-temporal dynamics of the ice bodies, and others. Analyses of dynamics of the ice in caves have been presented in several papers (Strug and Zelinka, 2008; Perşoiu and Pazdur, 2011; Gómez-Lende and Sánchez-Fernández, 2018; Perşoiu et al., 2021). Also, the ice measurement itself has been widely reviewed and presented (Gindraux et al., 2017; Alfredsen et al., 2018; Pfeiffer et al., 2022; Hruby, 2022). Authors Morard et al. (2010) recorded rapid changes in the Diablotins ice cave in Switzerland by monitoring the cave climate and suggested an hourly or daily monitoring interval based on a laser scanner or automatic cameras. The dynamics of ice bodies and their margins can also be monitored by data from a time-lapse camera and SfM photogrammetric processing (Mallalieu et al., 2017) or by UAS images and photogrammetric processing (Li et al., 2019). Over time, various technologies have been implemented and have been used with more or less success.

In this research, data from terrestrial laser scanning proved to be a good and quick technique to get a general spatial overview of the cave and the extent of the glaciated part with sufficient accuracy (Figs. 1, 10, and 14). However, determining changes in the ice volume by TLS can be problematic due to the properties of the laser beam incident on the ice surface. For this purpose, it is more appropriate to use digital tacheometry, which can provide a spatial position of individual points on the ice surface with high accuracy and, therefore, create a planimetric and altimetric map of the ice surface for individual epochs. The comparison of tacheometric data from years 2018 and 2023 revealed a significant loss of ice area, especially in the Small Hall

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and Collapsed Dome parts (Fig. 18). The vertical loss of the ice level over the 5 years amounts to - 0.3 to - 0.9 m. By comparing the amount of glaciation over this five-year period, it can be clearly stated that the ice volume has increased by 99.5 m^3 in some places but decreased by up to 667 m^3 in others. In 2018, the area covered by ice was 2986 m^2. Detailed inter-annual and inter-semi-annual (seasonal) measurements of the change in floor ice height will be analyzed in a separate paper.

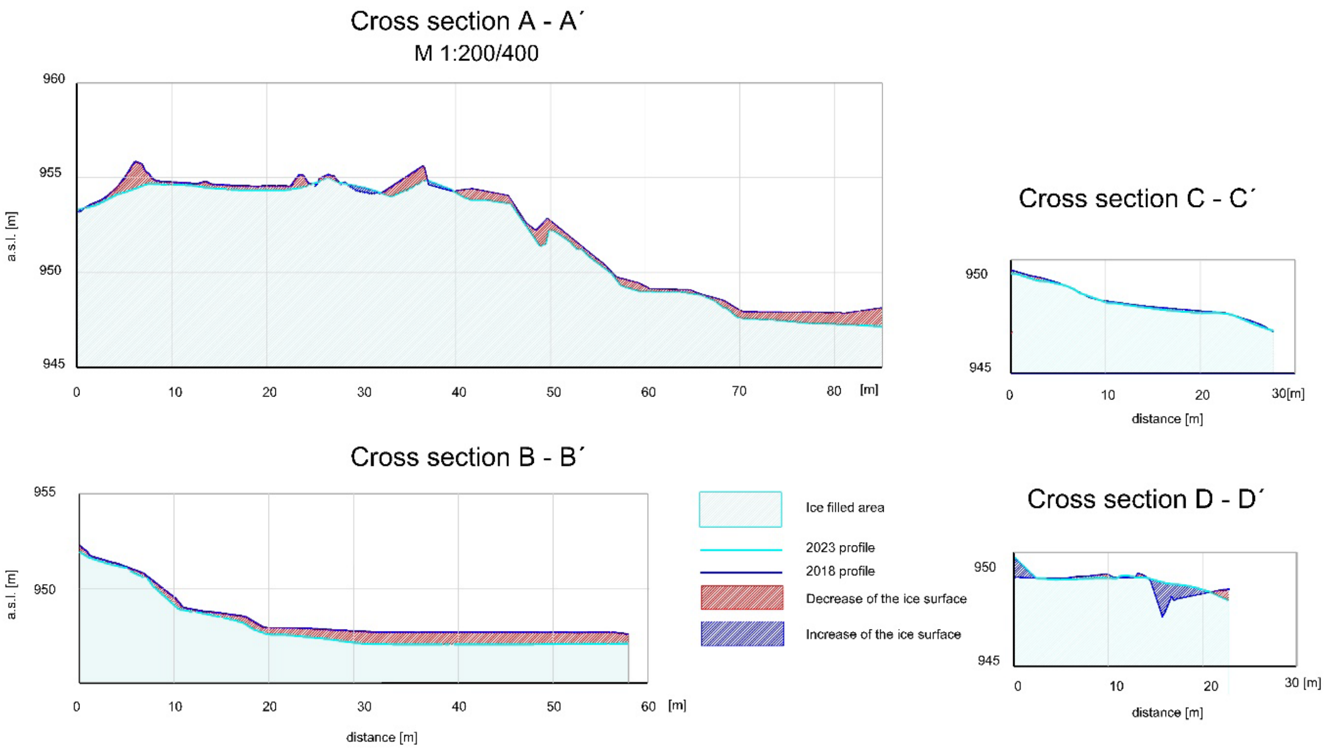

Figure 18 Longitudinal cross-sections through the Small Hall, Great Hall, and Collapsed Dome

On the other hand, digital tacheometry is suitable for use only in parts with horizontal (floor) ice, where it is possible to measure the spatial position of points using a common surveying prism. For specific parts in terms of their geometry, spatial orientation, and texture/structure of the ice, digital close-range photogrammetry would be the best option. In Dobšiná Ice Cave, we identified several specific glaciated parts suitable for the photogrammetric measurements. Due to the extensiveness of the research, we present results for two of them.

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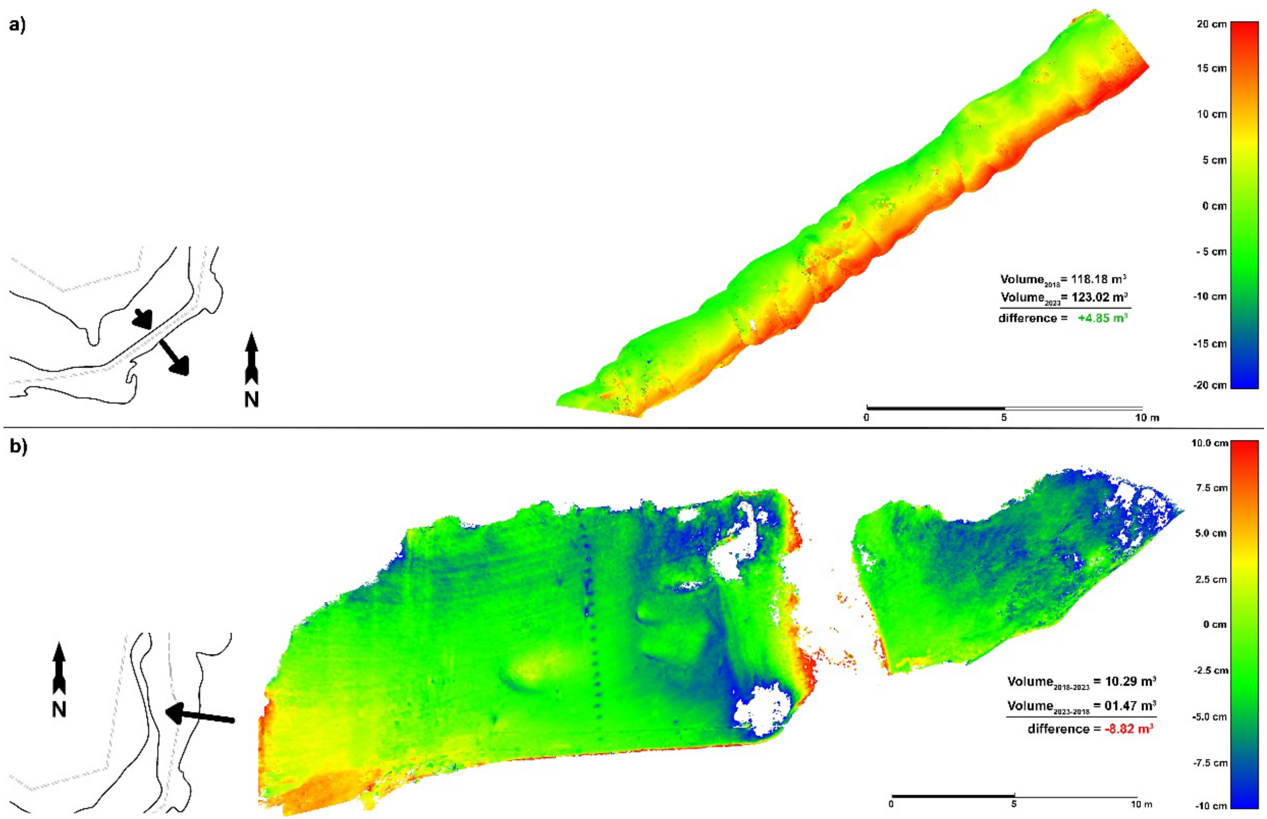

Figure 19 Results of the photogrammetric survey of the ice tunnel and Ruffiny's Corridor; a) image without cross-polarisation, b) cross-polarized image; c) resulting 3D digital model of the tunnel; d) top view on the difference model of the tunnel between epochs 2018-2023; e) front view on the difference model of the corridor between epochs 2018-2023.

Fig. 19a illustrates a difference model - i.e. spatial changes, for the ice tunnel between epochs 2018 and 2023. According to the difference model, we can say that the tunnel gradually but irregularly widens, with more significant changes in the southeast (S-E) direction. In the S-E wall, the ice surface has shifted by approx. 20 cm; while in the opposite N-W wall, the ice surface has shifted by only approx. 5-10 cm. The total volume of the tunnel has changed by +5 m^3.

Fig. 19b illustrates a difference model for the vertical ice wall in Ruffiny's Corridor between epochs 2018 and 2023. According to the difference model, we can say that in some parts of the wall, the ice surface is slowly retreating (green to blue color), and in some parts, the ice surface is increasing (yellow to red), in the range of 0 - 10 cm. The blank parts of the difference model represent parts with changes larger than 10 cm. The highest increase is recorded in the icefall (vertical blank part, caused by

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water slowly leaking from the upper parts) - more than 10 cm. The total change in the volume between 2018 and 2023 was recorded as an ice loss of -9 m^3.

However, if we look at the geodetic point monumented as an ice screw into the vertical wall (Figs. 8 and 20) in 2019, there are two apparent movements. The first is the retreat of the ice surface by 9 cm (this displacement can also be partially caused by pushing the screw out of the ice by the ice solid itself, but there is no clear evidence of that). The second is a spatial displacement of the point by 2 cm (1-year period), 2,5 cm (1-year period), and 3 cm (1,5-year period). Therefore, there can be a combination of ice retreat, movement of the ice body, and extrusion of the screw from the ice. The spatial change of this point (and the ice wall) is almost in the same direction as in the case of the ice tunnel.

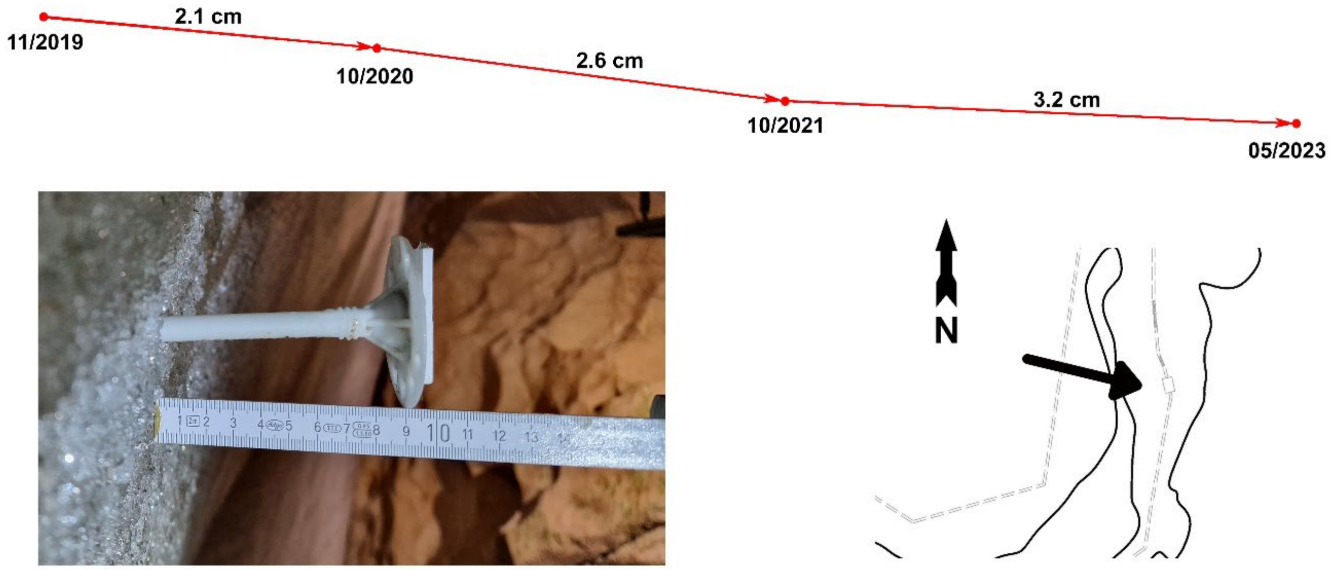

Figure 20 Spatial changes of the ice screw monumented in the vertical ice wall between 2019 - 2023.

In terms of geophysical methods, both of them proved to be suitable and, what is more important, complementary to TLS, tacheometry, and photogrammetry since they can provide data which are not obtainable by geodetic methods (mainly the depth of the ice body and its structure under the surface).

This means, from the point of view of speleologists, it is also important to map the total volume of ice in the cave, which is, however, a methodologically more complex and demanding task. At this stage of the study of the Dobšiná Ice Cave, we are able, on the basis of the measurements so far, to at least tentatively assess the possibility of determining the total thickness of the ice filling based on the interpretation of the CBA. In the calculation of CBA, state-of-the-art procedures were used with

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the use of Toposk software (Zahorec et al., 2017), detailed DEM5.0 based on aerial laser scanning (https://www.geoportal.sk/sk/zbgis/lls-dmr/, source: ÚGKK SR) and a spatial model of the cave derived from TLS and tachymetry. The calculated values of CBA along the profile were tentatively compared with the approximate calculation of the gravitational effect of the ice fill derived from the existing GPR measurements (Fig. 16b). A differential density of -1750 kg/m^3 was used for the ice, as the difference between the actual density of approx. 920 kg/m^3 and the CBA correction density of 2670 kg/m^3. The two curves are very similar, which indicates that gravimetry is potentially suitable for determining the total ice volume in the cave. This will require complex areal gravity mapping and subsequent 3D density modeling in the future.

In terms of ground penetrating radar, it has also been used in ice surveys for a long time. Dallimore and Davis (1992) used GPR to detect massive ground ice and map near-surface geology. GPR was also used in combination with SfM photogrammetry to describe the topography and ice thickness and determine the volume changes of a glacier in Greenland (Marcer et al., 2017). The usability of GPR technology to study permafrost rocks and the emergence of cryogenic processes was evaluated by Sokolov et al. (2020).

In Dobšiná Ice Cave, from repeated measurements along identical lines (acquired in both directions), the accuracy of the ice thickness could be estimated as the approximate value ±0.2 m. This error is relatively high when compared with other geodetic methods, but the transition between ice and basement is not a clear boundary but a zone where the basement rocks are broken by the influence of ice. For this reason, a repetition of measurements along each line is so important. This kind of interpretation (estimation of ice thickness or the depth of ice basement) can be performed along a system of parallel and crossing lines, and an area map of these values can be plotted – contributing to a 3D model of ice cover in selected parts of the cave.

This research demonstrates that various geodetic (digital tacheometry, laser scanning, digital photogrammetry) and geophysical methods (microgravimetry, ground penetrating radar) are necessary for a comprehensive study of ice-filling dynamics in an ice cave, especially in terms of long-time monitoring. Ice bodies in caves can have different characteristics for individual parts of the cave, with changes in the structure and/or texture, even in a small area. Therefore, combining these methods can give us a comprehensive view of ice-fill dynamics and a suitable tool for long-term monitoring. However, we see a potential for using modern laser scanners that are available to filter reflected laser beams according to the number of the returned signal. Using such, it is possible to measure these surfaces in a comparable density and accuracy as with digital photogrammetry.

6 Conclusions

In this study, we review the current methodologies for surveying the ice filling and the thickness of the underground ice, and the dynamics of its evolution in the Dobšiná Ice Cave. We evaluated the suitability of using different geodetic and geophysical methods and technologies depending on the expected results. Due to the physical properties of the laser beam and its penetration/reflection from the ice surface, as well as limiting factors in photogrammetric imaging, the use of different methodologies should be considered. We proposed the use of a tacheometric method to measure 3D data on the floor ice surfaces and a photogrammetric SfM method using cross-polarized light to measure the volumetric changes of ice in specific areas of the cave. We found the ground penetrating radar, geophysical method, and partial microgravimetry to be clearly successful in measuring the thickness of the ice. Modern ice cave research has not reached its zenith, and there is still room for improvement - depending on geodetic and geophysical measurement technology development. Since the underground glacier is characterized by its dynamic inter-annual changes, dependent on climatic developments in both the exterior and interior of the cave, as well as anthropogenic factors, there is a constant need for regular monitoring in order to preserve this unique natural phenomenon as much as possible. This research shows the high applicability and suitability of the combination of these methods and technologies to monitor spatio-temporal changes in ice caves over a long period.

7. Author contribution

All authors contributed to the fieldwork. KP conducted the research, processed the laser scanning and tacheometry data, and wrote the manuscript. KB conducted the photogrammetric research, processed the photogrammetric data, and wrote the manuscript in the photogrammetric measurements section. JG conducted the geodetic point field research and monumentation with subsequent adjustments and processed the tacheometric measurements. RP performed the GPR measurements and wrote the GPR section of the paper, PZ and JP performed the gravimetry survey and wrote the gravimetry section, LK, EA and DB carried out all the necessary field measurements, PB led the work on the paper in terms of geomorphology and cave glaciations, as well as research guidance, LD carried out the SLAM measurements.

8. Competing interests

The authors declare that they have no conflict of interest.

9. Acknowledgements

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11. Data Availability Statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

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