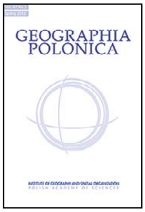


Geographia Polonica
2023, Volume 96, Issue 4, pp. 405-430
https://doi.org/10.7163/GPol.0262

INSTITUTE OF GEOGRAPHY AND SPATIAL ORGANIZATION
POLISH ACADEMY OF SCIENCES
www.igipz.pan.pl

www.geographiapolonica.pl

JASKINIA LODOWA W CIEMNIAKU (ICE CAVE IN CIEMNIAK), WESTERN TATRA, POLAND – OVER A CENTURY-LONG INVESTIGATIONS OF CLIMATE WARMING-CAUSED DEGRADATION OF SUBTERRANEAN ICE MASS

Jan Barabach[1] • Witold Szczuciński[2] • Ditta Kicińska[3] • Zuzanna Palińska[4] • Grzegorz Rachlewicz[4]

[1] Department of Land Improvement, Environmental Development and Spatial Management
Poznań University of Life Sciences
Piątkowska 94E, 60-649 Poznań: Poland
e-mail: jan.barabach@up.poznan.pl (corresponding author)

[2] Geohazards Research Unit, Institute of Geology
Adam Mickiewicz University, Poznań
Bogumiła Krygowskiego 12, 61-680 Poznań: Poland
e-mail: witek@amu.edu.pl

[3] Department of Dynamic Geology and Applied Petrography, Institute of Geology
Adam Mickiewicz University, Poznań
Bogumiła Krygowskiego 12, 61-680 Poznań: Poland
e-mail: ditta.kicinska@amu.edu.pl

[4] Cryosphere Research Unit, Institute of Geoecology and Geoinformation
Adam Mickiewicz University, Poznań
Bogumiła Krygowskiego 10, 61-680 Poznań: Poland
e-mails: zuzannapalinska@gmail.com • grzera@amu.edu.pl

Abstract

Jaskinia Lodowa w Ciemniaku (Ice Cave in Ciemniak), in the Tatra Mountains (Tatry), is believed to host the largest subterranean ice mass in Poland. It has been known for over a century, however, the onset of its scientific investigations dates back to 1922, when Tadeusz and Stefan Zwoliński mapped it. Since then, it has become one of the best-known caves in Poland. It was described in over a hundred scientific and popular science papers. They include findings of international importance, e.g. works related to radioisotopes, ice-mass balance and age. However, some of the questions asked a century ago are still partly unanswered. One may wonder if they will be delivered before climate warming causes the largest 'cave glacier' in Poland to disappear.

Key words

Speleology • cryosphere • Western Tatras • history of cave research • ice cave • climate change

Introduction

Ice caves, defined as caves hosting perennial ice masses, are vulnerable components of the cryosphere in the context of ongoing climate warming (Kern & Perşoiu, 2013). The value of cave ice accumulations is related not only to its uniqueness from a geodiversity point of view but also to the fact that this still poorly known ecosystem is an exceptional environmental archive recording natural and human-induced changes within and outside the cave through various proxies, e.g., stable isotopes, pollen or heavy metals (e.g., Leunda et al., 2018; Mavlyudow, 2018; Colucci & Guglielmin 2019; Wind et al., 2022). The unique world of ice caves is one of the most sensitive environments of a changing climate, just like mountain glaciers and ice sheets. Ice stalactites, stalagmites, columns, flowstones, and other ice forms fill the corridors of caves on all continents of the northern hemisphere. In many caves, ice and firn accumulations have persisted for thousands of years (e.g. Holmlund et al., 2005; May et al., 2011; Perşoiu et al., 2017; Kern et al., 2018; Racine et al., 2022); they may preserve a record of modern and past climate changes (as in the ice cores of Greenland and Antarctica), but due to their inaccessibility, ice caves are still considered to be likely the least known part of the cryosphere.

An ice cave used to be defined as any cave hosting ice masses throughout the year. This excludes caves formed in the ice or firn, which are usually named glacial cavities or glacial caves (Mavlyudov, 2018). Zwoliński (1953) suggested that a more appropriate term for an underground rock cavern in which ice occurs in should be called "iced cave" (Pol. "*jaskinia zalodzona*"), but due to the common use of the term "ice cave", changing the nomenclature is not likely. In general, the ice caves are of various origin, e.g., karst, volcanic, tectonic, etc. (Mavlyudov, 2018). Ice deposits in caves are formed as a result of water freezing, snow crystallization, and water vapor resublimation. The occurrence of ice in caves is conditioned by their (1) location in the climatic zone, where the average annual temperature oscillates around 0°C (observations have shown that the majority of ice caves occur in regions where the average annual air temperature exceeds 0°C) and (2) the morphology of caves that determines air circulation. These factors affect the cooling of the caves in winter and allow them to keep low temperatures during summer.

The ice caves in Poland at present occur exclusively in the Tatra Mountains, where 43 caves are considered to host perennial subterranean ice masses (Gradziński et al., 2018). Among them the best known is Jaskinia Lodowa w Ciemniaku (Ice Cave in Ciemniak), which until 1959 was the only reported ice cave in the Polish Tatra Mountains (Gaweł, 1949; Wójcik, 1962). This cave is often mentioned as the one with the largest volume of subterranean ice in Poland (e.g., Wójcik, 1969); which, due to the dramatic loss of ice mass during the last two decades, is no longer so certain. However, a recent rapid disappearance of ice and/or snow have been observed in most of the ice caves in the Tatra Mountains.

Jaskinia Lodowa w Ciemniaku (λ: 19°53'31.50" E, ϕ: 49°14'02.00" N; http://jaskiniepolski.pgi.gov.pl/) was created in the Upper Jurassic and Lower Cretaceous limestones belonging to the Kominy Tylkowe unit (Kotański, 1959; Lefeld et al., 1985) and is developed on a diagonal tectonic dislocation. The cave is located at an elevation of 1704 m a.s.l. (Fig. 1). The literature also mentions altitudes of 1695 m a.s.l. (Gradziński et al., 2018;), 1715 m a.s.l. (Zwoliński, 1933; Kowalski, 1953a) and approx. 1860 m a.s.l. (Kotański, 1961). The cave is 394.6 m long and its vertical extent is 44.6 m. The average annual air temperature at this altitude is 0-2°C, and the average precipitation is about 1800 mm per year (Hess, 1996).

Jaskinia Lodowa w Ciemniaku must have aroused curiosity among highlanders, who called it "The Glacier" (Pol. "*Lodowiec*"), for a long time. It was visited already in the 19th century, e.g. by poachers hunting chamois, which hid in the parts near the entrance in so-called "Chamois Shelter" (Pol. "*Kozia Koleba*") during the winter (Zwoliński, 1923). According to words of Mieczysław Murzydło from Ciche even in the 1960s local shepherds went to "Glacier" to cool down on hot days or to hide from the rain.

The cave has been called variously in Polish literature over the years: "*Grota Lodowa w Kamiennem*" (Zwoliński, 1923), "*Jaskinia Lodowa w Ciemniaku*", "*Lodowiec*", "*Lodowa*", "*Lodowa Jaskinia pod Czerwonym Wierchem*" or "*Dziura Lodowa*". The name of the cave was also presented differently in the English-language literature: "Lodowa Cave in Ciemniak", "Ciemniak Ice Cave", "Lodowa Cave in Mount Ciemniak" and "Ice Cave in Ciemniak".

Throughout last 100 years, since the onset of published scientific research in 1923 (Zwoliński, 1923), the cave was a frequent study site. It was a main object of the investigation in at least 55 publications, which makes this cavern undoubtedly the best-known ice cave in the Polish Tatras, as well as one of the most frequently described caves on the regional scale. The cave is also one of the several reference sites used in the assessment of changes in the cave ice mass balance of the northern hemisphere on a century scale (Kern & Perşoiu, 2013).

Ice masses in caves are very sensitive to regional and local climate changes, which recently lead to hemispheric-scale cave ice mass degradation (Kern & Perşoiu, 2013). It applies also to the subterranean ice in the Tatra caves in the 20th century. However, the ice masses are sensitive also to local changes in air circulation pattern, which may be locally altered by digging tunnels in snow blocking the entrance in spring by cavers, raising the air temperature by large groups of frequent visitors or intended destruction of ice formations (Strug, 2011). In case of Jaskinia Lodowa w Ciemniaku the impact of climate change has been playing the most important role and results in a very fast rate of ice loss over the last 40 years (Rachlewicz & Szczuciński, 2004; Gradziński et al., 2018), which correlates with an increase in the average annual temperature in the Tatra Mountains during this period (Łupikasza & Szypuła, 2019).

The aim of the paper is to review the long history of exploration and research conducted in Jaskinia Lodowa w Ciemniaku, since its first description 140 years ago (Ossowski, 1883) and first published scientific investigations a century ago (Zwoliński, 1923). The review is supplemented with new results including

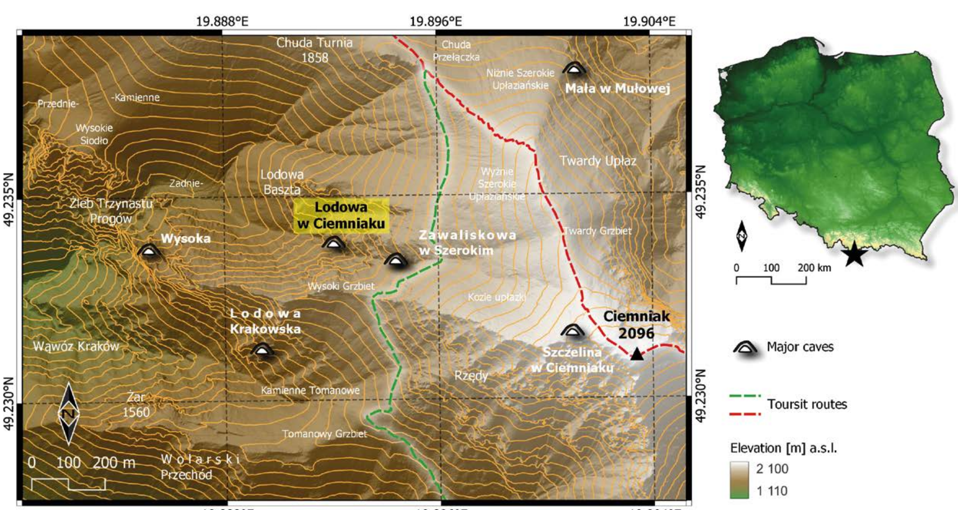


Figure 1. Location of Jaskinia Lodowa w Ciemniaku

the latest ice surface mapping survey from 2021. The popularization of the existence of caves with long-lasting ice cover in the Polish Tatra Mountains and the dramatic disappearance of this cover seems to be very important in the era of the ongoing climate crisis as the disappearance of the cave ice mass may serve as an "eye-witness report" of contemporary changes in the Earth's cryosphere. We also hope that the present work will provide a baseline for future studies on this intriguing and unique natural ice formation.

General description of the cave

Jaskinia Lodowa w Ciemniaku (Fig. 1) is located on the slopes of Ciemniak Mountain, in the upper reaches of Dolina Kościeliska (Kościeliska Valley), which is one of the largest main valleys in the northern part of the Tatra Mountains. The cave has single entrance (Kozia Koleba) facing west. The cave is developed mainly in horizontal arrangement. The main passage is in W-E direction and used to be covered by up to several meters thick ice cover. It is composed of two parts, the first one is a corridor (Wielki Korytarz), which is several meters wide and high, and is going from the entrance slightly upward. In the former time, when it was almost completely covered by the ice mass, it contained the step like relief including ice steps ("thresholds") and flat areas (so called "Ślizgawka" and "Platforma"). The second part – still mainly covered with ice, descends from, so-called "Upper Platform" and forms a vertical passage, which then goes down in form of so called Sala Lodowa I ("Ice Chamber I") (on the Fig. 2, 3), which

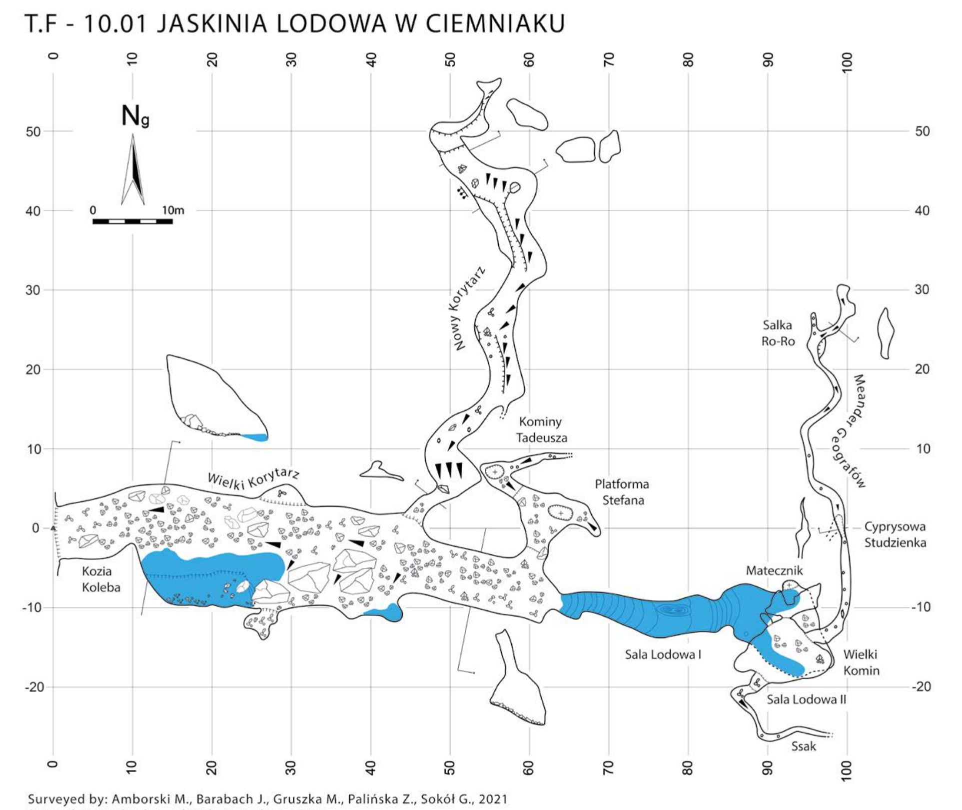


Figure 2. Plan of Jaskinia Lodowa w Ciemniaku; the area covered with ice on September 11, 2021 is marked in blue

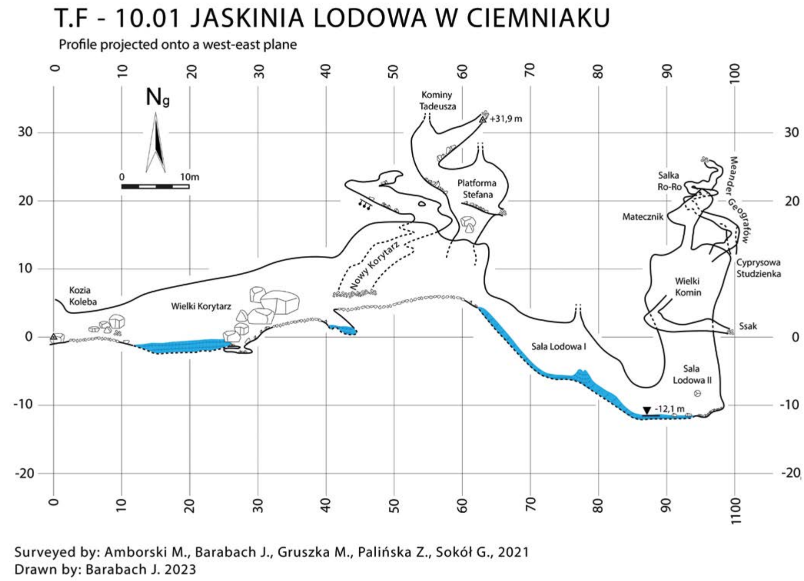


Figure 3. Cross-section of Jaskinia Lodowa w Ciemniaku; the area covered with ice on September 11, 2021 is marked in blue

ends with flat Sala Lodowa II ("Ice Chamber II"). Moreover, from the Upper Platform and from Sala Lodowa II, over 30 m high chimneys develop. There are also two major narrow passages heading towards the north, namely Nowy Korytarz and Meander Geografów.

The history of exploration

In the literature, Jaskinia Lodowa w Ciemniaku was first mentioned in 1883 by Gotfryd Ossowski (1835-1897), a geologist, archaeologist, and one of the first speleologists exploring the caves in the Tatra Mountains (Ślusarczyk, 2004, 2008). Ossowski's words indicated that he had not been in the cave, but he heard about it from local guides while visiting Jaskinia Zimna (Zimna Cave), then known as "Duda". He wrote: "*Sometimes ice stagnation in this cave throughout the summer* (he was mentioning the periodic occurrence of ice in parts near the entrance of Jaskinia Zimna) *is the reason that some local highlanders also call it an "ice grotto". However, I was assured that the actual ice grotto is completely different and is located in a gorge called Kraków. Due to the flooded valley this year, I could not get there*." (Ossowski, 1883). The first non-highlander visiting the cave was probably Jan Gwalbert Pawlikowski (1860-1939); a lawyer, economist, mountaineer, encyclopedist, and supporter of the idea of nature protection (Lewkowicz, 2014). In the volume XI of the *"Pamiętnik Towarzystwa Tatrzańskiego" (Memoirs of the Tatra Society)* entitled *"Podziemne Kościeliska"* (Underground Kościelisko) he mentioned *"an ice grotto that few people know about and almost nobody visits"* (Pawlikowski, 1887). He provided its approximate location – Twardy Upłaz over Kamienne, and two ways to get there – through Upłaz and through Wąwóz Kraków (the Kraków Gorge) which confirms that he has reached the proper cavern. Pawlikowski with local guide Maciej Sieczka visited the cave several times over at least two different years. He observed morphological changes in the ice in the cave – the formation of periodic water ponds and ice crevices. He also conducted the first size measurements, according to which the ice ridge (probably the ridge later called by the Zwoliński brothers as "Icefall" or the "III Threshold") was almost 10 meters high and 6 meters wide. In the *"Ilustrowany Przewodnik do Tatr, Pienin i Szczawnic" (Illustrated Guidebook to the Tatra Mountains, the Pieniny Mountains and Szczawnica region)* by Walery Eljasz (1896), *"Lodowa Jaskinia pod Czerwonym Wierchem"* (former name of Jaskinia Lodowa w Ciemniaku) was mentioned among the Tatra caves, and in Janusz Chmielowski's guide book – *"Przewodnik po Tatrach"* (1907), the "ice grotto" was mentioned again, following description from *"Podziemne Kościeliska"* by Pawlikowski.

Pawlikowski's article aroused the interest of mountaineers and scientists who wanted to find the cave, but despite the approximate location, for about 35 years no published record of any visit is preserved. According to Tadeusz Zwoliński (1923), Pawlikowski himself was unable to find the cave entrance after many years. Thus, Stefan Zwoliński suggested that perhaps Pawlikowski had never reached the cave and that his description was based on the stories of highlanders only (Zwoliński, 1951). The issue of the problem of the discovery is described in more detail by Kowalski (1953b) in a paper entitled *"Kto odkrył Jaskinię Lodową w Ciemniaku?"* (*Who has discovered the Ice Cave in Ciemniak*?) in which he suggests that most of the discoveries of easily accessible caves should be attributed to local shepherds, and it is unlikely to find out the name of the discoverer.

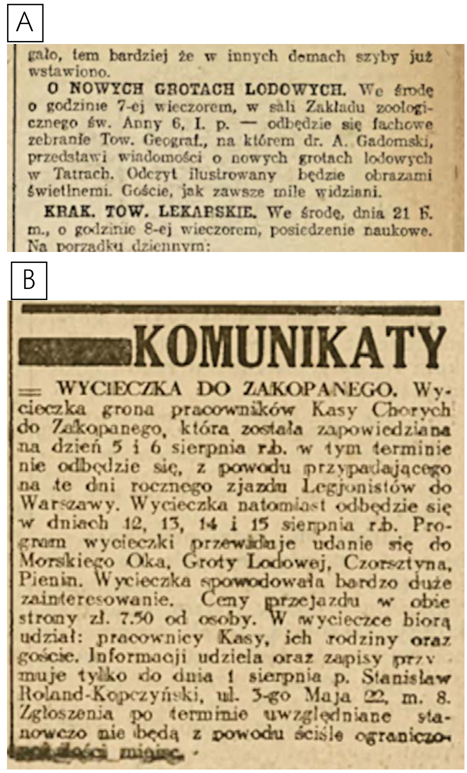
In August 1922, the brothers Tadeusz and Stefan Zwoliński visited the cave (Zwoliński, 1923) and a period of its detailed investigation began. On September 17, the Zwolińskis began exploring the cave and taking preliminary measurements. During several expeditions, they carefully mapped the cave and gave names to the known parts, including ice forms, some of which, such as Ślizgawka ("Slide") or Lodospad ("Icefall"; called also as "Treshold III"), did not survive to modern times. Zwoliński brothers observation of a strong airflow in the inner part of the main corridor led them to the conclusion that there must be a huge cavity behind the ice, which was discovered almost 30 years later (Zwoliński, 1951). The airflow suggested also potential presence of additional entrances to the cave.

The "rediscovery" of the cave caused a rapid increase in the interest documented by numerous publications. Only, in the period 1923-1927 Jaskinia Lodowa w Ciemniaku was mentioned 24 times by at least 7 [7 mentions were anonymous] different authors (Gadomski, 1923, 1924, 1925a, 1925b, 1925c, 1926a, 1926b, 1927; Zwoliński, 1923, 1924, 1925; Pawlikowski, 1923; Kwaśniewski, 1924; Goetel, 1923, 1925; Chrobak, 1925; Kreutz, 1925). The notes appeared not only in tourist and sightseeing or scientific magazines but also in the daily press. Authors writing about the cave used such terms as: *"a very rare phenomenon"* (Gadomski, 1924), *"the greatest sensational discovery"* (Goniec Krakowski, February 27, 1924), or *"the most interesting phenomenon of nature in the Tatra Mountains"* (Zwoliński, 1923). Open lectures were also organized (e.g. Ilustrowany Kuryer Codzienny, no. 293 22.11.1923, Wiadomości Geograficzne 1923, 1924) as well as scientific and sightseeing trips to the cave (Wiadomości Geograficzne 1925) (Fig. 4). Due to the huge interest, the perennial cave ice became the subject of protection already in 1925. In the guidelines of the Protection of the Tatra Mountains Section of the Polish Tatra Society (Sekcja Ochrony Tatr Polskiego Towarzystwa Tatrzańskiego), among the 10 general rules that should be followed in the Tatra Mountains there was one saying that destroying the speleothems, ice in caves, and using torches inside the caves are prohibited (Głos Zakopiański, no. 25 20.06.1925).

The importance of the discovery was also indicated by the rapidly created project (already in 1923) by the Polish Tatra Society of making the cave available to tourists (Goetel, 1923). The project was reviewed by the primary discoverer – Jan Gwalbert Pawlikowski (Pawlikowski, 1923). According to the project, a new tourist route should be led to the cave and the entrance should be secured with a gate constructed in such a way that it did not affect the microclimate of the cave.

In addition, steps should be carved in the ice, as well as other facilities should be installed allowing tourists to visit the cave. Meanwhile, Pawlikowski suggested postponing the works focused on providing tourist access to the cave until its thorough scientific research is carried out. He also pointed out that there is a threat of destroying the "original character" of the cave due to its adaptation for tourist purposes. Pawlikowski's concerns and recommendations probably slowed down the project and eventually, the new route has never been marked out and no infrastructure has been installed in the cave. Nevertheless, the number of visits to the cave significantly increased, probably also due to their advertisements published in the daily press (e.g., Goniec Krakowski 1924, Wiadomości Gegraficzne 1925, Kurier Zachodni 1933, Echo Krakowskie 27.08.1954 and 15.10.1954). In addition, in 1923, the fourth edition of the map entitled "*Tatry Polskie: mapa środkowej części Tatr*" ("Polish Tatra Mountains: the map of central part") was released by Tadeusz Zwoliński, with the entrance to Jaskinia Lodowa w Ciemniaku marked for the first time (Zwoliński, 1925). Zwoliński's series of maps was on the market for 11 years at that time, and due to its "*transparency and vividness of depicting the mountain area*" it was the most popular tourist map of this area. The fourth edition was published in 1924 (Głos Zakopiański 19.07.1924). Both the scale of the study – 1:37,500, the popularity of the map, as well as its touristic character probably also contributed to more frequent visits to the cave.

The scale of the popularity of the cave is also shown by the plans to include it in a documentary film about the nature of the Tatra Mountains. The spokesman of the movie was Marian Sokołowski (botanist, mountaineer, nature protection activist, and the supporter of Tatra National Park creation). In *Wszechświat* magazine, Sokołowski (1930) wrote: "*The real attraction of the movie could be shots taken in caves, e.g. from Ice Grotto in Kościeliska* (as was called Jaskinia Lodowa w Ciemniaku)*, showing the great phenomenon of nature that is found there, that is a real, although small, glacier*".


A

gało, tem bardziej że w innych domach szyby już wstawiono.

O NOWYCH GROTACH LODOWYCH. We środę o godzinie 7-ej wieczorem, w sali Zakładu zoologicznego św. Anny 6, I. p. — odbędzie się fachowe zebranie Tow. Geograf., na którem dr. A. Gadomski, przedstawi wiadomości o nowych grotach lodowych w Tatrach. Odczyt ilustrowany będzie obrazami świetlnemi. Goście, jak zawsze mile widziani.

KRAK. TOW. LEKARSKIE. We środę, dnia 21 b. m., o godzinie 8-ej wieczorem, posiedzenie naukowe. Na porządku dziennym:

B

KOMUNIKATY

= **WYCIECZKA DO ZAKOPANEGO.** Wycieczka grona pracowników Kasy Chorych do Zakopanego, która została zapowiedziana na dzień 5 i 6 sierpnia r.b. w tym terminie nie odbędzie się, z powodu przypadającego na te dni rocznego zjazdu Legjonistów do Warszawy. Wycieczka natomiast odbędzie się w dniach 12, 13, 14 i 15 sierpnia r.b. Program wycieczki przewiduje udanie się do Morskiego Oka, Groty Lodowej, Czorsztyna, Pienin. Wycieczka spowodowała bardzo duże zainteresowanie. Ceny przejazdu w obie strony zł. 7.50 od osoby. W wycieczce biorą udział: pracownicy Kasy, ich rodziny oraz goście. Informacji udziela oraz zapisy przyjmuje tylko do dnia 1 sierpnia p. Stanisław Roland-Kopczyński, ul. 3-go Maja 22, m. 8. Zgłoszenia po terminie uwzględniane stanowczo nie będą z powodu ściśle ograniczo- [illegible] miejsc.

Figure 4. A – Excerpt from Ilustrowany Kuryer Codzienny 22.11.1923 informing about the lecture on Jaskinia Lodowa w Ciemniaku; B – announcement about an organized trip to the cave (Kurier Zachodni 1933)

Apart from the exploration within the cave, the search for the hypothetical second, upper entrance, was also carried out on the surface. Gadomski (1926) mentioned that a couple hundred meters from Jaskinia Lodowa w Ciemniaku he found a vertically developed cave, with corridors filled with stones (probably he meant cave called Jaskinia Zawaliskowa w Szerokim). He also found several sinkholes, and in some of them, together with his companions made attempts to dig out in search of the expected cave corridors below. One of the cavers was lowered into the deepest sinkhole (probably Szczelina w Ciemniaku), but due to the rock debris blocking access to further parts of the cave, the exploration was abandoned. Despite the lack of evidence of a physical connection between these objects and Jaskinia Lodowa w Ciemniaku, this connection seemed highly probable to Gadomski (1926). A year later, the same author in the article *"Labirynt podziemny Czerwonych Wierchów"* ("The underground labirynth of Czerwone Wierchy massif") suggested also that the Jaskinia Lodowa w Ciemniaku is connected through rock crevices with Jaskinia Wodna pod Pisaną (Gadomski, 1927), which in the light of modern research seems to be likely (cf. Dąbrowski & Rudnicki, 1964; Dąbrowski, 1967).

The next important stage in the history of the cave exploration was in 1933, when Stefan Zwoliński and his companions observed: *"a serious decrease in the ice level in the cave"* (Zwoliński, 1933). He linked it with the winter of 1932/1933, which was not too cold and with little snowfall. At that time, not only was the thickness of the ice reduced (on average by about 1-1.5 m), but also the front of the "glacier" has retreated (Zwoliński, 1953). The second ice threshold, measuring approx. 2.5 m in height in 1922, was marked on the plan from 1933 with the annotation *"almost invisible, smaller than in 1922"*. As a result of this phenomenon, a small cavity was observed in the orographically right (northern) wall leading to previously unknown parts, called Nowy Korytarz (Fig. 2, 3). In this part a fungoid-like concretions (corraloids) were found for the first time in the cave. A newly discovered corridor was surveyed. It is worth emphasizing the accuracy of cartographic measurements made by the Zwoliński brothers; according to the plan from 1933, the final part of the Nowy Korytarz was 23 m above the cave entrance, this value is very similar to the results obtained during the new survey made in 2021 using a laser rangefinder (DistoX). Despite the much-reduced volume of ice in 1936, compared to previous measurements from 1922, the end of the Wielki Korytarz was closed with ice. A new fissure between ice and rock was observed along the south wall about 30 m from the cave's entrance. Its upper parts were too narrow for a man, which is why explorers decided to break through the ice and make the crevasse wider. Thanks to that Stefan Zwoliński descended on a rope and reached the 18-meter long chamber called Dolna Komora (nowadays this chamber is a part of Wielki Korytarz).

On October 3, 1950 (Fig. 5, Tab. 1) Stefan Zwoliński together with the hired workers through a narrow crevasse reached the major new chambers Sala Lodowa I and II (Fig. 2, 3) (Zwoliński, 1951, 1961). In the first chamber (Sala Lodowa I), with ice-covered floor, there was an ice pillar (nowadays it is an ice stalagmite). The second, much larger chamber (Sala Lodowa II) was also ice-covered and in the middle of it, there was an impressive mound of ice. Zwoliński did not exclude the existence of empty caverns under a thick layer of ice (currently, there is only residual ice inside the cave, and most of the floor is covered with rock rubble). Moreover, he suggested that the known corridors are just a beginning of a larger cave system (Zwoliński, 1955). Above the Sala Lodowa II, they noticed a great chimney (Wielki Komin), which, according to them, was possibly connected with the surface by narrow cracks (the exploration of the upper parts carried out 40 years later has not yet confirmed this hypothesis). The discovery of Wielki Komin, as well as the chimneys above the innermost part of Wielki Korytarz, namely Kominy Tadeusza contributed to understanding of potential water and air circulation in the cave.

Although the newly discovered parts of the cave were undoubtedly beautiful, due to the difficulties in access, S. Zwoliński saw no chance of making it available to a wider group of tourists (Liberak, 1950). Despite this, in the 1950s, Jaskinia Lodowa w Ciemniaku was among the ten most visited caves in the Polish Tatra Mountains, however, it was not mass-tourism, as for instance in Jaskinia Mylna (Kowalski, 1953a).

The next three decades of exploration have not brought any significant successes. Although, on 16 September 1953 a folded mast was tested in the Wielki Komin (Fig. 6). However, it was a test attempt only, as the construction was to be used in the exploration

Table 1. Morphometric changes of known parts of the cave throughout the last 100 years of ice mass loss and exploration progress

Year	Length [m]	Depth [m]	Denivelation [m]	Source
1922	67.0	0.0	30.0	Zwoliński, 1923
1933	137.0	0.0	30.0	Zwoliński, 1933
1950	200.0	9.5	39.5	Zwoliński, 1951
1990	≈ 220	11.0	36.8	Iwanejko, 1991; Rygielski et al., 1995
1991	365.5	11.0	36.8	Iwanejko, 1991; Rygielski et al., 1995
1994	390.0	11.0	42.0	Siarzewski, 1994
2021	394.6	12.1	44.6	The survey from 2021 described in this article

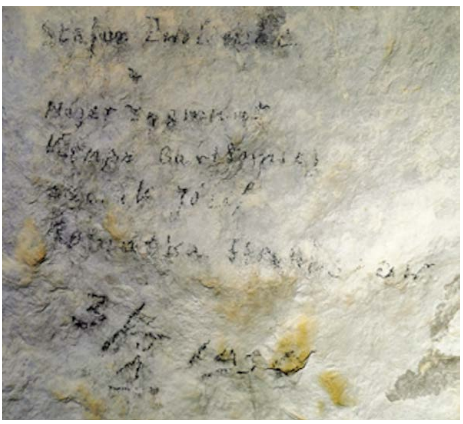


Figure 5. Inscription on a rock in the Sala Lodowa II commemorating Stefan Zwoliński's stay with hired workers: "Stefan Zwoliński, Majer Zygmunt, Krupa Bartłomiej, Łaciak Józef, Kobiałka Stanisław 3 / X 1950" (Photo J. Barabach, 2021)

of Jaskinia Zimna (Iwanejko, 1991). In 1957, an exploration of Jaskinia Wysoka was carried out, in which the newly discovered parts were heading towards Jaskinia Lodowa w Ciemniaku (Echo Krakowa 22.09.1957). However, the chances for the caves to be connected are negligible; modern measurements show that the closest points in both caves are approximately 120 m apart horizontally and 60 m vertically.

At the beginning of the 1990s speleologists associated in the Academic Speleoclub Poznań (Speleoklub Akademicki Poznań, currently Wielkopolski Klub Taternictwa Jaskiniowego / Wielkopolski Caving Club) explored

Figure 6. Installation of the mast for exploration of chimneys in Jaskinia Lodowa w Ciemniaku (Photo R. Gradziński, 1953 (Gradziński, 1953))

the upper parts of the Wielki Komin chimney, and new parts were discovered, namely the Meander Geografów, Matecznik, Ssak, and Dziupla (Iwanejko, 1991). This exploration was possible because, for the first time since 1987, a gap between the ice and the rocky ceiling heading toward the lower chambers (Sala

Lodowa I and II) was opened. The exploration did not confirm the expected connection between Jaskinia Lodowa w Ciemniaku and Jaskinia Zawaliskowa w Szerokiem, however, the end of the Meander Geografów that was filled with stones led in its direction. The new corridors discovered by cavers from Poznań increased the interest and expectations related to the quest on finding hypothetical large unknown cave system in Ciemniak massif, the existence of which was supposed to be an argument for the existence of such large ice deposits in the cave (Wiśniewski, 1991).

On January 27-28, 1993, another exploratory discovery was made in the cave. During the geodetic survey, a new corridor between the ice mass and the cave wall was observed at Dolna Komora. The passage was heading not only towards the massif, as it was previously observed, but also to the west – towards the entrance, consequently this part of the cave turned out to be longer by approx. 20-30 m (Rachlewicz, 1996).

The present exploration focuses on using the advanced mapping techniques and mapping the changing ice cover in the cave. The remapping of the cave in 2021, revealed 2 small cavities, that had not been drawn on previous plans and confirmed the intense disappearance of the ice cover in the Wielki Korytarz. The future new findings are expected mainly in the parts recently released from ice.

The cave climate and ice formation

Since the very beginning of the investigations of Jaskinia Lodowa w Ciemniaku, the key questions were related to the cave climate and the ice deposit formation processes. The investigations of the cave climate were started by the Zwoliński brothers who installed maximum and minimum thermometer (Zwoliński, 1924) and left it for the winter. The lowest value recorded between October 29, 1922, and May 25, 1923, was -17.7°C (Kwaśniewski, 1924). The first measurements conducted in the cave suggested that the cave climate was characterized by relatively high temperature variability and the presence of airflow. At that time, these features were in opposition to common views on ice cave formation. The latter were expressed in a book *"O jaskiniach lodowych" ("On ice caves")* by Franciszek Czerny (1884). He listed a number of conditions required for the formation of ice in caves, including lack of significant airflow and the location of the cave entrance higher than the rest of the cave. These were conditions considered to be typical for, what we call right now a static-type ice cave, as they favor trapping of the winter cold air inside the cave.

At the beginning of the 20th century, the presence of ice in caves was often explained by the cooling of water seeping through porous rocks into the caves (Anonymus, 1905). However, this mechanism has not explained why ice was observed all year round in Jaskinia Lodowa w Ciemniaku, while it was absent in most caves in the Tatra Mountains. Thus, Zwoliński (1923) suggested that the existence of the ice body was possible due to a seasonal gap between the ice mass and the rocky ceiling inside Wielki Korytarz called Wietrzna Szczelina ("*Windy Gap*"), considered at that time to be the innermost part of the cave (Fig. 7). He hypothesized that the gap was opened in winter which allowed the flow of cold air from the inner, so far, unknown parts of the cave and as a result, the ice could be deposited. In summer the gap between the ice and ceiling was to be closed with ice, changing the air circulation, which allowed to keep a lower temperature inside the cave.

In the following years, Walery Goetel – geologist, ecologist, creator of the term sozology, and rector of the AGH University of Krakow (Akademia Górniczo-Hutnicza im. Stanisława Staszica w Krakowie), joined the group of scientists studying Jaskinia Lodowa w Ciemniaku (Wójcik, 1973). He compared the cave to the Alpine ice caves called *Windröhre* or *Durchgangshöhle,* characterized by strong airflow, and two or more entrances (Goetel, 1925). In the case of Jaskinia Lodowa w Ciemniaku, the hypothetical upper cave entrance was to be in the form of a vertical,

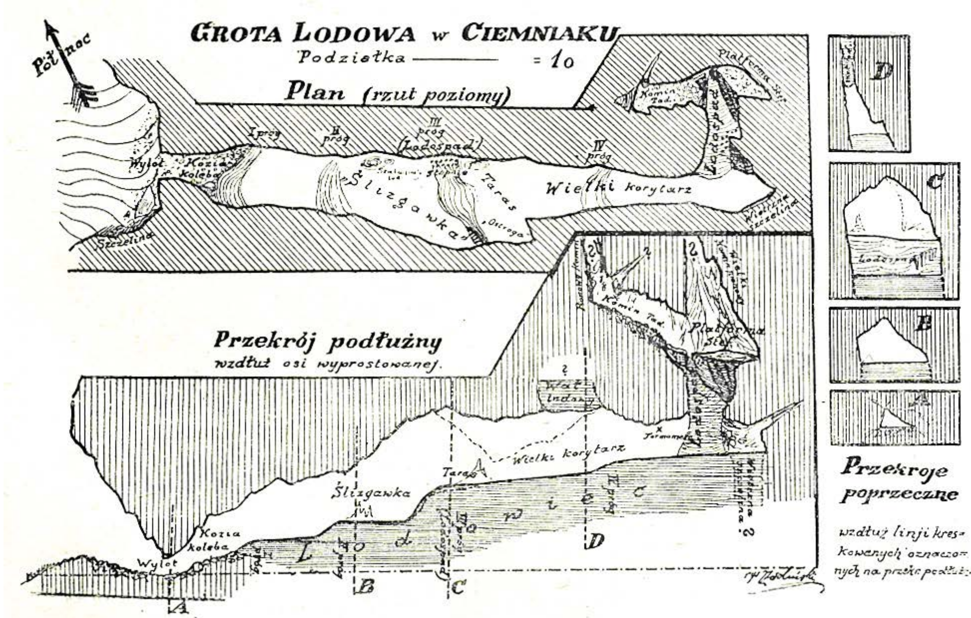


Figure 7. The first plan and cross-section of the cave (Zwoliński, 1923). Most of the ice cover and ice forms disappeared throughout the last 100 years. According to the first researchers, the seasonal closing and opening of Wietrzna Szczelina (*Windy Gap*) were essential for the development of ice phenomena inside the cavern

narrow chimney, located at the end of the Wielki Korytarz. However, the entrance has not been found so far.

The formation of ice was also discussed by Wrzosek (1933), who shared Goetel's (1925) opinion on the influence of air circulation on the formation of the ice cover. The author believed that a strong airflow facilitates the evaporation of water, lowering the average air temperature inside the cave, which, in turn, contributes to the development of ice phenomena.

Due to the discovery of new parts of the cave in 1933 (Zwoliński, 1933), and lack of evidence of connection of the inner part of Wielki Korytarz with hypothetical further parts of the cave, Stefan Zwoliński suspended his earlier hypotheses that the airflow in the cave affecting the formation of ice was caused by air exchange between large unknown cavities located behind the ice and connected by narrow crevasses with the surface and known parts of the cave. His new hypothesis explaining the formation of the ice suggested the existence of tight, inaccessible cracks in the cave floor, through which airflow is circulating.

The existing views on air circulation in Jaskinia Lodowa w Ciemniaku were to be revised due to new discoveries in 1950, when the relatively long lower part of the cave (Sala Lodowa I and II), containing extensive ice mass, as well as a large chimney (Wielki Komin) were discovered (Zwoliński, 1951, 1961). The chimney, according to Zwoliński, could be connected with the surface by narrow cracks. The discovery led to the new concept of seasonal changes in the cave. He hypothesized that by the end of summer, water flowing down from the chimneys at the end of the Wielki Korytarz (*Kominy Tadeusza*) and the warming of the limestone walls of the cave cause the formation of open space between the ice and the cave walls, leading to connection with the lower part of the cave (Sala Lodowa I and II). Because the Wielki

Komin chimney, at the end of the lower part, is likely connected to the surface, the relatively warm air may be sucked from the cave into the chimney and facilitates airflow through the entire cave and consequently melting the ice surface. In autumn, when the temperature drops a strong draft of cold air cools down the interior of the cave, and the mass of ice could increase leading to the closure of the connection between Wielki Korytarz and the lower parts. In summary, Zwoliński concluded that Jaskinia Lodowa w Ciemniaku, depending on the season, could be classified as a dynamic type ice cave (when the connection between the upper and the lower part is open) and static type ice cave (when the two parts are separated) (Zwoliński, 1955).

Zwoliński (1951) suggested that the cave ice volume increases in winter. On the contrary, Kowalski (1953a) hypothesised that ice accumulation takes place in late autumn, early winter, and in particular in spring when the largest increase in ice mass takes place. He based his concept on monitoring studies in 1951-1952 measuring minimum and maximum temperature at two locations inside the cave, and one outside, where a standard thermometer was installed (Kowalski, 1955). A modified scheme of cave climate and ice formation based on Kowalski's (1953a) idea, is shown in Figure 8. According, to that at the turn of autumn and winter, the air temperature in the cave is relatively low, and there is liquid water on the ground surface. When the water, flowing through numerous cracks, reaches the cold interior of the cave, it freezes. He supposed that in winter, due to the lack of water supply, because of temperatures below 0°C outside the cave, and low temperatures inside the cave, the ice stagnates (this view was questioned later on by Rachlewicz and Szczuciński (2004)). In spring, a large amount of snow-generated meltwater reaches the cave, where the cave air temperatures are still below 0°C, and new ice forms. In the summer the temperature inside the cave rises, and rainwater reaching the cave does not freeze, and probably accelerates the ice ablation. He pointed out that the annual alterations of rainfall and temperatures in the area of the Ciemniak massif and any weather anomalies can have a significant impact on the process of ice formation or decay.

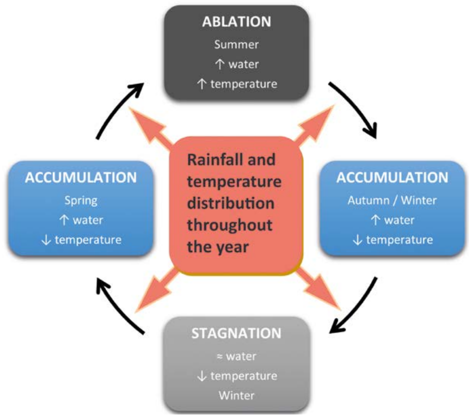


Figure 8. Graphical schematic diagram of the development of cave ice based on Kowalski's description of this phenomenon (1953; changed). The modern views (Rachlewicz & Szczuciński, 2004) do not support significant ice accumulation in autumn/winter period, and ice mass stagnation in the winter, when actually a significant ice mass loss take place due to sublimation

Extensive measurements of the wave climate were conducted in 1986 and 1987 by Rygielski et al. (1995). They measured the temperature along the cave, as well as in the vertical profiles, and made important observations on the airflow in the cave. According to them, the crucial role in the formation and ablation of the ice is the annual cycle of air circulation, conditioned by the morphology of the cave. They pointed out, the particular importance of the presence of chimneys and fissures which provide a connection between the cave air and the external atmosphere. They also noted that the shape of the longitudinal profile of the cave, for a long time regarded to be essential for ice cave formation is of smaller importance.

The monitoring of cave air temperature and ice mass balance has been the subject of research since 2000 by Rachlewicz and Szczuciński (2004). They found a very good correlation of the air temperature with the air temperature on the surface (data from Kasprowy Wierch) during the period of negative air temperatures, while during the time when the outside temperature was above 0°C, the temperature in the cave was almost stable, as the heat was consumed in the ice melting process. The results of ice mass monitoring allowed the authors to conclude that in the upper part of the cave (Wielki Korytarz) ice disappears not only as a result of its melting in summer and autumn, but also in winter as a result of sublimation due to rapidly descending dry and cold air through the chimneys and fissures. The sublimation was the most effective during the coldest periods, with outside temperatures well below -10°C. On an annual scale, sublimation was responsible for 31% of ice loss, and the remaining 69% of ice mass loss occurs in the warm period due to its melting. The ice formation was noted in spring season, when the surface meltwaters seeped into the cave.

At present the air temperature monitoring is continued by prof. G. Rachlewicz (Faculty of Geographical and Geological Sciences, Adam Mickiewicz University, Poznań) and collaborators in the upper and lower part of the cave in order to follow the development of the ice cave climate in response to changes in cave morphology (due to ice mass degradation) and general climate warming.

The cave ice forms and structure

The ice in Jaskinia Lodowa w Ciemniaku is in the form of perennial ice masses (the main ice block covering the cave floor and some multiyear stalagmites) as well as seasonal forms representing a wide variety of forms present mainly in spring and known also from other caves in the Tatra Mountains (e.g., Pulinowa and Pulina, 1972; Siarzewski, 1994b; Gradziński et al., 2018). More detailed investigations of the types of ice were conducted since the very beginning of the cave studies, as they were considered to be the key to getting insight into the history of the cave ice mass.

The first crystallographic ice analyses were carried out by Chrobak (1925). He described that the ice columns and the floor ice mass consisted of coarse-crystalline ice with single crystals up to 3 cm in diameter. The smaller stalactites were characterized by a radial structure, while Lodospad (icefall – not existing today) was built of grains with sharp, clear edges. He also observed the stratification of the ice, which was supposed to indicate different periods of its formation. However, in the 1920s, the ice tightly filled the entire floor of the known parts of the cave (with the exception of the parts near the entrance) and ice exposures with well-visible ice stratification were not available at that time. Even marginal fissures (*"odparzeliny"*) between the walls and the ice were not observed (Gadomski, 1926b).

The more detailed observations of the layered structure of the ice mass were conducted by Zwoliński (1953) after the new passages were opened due to a reduction in ice mass in 1933, when he also estimated the thickness of ice mass to range from 5 to 9 meters (Zwoliński, 1933). Altogether, he counted over 400 ice laminae being 1 to 5 cm thick and separated from each other by a thin ice layer enriched in fine clayey sediments. He hypothesized that they are annual layers (Zwoliński, 1951).

Further information was provided by Rygielski et al. (1988) on the basis of ice surface observations supplemented with over 20 boreholes. They focused on ice mass thickness, structure (stratification and mineral content), ice thermal variability in the vertical and horizontal profile, and ice chemistry (Ca^{+2} concentration, electrolytic conductivity, and pH). Unfortunately, the article was a preliminary report and only part of the results was shown. Among, the novel data were the results of ice temperature measurements. It appeared that at a depth of 6 cm the ice temperature is constant and equals -0.3°C, then it gradually drops with depth to -0.6°C in the middle of the ice profile, and then slightly increases towards the bottom. The basic chemical composition and electrolytic conductivity were also studied in the summer of 1989 and in the winter of 1990 by Kędzia (1991).

More detailed insight into the vertical ice structure was presented by Rygielski et al. (1995). They studied mainly the ice mass in Wielki Korytarz (Fig. 9), where they estimated its thickness at that time to reach at least 5.7 m. They noted ice stratification, with particular layers being usually 0.1-2 cm thick, but in some cases reaching up to 12.5 cm. They interpreted them as summer and winter layers. The so-called "summer layers" were often enriched in fine limestone dust, clay, and debris, which were considered as the record of summer ablation of the ice surface. The thicker layers rich in clastic material were considered to present potential hiatuses and longer periods of melting. Rygielski et al. (1995) noted also that the lower portion of ice mass is richer in limestone debris and clay.

The major changes in ice layering structure were documented by Hercman et al. (2010). They identified two generations – the older one with thicker layers and transparent crystals, and the younger one with thinner, made of more opaque ice layers. The contact between the two structures forms unconformity, possibly indicating intensive ice melting, and was assigned by Hercman et al. (2010) as a potential record of the boundary between the Medieval Climate Optimum and the Little Ice Age ice.

The cave ice changes in time – ice mass balance

The century-long observations of ice mass in Jaskinia Lodowa w Ciemniaku, provided a unique opportunity to provide a long-term assessment of ice mass balance changes. It is one of a dozen or so ice caves worldwide with such a long and detailed record (Kern & Perşoiu, 2013).

The presence of the large ice body in Jaskinia Lodowa w Ciemniaku inspired a number of questions related to its changes in time. However, the first considerations of the cave ice mass changes were not related only to its melting and freezing. The finding of large subterranean ice mass called the comparisons with alpine glaciers. Thus, one of the first research questions was whether "the glacier" (ice mass filling the cave) was stagnating, expanding, or retreating, as it was expected that it should behave in the same way as glacier ice. Observations from 1923 (Kwaśniewski, 1924) indicated a slow movement of the ice mass towards the entrance; the glacier front moved 8 cm during the studied period. However, it is not clear if it was really a movement or rather expansion of ice through the formation of new ice in its marginal part (ice accretion). Kowalski (1965) stated that, although seasonal changes in mass balance can be observed, comparing it to a waxing and waning glacier is unjustified because cave ice does not deposit any moraine.

The question of the movement of ice mass was critically discussed by Rygielski et al. (1995). They found it difficult to assess if the ice in Jaskinia Lodowa w Ciemniaku still moved. However, they presented some indicators of possible small ice movement in the past. The indicators included fissures and

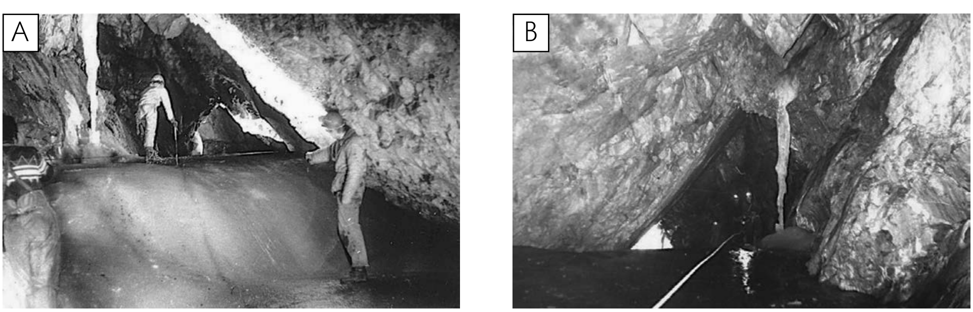


Figure 9. Ice mass investigation in Wielki Korytarz – climbing gear in use. A – 1985, B – 1986 (Kronika Sekcji Speleologicznej, 1979-1998)

cracks in the ice, some ice layering deformations in the basal part of the ice mass, orientation of debris in ice, as well as the geometry of the ice mass in relation to the cave morphology.

Over time much more attention was given to general ice mass changes. The 30 years of ice cave mass shape observations conducted by Stefan Zwoliński (1951) led him to conclude that there are both seasonal and perennial changes in ice mass balance. The seasonal changes may cause a slight increase or decrease of the ice mass, while the decadal, long-term trend of slow loss of the ice mass he assigned to the "general warming of our planet" (Zwoliński, 1951). He also emphasized the importance of Jaskinia Lodowa w Ciemniaku as an object of research on climate change and expressed concern (Zwoliński, 1951, 1953) about the possibility of a complete disappearance of the ice mass. According to him, it could take place if the seasonal opening in the ice mass (Wietrzna Szczelina) separating the upper and the lower part of the ice-covered portion of the cave ceased to be seasonally closed. However, currently, the connection is wide open throughout the year, while the ice mass, although degraded is still present.

Along with the assessments of relative changes, the first attempts to assess the total ice mass were made. The first estimations of the ice volume were made by Gradziński and Wójcik (1961), according to which in the middle of the 20th century, there was about 1500 m^3 of ice in the cave.

In the 1980s, scientists from Adam Mickiewicz University, Poznań (Rygielski & Wieliczko, 1988; Rygielski et al., 1988, 1995) conducted a detailed cave survey, which was the basis for ice mass balance estimation. They compared their calculations with previous measurements of ice mass carried out by Zwoliński (Zwoliński, 1923, 1951). They noted significant ice loss over the previous 64 years (Fig. 10, 11). For instance, near the entrance, the ice mass receded and the ice thickness declined by about 3 meters, the part called *Ślizgawka* ("*Slide*") in the western part of Wielki Korytarz was lowered by approximately 2 meters, and *Lodospad* ("*Icefall*") in the middle part of the Wielki Korytarz had completely disappeared (lowering by at least 6 meters). In the innermost part of Wielki Korytarz the ice thickness decreased by 3.8 m in comparison to 1922, and by 2.6 m to 1950 (Rygielski & Wieliczko, 1988). Rygielski et al. (1995) ascribed the ice mass reduction to two factors, frequent visits affecting the local circulation and stability of ice masses, as well as general climate warming.

Siarzewski (1996), involved in the exploration of caves on behalf of the Tatra National Park in the period 1986-1996, systematically monitored ice level fluctuations, which in the initial period were usually ±10 cm per year. However, since the early 1990s, prominent ice loss was observed, and from 1994 and 1995 Siarzewski described it as "very rapid". Despite this, in comparison to other ice caves he studied on the Polish part of the Tatra Mountains, he classified the conditions of ice preservation in Jaskinia Lodowa w Ciemniaku as relatively stable and he assessed the susceptibility of local ecosystem to anthropogenic influences as "medium".

The extensive study on ice mass balance changes in Jaskinia Lodowa w Ciemniaku on seasonal, annual, and decadal time scales were conducted by Rachlewicz and Szczuciński (2004). They described above seasonal changes and monitored the ice mass for four years, mapped the ice cover, and compared it with the earlier observations (Zwoliński, 1961; Rygielski et al., 1995). The main finding was that the ice was characterized by negative mass balance throughout the entire observation period (80 years), however, the rate of degradation accelerated with time. The average annual ice loss in the years 1922-1950 was 23 m^3 of water equivalent, while in the period 2002-2004 this value was almost three times higher and amounted to 66.8 m^3/year (Figs. 10, 11). Altogether, during the 80 years at least 2,250 m^3 of ice was lost. Rachlewicz and Szczuciński (2004) also concluded that by 2030-40 the ice mass in the Wielki Korytarz is likely to be completely

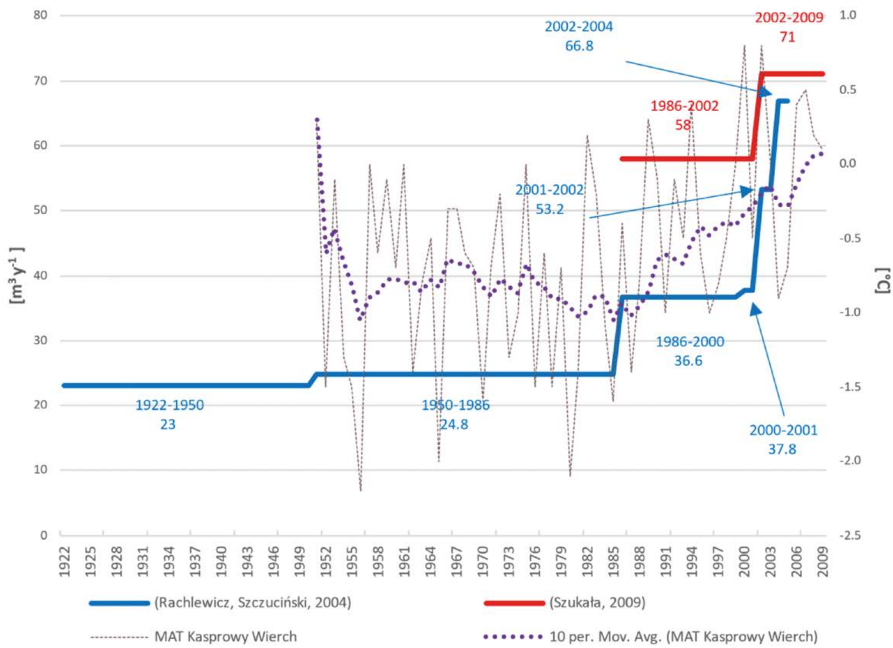


Figure 10. The rate of ice loss in the Wielki Korytarz (Big Corridor) in Jaskinia Lodowa w Ciemniaku between 1922-2009 and changes in the mean annual temperature (MAT) on Kasprowy Wierch meteorological station in the years 1951-2009 (https://meteomodel.pl/). Note that the difference in the mass balance figures is related to different methodological approach

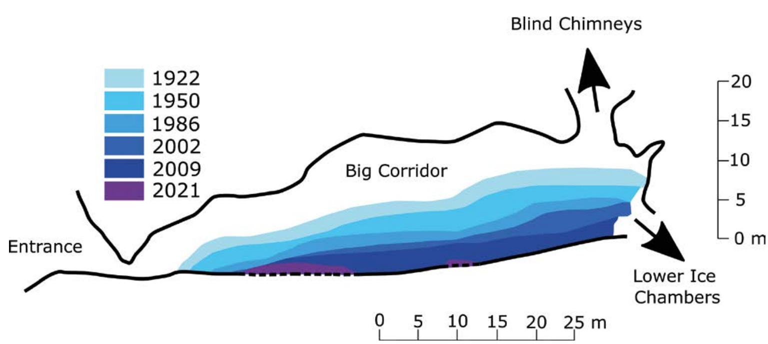


Figure 11. Change in ice level in the Wielki Korytarz (Big Corridor) over the last century (1922-2021) – schematic cross-section after Gradziński et al. (2018), supplemented with new own measurements from 2021. Data sources: for particular years: 1922 – Zwoliński (1923), 1950 – Zwoliński (1951), 1986 – Rygielski et al. (1995), 2002 – Rachlewicz, Szczuciński (2004), 2009 – Szukała (2010), 2021 – present study

gone and they attributed that mainly to climate warming (Fig. 10). Actually, as the new mapping presents (Figs. 2 & 3) there is already almost no ice in that part of the cave.

The monitoring of the ice mass was continued until 2009 by Szukała (2010), who applied three-dimensional modeling of the ice mass (Fig. 10, 11). His methodological approach included not only the main ice mass in Wielki Korytarz, so the obtained negative mass balance figures appeared to be even larger then previously measured (Fig. 10).

The latest ice mass measurements, conducted during the re-mapping of the cave in 2021, confirmed the intense disappearance of the ice cover in the Wielki Korytarz (Figs. 2, 12, Palińska, 2022). There is only a small part along the corridor lowering in its southern part, where still an almost 2 m thick mass of layered ice was present (Fig. 13). The ice mass in the lower part of the cave (Sala Lodowa I and II) was largely diminished and once impressive ice stalagmite was a minor form.

Cave ice age and environmental record

The next intriguing key problem related to the ice mass in Jaskinia Lodowa w Ciemniaku is the age of ice. After the major discovery of new parts in 1933 (Zwoliński, 1933), which revealed access to a layered section of ice mass, nearly 400 ice laminae were counted and hypothesised that they are annual layers (Zwoliński, 1951), thus suggesting that the ice is at least several hundreds years old.

New light on the age of the ice in the cave was shed by Wójcik (1968), who found subfossil remains of the Bechstein's bat (*Myotis bechsteinii*) in *Nowy Korytarz* (*"New Corridor"*). This species is considered to be thermophilic and inhabited the Tatra caves during the Holocene climatic optimum. The access to this part of the cave was likely cut off until around 1933, so the bat probably have got into it before the ice mass in the Wielki Korytarz developed. On this basis, Wójcik (1968) suggested that the formation of the cave ice was related to the cooling of the climate during the late Holocene.

An attempt to estimate the age of the ice was made with the help of pollen analysis (Rygielski et al., 1995). The oldest ice layers revealed the presence of trace amounts of cereal pollen grains, associated with the development of agriculture in Podhale (a region next to the Tatra Mountains) in the 13th and 14th centuries. Thus, the authors suggested that the cave ice accumulation most likely was linked with the climate cooling of the Little Ice Age. However, they also noted that the ice melts not only from the top but also from the bottom by ablation of the oldest layers, thus determining that the precise dating of actual beginning of its accumulation may not be possible.

New data related to the age of the ice in Jaskinia Lodowa w Ciemniaku were provided by Hercman et al. (2010), who radiocarbon dated the remains of two moths (probably *Triphosa dubitata*) found in the ice mass. As mentioned above, they documented two generations of ice – the older with thicker layers and transparent crystals, and the younger with thinner and opaque ice layers. They were separated by unconformable contact, suggesting a prolonged period of melting. Both moths were found in ice belonging to the younger generation. The oldest moth was dated to the period 1660-1790, which confirms that ice accumulation took place during the Little Ice Age. Hercman et al. (2010) suggested that the boundary between different ice types could be a record of the Medieval Climate Optimum. The beginning of the formation of older ice generation is unknown. However, Hercman et al. (2010) hypothesized that it could have occurred within the Late Holocene during the cold period preceding the Medieval Warm Period.

The layered ice mass tempted many researchers to consider it as a natural archive of natural and anthropogenic changes, an equivalent of ice cores from glaciers. The first attempts were made by Jaworowski (1966, 1968, 1982). He followed the hypothesis of Zwoliński (1951) and assumed that the ice layers represent annual accumulation, and analysed the elemental lead (Pb), as well as ^{210}Pb radioisotope in ice samples reaching back to circa 1861 AD (based on ice layer counting). The results and applied methods were novel at that time and were published in the prestigious journal: *Nature* (Jaworowski, 1966, 1968). The first, innovative work by Jaworowski (1966) focused on analyses of ^{210}Pb (lead-210, at that time called "radium D"). He analysed it along the vertical ice profile in samples dated (based on ice layer counting) to the period ~1923 to 1963. The maximum concentrations of ^{210}Pb were recorded in the youngest samples from 1958-59 and 1962-63, which according to the author corresponded with the increased number of nuclear tests in the world (UNSCEAR, 2000). However, right now it is known that ^{210}Pb is a part of the natural radioactive decay chain of ^{238}U radionuclide, and its activities were not significantly affected by the nuclear weapon tests. On the contrary, it is commonly used for dating up to 100-150 years old sediments (e.g. Koide et al., 1972; Barsanti et al., 2020), snow and ice (Gäggeler et al., 2020). Thus, the decline of the ^{210}Pb with depth noted by Jaworowski could be in fact used as a dating tool for the ice layers.

The second work by Jaworowski (1968) presented the analyses of stable lead concentration in ice and showed a clear increase over time from an average value of 5 μg/L (for years 1861-66 AD), to 80 μg/L in ice surface samples (representing 1960-65 AD). Jaworowski (1968) linked the increase in lead pollution to the development of global industry but was not convinced to link the pollution to the usage of fossil fuels. While Koisar and Parma (1971) had no doubts about this and wrote that *"the increase in lead concentration* [in ice in Jaskinia Lodowa w Ciemniaku] *is closely related to the total annual contribution of coal and other fuels to the world's energy system"*.

In the following decades, there were several attempts to explore the ice mass as a potential natural archive of environmental changes. However, the researchers faced problems with technical matters (drilling of ice cores in caves), as well as dilemma related to natural contamination of the record by percolating water and doubts about the record continuity (e.g., Rygielski et al., 1995; Rachlewicz & Szczuciński, 2004; Hercman et al., 2010). The understanding of the modern processes causing ablation, sublimation, and freezing to occur unevenly within the cave (Rachlewicz & Szczuciński, 2004), was suggested to be taken into consideration in the studies based on ice stratigraphic analysis. The above-mentioned problems were also noted by authors of several preliminary attempts to apply various isotopic techniques in the studies of ice (e.g., Celejowska et al., 2007; Celejowska, 2008; Szynkiewicz & Solarczyk, 2010; Duliński, 2010).

One of the mentioned attempts by Duliński (2010) focused on the application of tritium (^3H) radioisotope concentration in the ice. The results suggested that older ice layers may be locally enriched in ^3H redistributed from younger layers. Celejowska et al. (2007) and Szynkiewicz and Solarczyk (2010) applied stable oxygen isotopic ratios ($\delta^{18}O$) for the investigation of cave ice in Jaskinia Lodowa w Ciemniaku. Szynkiewicz and Solarczyk (2010) tried to correlate the $\delta^{18}O$ record from vertical ice profiles with changes in average summer air temperatures recorded in nearby Zakopane for the period 1915-1952. They identified three groups of ice layers

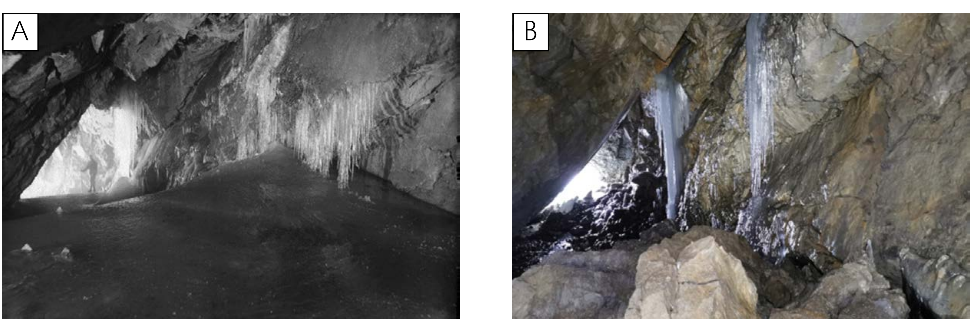


Figure 12. A – Jaskinia Lodowa w Ciemniaku – view towards the entrance. In the background, a person for scale (Photo T. Malicki, 1922; source: Muzeum Tatrzańskie archive), B – Contemporary photo taken from the same perspective, the ice mass on the floor is completely melted away (Photo J. Barabach, 2021)

formed in different periods and climatic conditions. Group 1 (probably corresponding to the years 1915-1940) illustrated a period of cyclical changes with a slight warming tendency; group 2 was interpreted as a record of cooling (1940-1942), while group 3 (1942-1952) showed cyclical changes within a relatively warmer period – similar to the group 1, but slightly cooler. However, data on temperature variability over a longer period revealed that the cooling in the early 1950s reflected just a short-term episode (Łupikasza & Szypuła, 2019).

The dramatic degradation of ice mass in Jaskinia Lodowa w Ciemniaku (Fig. 11) causes that also the potential record of environmental and climate changes to be almost lost. One of the challenges in the near future is to take action to preserve at least a small part of that record for future studies, it could be done for instance by a drilling campaign in the lower parts (Sala Lodowa I) of the cave. However, the detailed age dating and careful estimation of potential contamination and spatial variability in the record must be certainly taken into account.

Biological investigations

Jaskinia Lodowa w Ciemniaku serves also as a unique ecosystem. Already in the 1920s or 1930s Wiktor Kuźniar, Mieczysław Limanowski (geologists), and Alfred Lityński, the pioneer of Polish hydrobiology, carried out some observations related to the cave biota (Wójcik, 1997), however, the results of their activities were not published.

The first systematic studies of the fauna inhabiting Jaskinia Lodowa w Ciemniaku were carried out by Kowalski (1951, 1953a), and revealed, for instance, numerous bat bones in Nowy Korytarz (New Corridor) and newly discovered lower parts of the cave. Detailed results of these studies were published in 1955 (Kowalski, 1955) documenting the presence of the snail: *Chilostoma cingulella*, arachnids: *Ischyropsalis milleri*, springtails: *Onychiurus armatus*, *Onychiurus fimetarius*, beetles: *Omalium excavatum*, *Nebria tatrica*, butterflies: *Triphosa dubitata*, caddisflies: *Stenophylax permistus*, flies: *Eccoptomera emarginata*, *Eccoptomera emarginata*, *Amoebaleria spectabilis*, *Crumomyia nitida*, and bats: *Myotis mystacinus*. The finding of *M. mystacinus* was considered by Kowalski (1965) to be the highest recorded position of this species in the Tatra Mountains. Moreover, the presence of pine marten (*Martes martes*) was also suspected. It is worth mentioning that the population of *S. permistus* was larger than in the other investigated caves in the Tatra Mountains.

The melting waters from the ice in Wielki Korytarz were subjected to pioneering research in Poland in terms of the presence of bacteria and protozoa (Chardez & Delhez, 1981). The study revealed existence of bacteria of the genus *Bacillus* and protozoa: *Bodo minimus*, *Bodo saltanus*, *Valkampfia guttula* and *Trinema lineares*.

Cave exploration progress in the early 1990's was followed by biological investigations in the new parts. Namely, in the Ssak and Meander Geografów (Fig. 2, 3), where numerous skeletal remains of bats belonging to five species were found: *M. mystacinus*, *Myotis brandti*, *Eptesicus nilssoni*, *Plecotus aurutus* and *Barbastella barbastellus* (Nowosad et al., 1992). The authors were puzzled by the number of bones they found because the presence of bat colonies or their guano was not observed in the cave. Nowosad et al. (1992) hypothesized that the accumulation of the remains was due to their redeposition by the water flowing down through the crevices. Unfortunately, the age of the bones has not been determined, however, according to the presentation at the chiropterological conference in 1993, more bat remains were found, including some with partially preserved soft tissues.

The following decades brought more observations of bats. For instance, Kowalski and Ostrach (1994) found the remains of a parti-colored bat (*Vespertilio murinus*) to be embedded in a layer of ice dated approximately at 100 years old. Bat observations in Jaskinia Lodowa w Ciemniaku were also conducted by Kepel (1995), Piksa (1998), and Piksa and Nowak (2002). The presence of bat tick (*Carios vespertilionis*) was noted by (Siudai et al., 2009). It was a new finding, extending the so far known distribution range of this species in Poland. More recently, Piksa et al. (2011) inventored bats during the swarming period together with arachnids parasitizing them.

Conclusions

Jaskinia Lodowa w Ciemniaku, so far known as hosting the largest subterranean ice mass in Poland, was first described 140 years ago and it has been subjected to scientific investigations for the last 100 years, since 1922. During that period of time, the cave changed significantly, mainly due to a massive loss of ice (Fig. 9, 10, 11). The ice mass filling the Wielki Korytarz, most frequently investigated and originally being almost 10 m thick, is almost completely gone (Fig. 11, 13). While the fissure at the end of the Wielki Korytarz leading to the inner cave corridors is no longer a fissure but a big passage with no prospects for ice sealing.

Over the last 100 years, Jaskinia Lodowa w Ciemniaku has been mentioned in more than a hundred scientific works, and in at least 55 studies it was the main or one of the main objects of research. Meanwhile, the length of the known corridors has increased almost six times (Tab. 1, Fig. 13), and the volume of ice has dramatically decreased (while the volume of the cave increased). There is a large progress in our understanding of its specific and seasonally changing climate and conditions leading to ice formation and degradation (melting and sublimation). A lot of effort was paid to investigate the ice origin, age, structure, and changes of its ice mass balance over time, as well as the environmental records preserved in the cave ice archive and biota inhabiting the cave. It has become one of the best-known caves in Poland and is among the best-studied ice caves globally. Some of the findings appeared to be of international importance and were cited tens

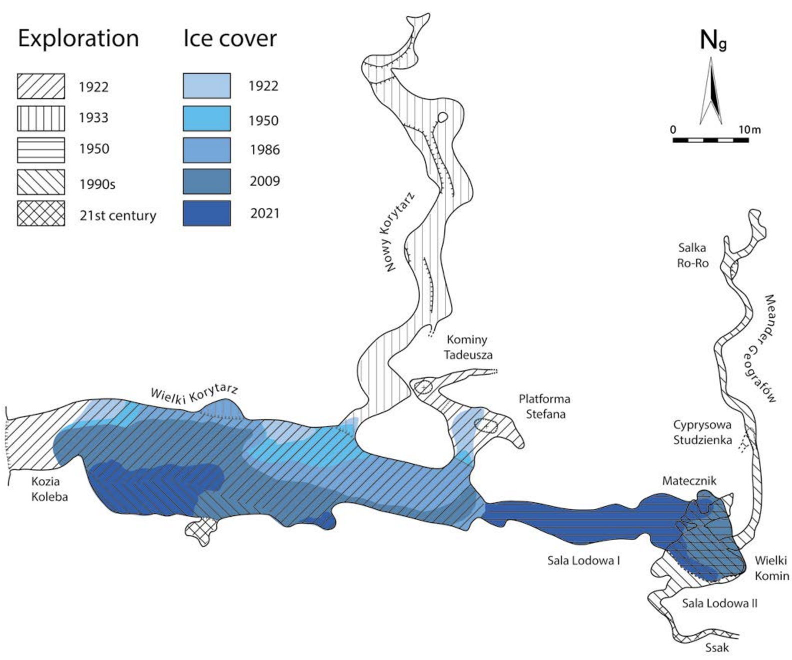


Figure 13. The history of cave exploration and ice loss in Jaskinia Lodowa w Ciemniaku

of times, e.g., early works related to the concentration of radioisotopes and pollutants in the cave ice record (Jaworowski 1966, 1968), the studies of seasonal to decadal ice-mass balance changes (Rachlewicz & Szczuciński, 2004) and the age of the ice mass (Hercman et al., 2010).

Despite the progress, some of the basic questions asked a century ago are still partly unanswered. For instance, we still do not have a precise answer on the timing and conditions leading to the formation of the first perennial cave ice mass, as well as about its later evolution. The cave climate is still changing due to changes in the cave volume and reduction in ice masses, it is an open question if the globally changing climate and locally changing cave air circulation would sustain the presence of cave ice deposits in the future. Certainly answering this question would require extending the *in situ* studies by cave climate modeling. The ice mass balance change dataset belongs to the longest records worldwide and it is certainly worth continuing its monitoring, including into it also the lower parts of the cave (Sala Lodowa I and II). The remaining ice deposits may contain a valuable climate and environmental change archive, and there is an urgent need to properly collect ice cores from the existing ice mass before it is completely melted away. The ice cave is also a unique ecosystem, which is likely to disappear, thus it should be investigated using the modern environmental and ancient DNA approaches to document its past and present state as a reference for the future. Last but not least, the investigations should be focused not only on Jaskinia Lodowa w Ciemniaku but also on the remaining ice caves in the Tatra Mountains (Gradziński et al., 2018), as some of them lack even basic information about the ice mass extent.

We hope that the presented review and new data will encourage the research community to undertake the effort of investigating the unique and declining part of the Polish cryosphere. One may wonder if the answers to presented above questions will be delivered before climate warming causes the largest 'cave glacier' in Poland to disappear.

Acknowledgments

The authors would like to thank the Muzeum Tatrzańskie (Tatra Museum) for providing archival data, prof. Małgorzata Mazurek for help in identifying the archival typescript, Tatrzański Park Narodowy (Tatra National Park) for permission to conduct research in the cave, Michał Amborski, Martyna Gruszka, and Grzegorz Sokół for help in fieldwork, and Michał Filipiak and Adam Łada for help in drawing the plan of the cave. We kindly acknowledge thoughtful and inspiring reviews by prof. Michał Gradziński and an anonymous reviewer.

Editors' note:
Unless otherwise stated, the sources of tables and figures are the author's, on the basis of their own research.

References

Anonymus, (1905). An explanation of ice caves. *Scientific American,* June 17, 92(24), 1-479. https://doi.org/10.1038/scientificamerican06171905-479b

Barsanti, M., Garcia-Tenorio, R., Schirone, A., Rozmaric, M., Ruiz-Fernández, A. C., Sanchez-Cabeza, J. A., ... & Osvath, I. (2020). Challenges and limitations of the ^{210}Pb sediment dating method: Results from an IAEA modelling interlaboratory comparison exercise. *Quaternary Geochronology, 59*. https://doi.org/10.1016/j.quageo.2020.101093

Celejowska, P. (2008). *Analiza izotopowa tlenu w profilach lodowych w Jaskini na Ciemniaku w Tatrach Polskich, jako wskaźnik zmian paleoklimatycznych*. Master's thesis, Archives of the Institute of Geological Sciences of the University of Wrocław.

Celejowska, P., Głazek, J., Jędrysek, M. O., Kicińska, D., Solarczyk, S., Szynkiewicz, A., & Zieliński, M. (2007). Badania składu izotopowego tlenu w warstwach lodowca Jaskini Lodowej w Ciemniaku (Tatry). In K. Stefaniak, M. Szelerewicz, & J. Urban (Eds), Materiały *41. Sympozjum Speleologicznego, Kletno. Sekcja Speleologiczna PTP, Kraków* (p. 40).

Chardez, D., & Delhez, F. (1981). Przyczynek do znajomości mikroorganizmów jaskiń Polski. *Rocznik Muzeum Częstochowskiego, Przyroda*, *5*, 9-13.

Chmielowski, J. (1907). *Przewodnik po Tatrach*. [Cz.] *1. Cz. ogólna – Tatry Zachodnie*, Lwów. Warszawa: E. Wende i Spółka. http://mbc.malopolska.pl/dlibra/docmetadata?id=83985&from=publication

Chrobak, L. (1925). Kilka spostrzeżeń poczynionych w grocie lodowej w Kamiennem. *Wierchy, 3*, 215-216.

Colucci, R. R., & Guglielmin, M. (2019). Climate change and rapid ice melt: Suggestions from abrupt permafrost degradation and ice melting in an alpine ice cave. *Progress in Physical Geography: Earth and Environment*, *43*(4), 561-573. https://doi.org/10.1177/0309133319846056

Czerny, F. (1884). *O jaskiniach lodowych*. Kraków: s.n.

Dąbrowski, T. (1967). Podziemne przepływy krasowe potoków w Tatrach Zachodnich. *Acta Geologica Polonica,* 17, 593-622.

Dąbrowski, T., & Rudnicki, J. (1964). Obserwacje nad warunkami hydrogeologicznymi krasu w obrębie serii Kominów Tylkowych i Czerwonych Wierchów. *Seminarium Speleologiczne I Ogólnopolskiego Zjazdu Badaczy Krasu, Św. Katarzyna, 29.05.-1.06.1963* (pp. 21-35).

Duliński, M. (2009). Sprawozdanie z badań składu izotopowego oraz stężenia trytu w 3 próbach lodu z Jaskini Lodowej w Ciemniaku. In A. Szynkiewicz,& S. Solarczyk (Eds.) *Badania lodu w Jaskini Lodowej w Ciemniaku (Tatry Zachodnie) 2007-2009 r.* (pp. 48-56). Archives of the Tatra National Park.

Eljasz-Radzikowski, W. (1896). *Ilustrowany przewodnik do Tatr, Pienin i Szczawnic*. Wydanie 5 przerobione i uzupełnione, Kraków: Nakładem J. K. Żupańskiego.

Gadomski, A. (1923). Grota lodowa w Tatrach. *Wiadomości*, *1*(8), 141.

Gadomski, A. (1924). Nowe groty lodowe w Tatrach. *Orli Lot*, *5*(1), 12-16.

Gadomski, A. (1925a). Przyczynki do poznania grot lodowych w Tatrach. *Wierchy*, *3*, 216-218.

Gadomski, A. (1925b). Lodowce i wieczne śniegi tatrzańskie. *Przyrodnik,* 4, 164-177.

Gadomski, A. (1925c). Kronika. *Wierchy, 3*, 252-253.

Gadomski, A. (1926a). Groty lodowe w Tatrach. In A. Gadomski (Ed.), *Morfologia glacjalna północnych stoków Wysokich Tatr* (pp. 137-142). Książnica Cieszyńska.

Gadomski, A. (1926b). Na lodowcu tatrzańskim (Wrażenia i spostrzeżenia z lata 1925). *Wierchy*, 31-37

Gadomski, A. (1927). Labirynt podziemny Czerwonych Wierchów z Tatrach. *Tygodniowy Kurjer Podhalański*, *22*, 1-8.

Gaweł, A. (1949). Śnieg i lód. *Wszechświat*, *1*(1784), 1-6.

Gäggeler, H. W, Tobler, L., Schwikowski, M.,& Jenk, T. M. (2020). Application of the radionuclide ^{210}Pb in glaciology – an overview. *Journal of Glaciology*, *66*(257), 447-456. https://doi.org/10.1017/jog.2020.19

Gradziński, R. (1953). Montaż masztu w Jaskini Lodowej. *Grotołaz,* 6.

Gradziński, M., Nowak, J., Rachlewicz, G., Siarzewki, W., Strug, K., & Szczuciński, W. (2018). Ice Caves in Poland. In A. Perşoiu, & S. E. Lauritzen (Eds.) *Ice caves* (pp. 493-510). Elsevier. https://doi.org/10.1016/B978-0-12-811739-2.00024-3

Gradziński, R., & Wójcik, Z. (1961). Szata naciekowa jaskiń polskich. *Ochrona Przyrody,* 27, 213-238.

Goetel, W. (1923). *Projekt budowy nowej ścieżki od Dol. Kościeliskiej do Groty Lodowej w Czerwonych Wierchach, ubezpieczenie i zabezpieczenie tej groty w 1923 r*. Typescript, Tatra Museum – Archival Collections, sygn. AR_NO_286_2_33.

Goetel, W. (1925). Przyczynki do poznania grot lodowych w Tatrach. I. W sprawie powstania Groty Lodowej w Kamiennem. *Wierchy, 3*, 214-215.

Hercman, H., Gąsiorowski, M., Gradziński, M., & Kicińska, D. (2010). The first dating of cave ice from the Tatra Mountains, Poland and its implication to paleoclimate reconstructions. *Geochronometria,* 36, 31-38. https://doi.org/10.2478/v10003-010-0016-2

Hess, M. T. (1996). Climate. In Z. Mirek, Z. Głowaciński, K. Klimek, H. Piękoś-Mirkowa (Eds.), *Przyroda Tatrzańskiego Parku Narodowego* (pp. 53-69). Zakopane: Tatrzański Park Narodowy.

Holmlund, P., Onac, B. P., Hansson, M., Holmgren, K., Mörth, M., Nyman, M., & Persoiu, A. (2005). Assessing the palaeoclimate potential of cave glaciers: The example of the Scărişoara Ice Cave (Romania). *Geografiska Annaler: Series A, Physical Geograph*y, *87*(1), 193-201. https://doi.org/10.1111/j.0435-3676.2005.00252.x

Iwanejko, O. (1991). Lodowa w Ciemniaku. *Eksplorancik, 1*(17), 9-10.

Jaskinie Polski.(2023). Państwowy Instytut Geologiczny. Państwowy Instytut Badawczy. http://jaskiniepolski.pgi.gov.pl/

Jaworowski, Z. (1966). Temporal and geographical distribution of radium D (lead-210). *Nature,* 212, 886-889. https://doi.org/10.1038/212886a0

Jaworowski, Z. (1968). Stable lead in fossil ice and bones. *Nature, 217*, 152-153. https://doi.org/10.1038/217152a0

Jaworowski, Z. (1982). *Influence of industry on pollution of the environment and human population with natural radionuclides and havy metals*. Report No. CIOR-116/D. https://inis.iaea.org/collection/NCLCollectionStore/_Public/18/018/18018439.pdf

Kepel, A. (1995). Nietoperze zimujące w jaskiniach tatrzańskich – wyniki spisów przeprowadzonych w sezonach 1992/93, 93/94, 94/95. *Przegląd Przyrodniczy*, 6(2), 75-80.

Kern, Z., Palcsu, L., Pavuza, R., & Molnár, M. (2018). Age estimates on the deposition of the cave ice block in the Saarhalle Dachstein-Mammoth Cave (Mammuthöhle, Austria) based on 3H and 14C. *Radiocarbon*, *60*, 1379-1389. https://doi.org/10.1017/RDC.2018.96.

Kern, Z., & Perşoiu, A. (2013). Cave ice – the imminent loss of untapped mid-latitude cryospheric palaeoenvironmental archives. *Quaternary Science Reviews, 67*, 1-7. https://doi.org/10.1016/j.quascirev.2013.01.008

Kędzia, D. (1991). *Formy lodowe w jaskiniach tatrzańskich i ich właściwości fizyko-chemiczne*. Archive of the Faculty of Geographic and Geological Sciences of Adam Mickiewicz University.

Koide, M., Soutar, A. & Goldberg, E. D. (1972). Marine geochronology with ^{210}Pb. *Earth and Planetary Science Letters, 14*, 442–446. https://doi.org/10.1016/0012-821X(72)90146-X

Koisar, B., & Parma, Ch. (1971). Lodowe jaskinie w Tatrach. *Taternik,* 47, 68-71.

Kotański, Z. (1959). Profile stratygraficzne serii wierchowej Tatr Polskich. *Biuletyn Instytutu Geologicznego*, *139*, 1-160.

Kowalski, K. (1951). Badania fauny jaskiń tatrzańskich. *Wierchy, 20*, 235.

Kowalski, K. (1953a). Kto odkrył Jaskinię Lodową w Ciemniaku. *Grotołaz, 11*, 18-20.

Kowalski, K. (1953b). *Jaskinie Polski. T. 2. Jaskinie Tatr Polskich*. Warszawa: Państwowe Muzeum Archeologiczne.

Kowalski, K. (1955). Fauna jaskiń Tatr Polskich. *Ochrona Przyrody, 23*, 283-333.

Kowalski, K. (1965). *Jaskinie Polskie*. Warszawa: Wiedza Powszechna.

Kowalski, M., & Ostrach, A. (1994). Kronika naukowa. VII Ogólnopolska Konferencja Chiropterologiczna Poznań, 23-24 października 1993 roku. *Kosmos*, *43*(2), 317-324.

Kreutz, S. (1925). Kronika. Badania naukowe. Prace Zakładu Mineralogicznego Uniwersytetu Jagiellońskiego. *Wierchy*, 255-258.

Kronika Sekcji Speleologicznej. (1979-1998). Kronika Sekcji Speleologicznej Studenckiego Koła Naukowego Geografów, Uniwersytet im. Adama Mickiewicza w Poznaniu.

Kwaśniewski, K. (1924). Badania Groty Lodowej. *Głos Zakopiański, 2*(18), 2.

Lefeld, J., Gaździcki, A., Iwanow, A., Krajewski, K., & Wójcik, K. (1985). Jurassic and Cretaceous lithostratigraphic units of the Tatra Mountains. *Studia Geologica Polonica, 84*, 1-93.

Leunda, M., González-Sampériz, P., Gil-Romera, G., Bartolomé, M., Belmonte-Ribas, Á., Gómez-García, D., & Sancho, C. (2019). Ice cave reveals environmental forcing of long-term Pyrenean tree line dynamics. *Journal of Ecology*, *107*(2), 814-828. https://doi.org/10.1111/1365-2745.13077

Lewkowicz, Ł. (2014). Działalność speleologiczna Jana Gwalberta Pawlikowskiego. In: P. Dąbrowski, P., B. Zawilińska (Eds), *Jan Gwalbert Pawlikowski. Humanistyczna wizja ochrony przyrody i turystyki* (pp. 309-328). Kraków.

Liberak, A. (1950). Wśród dziwów i tajników Tatr. *Echo Krakowskie,* 04.12.1950, *4*.

Łupikasza, E., & Szypuła, B. (2011). Vertical climatic belts in the Tatra Mountains in the light of current climate change. *Theoretical and Applied Climatology, 136*, 249-264. https://doi.org/10.1007/s00704-018-2489-2

Mavlyudov, B. R. (2018). Ice genesis and types of ice caves. In A. Perşoiu, S-E. Lauritzen (Eds.), *Ice caves* (pp. 34-68). Elsevier. https://doi.org/10.1016/B978-0-12-811739-2.00032-2

May, B., Spötl, C., Wagenbach, D., Dublyansky, Y., & Liebl, J. (2011). First investigations of an ice core from Eisriesenwelt cave (Austria). *The Cryosphere*, *5*(1), 81-93. https://doi.org/10.5194/tc-5-81-2011

Nowosad, A., Jagielska, A., & Strzelczyk, J. (1992). Szczątki kostne nietoperzy i kuny z Jaskini Lodowej w Ciemniaku [Tatry Zachodnie]. *Przegląd Zoologiczny, 36*, 199-205.

Ossowski, G. (1883). Czwarte sprawozdanie z badań antropologiczno-archeologicznych w jaskiniach okolic Krakowa dokonanych w 1882 r. oraz rozpoznanie przygotowawcze do badań jaskiń tatrzańskich. *Zbiór Wiadomości do Antropologii Krajowej*, 7, 66-88.

Palińska, Z. (2022). *Lód w Jaskini Lodowej w Ciemniaku – ewolucja i stan wobec zmian klimatycznych*. Master's thesis, Archives of the Institute of Geoecology and Geoinformation of the University of Adam Mickiewicz.

Pawlikowski, J. G. (1887). Podziemne Kościelisko. *Pamiętnik Towarzystwa Tatrzańskiego, 11*, 33-48.

Pawlikowski, J. G. (1923). *Opinia o projekcie Komisji dla robót w Tatrach, dotyczącym udostępnienia Groty Lodowej w Ciemniaku*. Muzeum Tatrzańskie – Zbiory Archiwalne, sygn. AR_NO_265_098, Lwów 18.04.1923.

Perşoiu, A., Onac, B. P., Wynn, J. G., Blaauw, M., Ionita, M., & Hansson, M. (2017). Holocene winter climate variability in Central and Eastern Europe. *Scientific Reports*, 7, 1196. https://doi.org/10.1038/s41598-017-01397-w

Piksa, K. (1998). The chiropterofauna of the Polish Tatra Mts. *Vespertilio*, *3*, 93-100.

Piksa, K., & Nowak, J. (2002). Noteworthy records of northern bat *Eptesicus nilssonii* (Chiroptera: Vespertilionidae) in the Tatra Mountains. *Acta Zoologica Cracoviensia, 45*, 321-324.

Piksa, K., Skwarek, M., & Siuda, K. (2011). Argasid and spinturnicid mite load on swarming bats in the Tatra mountains. Poland. *Folia Parasitologica, 58*(4), 322-325.

Pogoda i klimat. (2023). https://meteomodel.pl/

Pulinowa, M. Z., & Pulina, M. (1972). Phénomènes cryogènes dans les grottes et gouffres des Tatras. *Biuletyn Peryglacjalny,* 7, 207-235.

Rachlewicz, G. (1996). Dwa razy „Lodowa". *Pamiętnik Polskiego Towarzystwa Tatrzańskiego*, 227-235.

Rachlewicz, G., & Szczuciński, W. (2004). Seasonal, annual and decadal ice mass balance changes in the ice cave Jaskinia Lodowa w Ciemniaku, the Tatra Mountains, Poland. *Theoretical and Applied Karstology, 17*, 11-18.

Racine, T. M., Reimer, P. J., & Spötl, C. (2022). Multi-centennial mass balance of perennial ice deposits in Alpine caves mirrors the evolution of glaciers during the Late Holocene. *Scientific Reports*, *12*(1), 11374. https://doi.org/10.1038/s41598-022-15516-9

Rygielski, W.,& Siarzewski, W. (1996). Pokrywa lodowa Jaskini Lodowej w Ciemniaku w Tatrach Zachodnich. *Dokumentacja Geograficzna, 4*, 57-70.

Rygielski, W., & Wieliczko, P. (1988). Pomiary geodezyjne i dynamika lodu w Jaskini Lodowej w Ciemniaku. *Sprawozdania Polskiego Towarzystwa Przyjaciół Nauk o Ziemi,* 163-166.

Rygielski, W., Siarzewski, W., & Wieliczko, P. (1990). *Zmienność pokrywy lodowej oraz reżim termiczno--cyrkulacyjny jaskini Lodowej w Ciemniaki, Tatry Zachodnie*. Archive of the Faculty of Geographic and Geological Sciences of Adam Mickiewicz University.

Rygielski, W., Siarzewski, W., & Wieliczko, P. (1995). Variability of the ice deposits in Ice Cave on Mount Ciemniak in the West Tatra Mountains. *Questiones Geographicae, 17*(18), 55-64.

Rygielski, W., Siarzewski, W., Volker, R., Wieliczko, P. (1988). Badania glacjologiczne i geologiczne w Jaskini Lodowej w Ciemniaku. *Sprawozdania Polskiego Towarzystwa Przyjaciół Nauk o Ziemi*, *105*, 43-46.

Siarzewski, W. (1994a). Jaskinia Lodowa w Ciemniaku. In J. Grodzicki (Ed.), *Jaskinie Tatrzańskiego Parku Narodowego, Tom 5. Jaskinie Wąwozu Kraków* (pp. 142-153). Warszawa, Zakopane: Polskie Towarzystwo Przyjaciół Nauk o Ziemi, Tatrzański Park Narodowy.

Siarzewski, W. (1994b). Jaskinie Lodowe w Tatrach. In J. Grodzicki (Ed.), *Jaskinie Tatrzańskiego Parku Narodowego, Tom 5. Jaskinie Wąwozu Kraków* (pp. 11-47). Warszawa, Zakopane: Polskie Towarzystwo Przyjaciół Nauk o Ziemi, Tatrzański Park Narodowy.

Siarzewski, W. (1996). Ice caves in the Polish Tatra Mountains. In A. Kotarba (Ed.), *Przyroda Tatrzańskiego Parku Narodowego a człowiek. Tom I. Nauki o Ziemi* (pp. 98-101). Zakopane: Tatrzański Park Narodowy.

Siarzewski, W. (1996b). Warunki mikroklimatyczne jaskiń tatrzańskich. In J. Grodzicki (Ed.), *Jaskinie Tatrzańskiego Parku Narodowego, Tom 6. Jaskinie zachodniego zbocza Doliny Miętusiej* (pp. 13-29). Warszawa: Polskie Towarzystwo Przyjaciół Nauk o Ziemi, Tatrzański Park Narodowy.

Siuda, K., Stanko, M., Piksa, K., & Górz, A. (2009). Ticks (Acari: Ixodida) parasitizing bats in Poland and Slovakia. *Wiadomości Parazytologiczne, 55*(1), 39-45.

Sokołowski, M. (1930). O film ochroniarski. *Wszechświat, 10*(1684), 322-324.

Strug, K. (2011). Klimatyczne uwarunkowania rozwoju zjawisk lodowych w jaskiniach o odmiennych cechach środowiska. *Rozprawy Naukowe Instytutu Geografii i Rozwoju Regionalnego Uniwersytetu Wrocławskiego*, *18*, *Wrocław 2011, 1-163.*

Szukała, P. (2010). Zmiany bilansu masy lodu w Jaskini Lodowej w Ciemniaku (Tatry Zachodnie, Polska) z zastosowaniem technik trójwymiarowego modelowania jaskiń. In *Nauka a zarządzanie obszarem Tatr i ich otoczeniem,* tom I (pp. 145-149). Tatrzański Park Narodowy, Zakopane.

Szynkiewicz, A., Solarczyk, S. (2009). *Badania lodu w Jaskini Lodowej w Ciemniaku (Tatry Zachodnie) 2007-2009 r.* Archives of the Tatra National Park.

Ślusarczyk, J. M. (2004). Badania speleologiczne w materiałach i pracach Towarzystwa Tatrzańskiego i Polskiego Towarzystwa Tatrzańskiego. *Pamiętnik Polskiego Towarzystwa Tatrzańskiego.*

Ślusarczyk, J. M. (2008*). Problematyka naukowa i ochrona przyrody w działalności Polskiego Towarzystwa Tatrzańskiego w latach 1873-1950.* Podhalańska Państwowa Wyższa Szkoła Zawodowa w Nowym Targu.

UNSCEAR, (2000). UNSCEAR 2000 Report, Sources and Effects of Ionizing Radiation, vol. I: Sources.

Wiadomości Geograficzne. (1924). Sprawy Krakowskiego Oddziału Polskiego Towarzystwa Geograficznego.

Wind, M., Obleitner, F., Racine, T., & Spötl, C. (2022). Multi-annual temperature evolution and implications for cave ice development in a sag-type ice cave in the Austrian Alps. *The Cryosphere*, *16*(8), 3163-3179. https://doi.org/10.5194/tc-16-3163-2022

Wiśniewski, W. (1991). Przez Lodową w Ciemniaku we wnętrze masywu? *Taterniczek*, 39, 40.

Wójcik, S. (1962). Jaskinie lodowe w Tatrach Polskich. *Wierchy,* 30, 227-233.

Wójcik, Z. (1968). Rozwój geomorfologiczny wapiennych obszarów Tatr i innych masywów krasowych Karpat Zachodnich. *Prace Muzeum Ziemi, 13*, 3-169.

Wójcik, Z. (1969). Wąwóz Kraków w Tatrach. *Ochrona Przyrody, 34*, 227-253.

Wójcik, Z. (1973). Walery Goetel 1889-1972. *Kwartalnik Historii Nauki i Techniki, 18*(2), 347-354.

Wójcik, Z. (1997). O Alfredzie Lityńskim i jego badaniach przyrodniczych w Tatrach. *Rocznik Podhalański, 7*, 263-268.

Wrzosek, A. (1933). Z badań nad zjawiskami krasowymi Tatr Polskich. *Wiadomości Służby Geograficznej, 7*, 235-273.

Zwoliński, T. (1923). Nieznane groty Doliny Kościeliskiej. *Wierchy, 1*, 26-43.

Zwoliński, T. (1924). Z podziemi tatrzańskich. I. Badanie grot w Tatrach polskich w r. 1923. *Wierchy, 2*, 47-54.

Zwoliński, T. (1925). *Tatry Polskie: mapa środkowej części Tatr*. Zakład Kartograficzny G. Freytaga i Berndta, Wiedeń.

Zwoliński, S. (1933). Z podziemnego świata Tatr. *Wierchy, 11*, 205-208.

Zwoliński, S. (1951). Grota lodowa w Tatrach. *Zabytki Przyrody Nieożywionej, 1*(4), 19-23.

Zwoliński, S. (1953). Jaskinie lodowe. *Wszechświat, 54*, 55-61.

Zwoliński, S. (1955). Tatrzański rejon krasowy. *Światowid, 2-3*, 55-61.

Zwoliński, S. (1961). *W podziemiach tatrzańskich*. Warszawa: Wydawnictwa Geologiczne.

Article first received • May 2023
Article accepted • November 2023