GLACIOLÓGIA A SPELEOKLIMATOLÓGIA

QUANTITATIVE CHARACTER OF THE BOTTOM ICE IN THE DEMÄNOVSKÁ ICE CAVE (SLOVAKIA)

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Abstract: This paper presents the latest results of the bottom ice measurements in the Demänovská Ice Cave (The Low Tatra Mts, Slovakia). In May 2005, authors carried out precise measurements thickness of the bottom ice, and two months later leveled its surface. Based on the results of this examinations and by using the method of interpolation: kriging and tools from 'SURFER 8 software' the complete volume and area of the bottom ice was calculated. Conducted measurements will allow in the future for permanent observation of the changes of bottom ice volume in the cave.

Key words: Demänovská Ice Cave**,** bottom ice, volume of bottom ice

INTRODUCTION

The Demänovská Ice Cave (Fig. 1) is the second among 66 ice caves in Slovakia with regard to its ice volume. However, it is in further place when compared to the ice caves in Europe (Tab. 1).

Bottom ice constitutes the base of the ice filling in the Demänovská Ice Cave. A. Droppa (1957a) calls the bottom ice 'stable autochthonous sediment'. According to the definitions included in the literature, the bottom ice (ice filling, ice block, ice monolith) is durable, perennial, compact, thick ice mass lying on a large surface area, which fills the bottoms of the cave chambers and corridors in part or in full. It forms from freezing water (hydrogenic genesis), which gets into the frozen interior of the cave through crevices or entrance openings (V. Panoš, 2001; A. Droppa, 1957a; J. Kunský, 1956; G. Racoviţă – B. P. Onac, 2000; W. Siarzewski, 1994). The most typical features of this sediment are the following: changes of the ice mass volume within a year, a layer structure (yearly ice layers are separated by mineral and organic particles), transparency or milky colour caused by a different value of specific heat of ice and rock and their separation by empty space (which does not occur everywhere) (V. Panoš, 2001; A. Droppa, 1957a; J. Knap, 2000; J. Kunský, 1956; W. Rygielski – W. Siarzewski, 1996).

Only a few pieces of information on the ice monolith volume and surface area in the cave have been found in the source materials. No data can be obtained related to the period from the first exploration of the cave performed by J. Buchholtz in 1719 to its research started by A. Droppa (1957a, 1972) in 1952. A. Droppa (1957a) was the first to estimate the volume, surface area and age of the bottom ice. According to his estimation, the ice volume amounted to approximately 880 m^3; the surface area – approx. 440 m^2, an average thickness

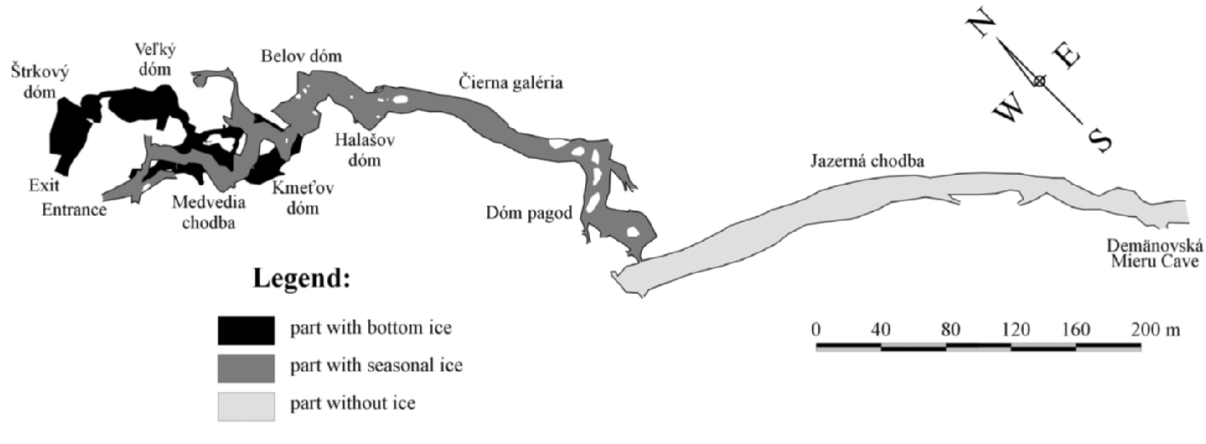

Fig. 1. Demänovská Ice Cave

Table 1. Ice caves in Europe

Ice cave	Volume of bottom ice [m³]	Area of bottom ice [m²]	Maximum depth of bottom ice [m]	Country
Eisriesenwelt (G. Abel, 1971,[1,4])	200,000*	30,000	26.0	Austria
Dobšinská Ice Cave (J. Tulis – L. Novotný, 1995)	110,132	9,772	26.5	Slovakia
Scărişoara Ice Cave (G. Racoviță – B. P. Onac, 2000)	75,000	3,000	22.5	Romania
Borțig Ice Cave (G. Racoviță – B. P. Onac, 2000)	30,000	–	–	Romania
Dachstein-Rieseneishöhle[3]	30,000*	5,000*	25.0*	Austria
Ledena jama v Stojni (F. Habe, 1971)	25,000*	–	–	Slovenia
Focul Viu Ice Cave (G. Racoviță – B. P. Onac, 2000)	24,900	–	–	Romania
Monlesi Ice Cave[2]	10,000*	–	–	Switzerland
Veľká ľadová jaskyňa v Paradane (F. Habe, 1971)	4,000*	–	–	Slovenia
Glacière de Pré de Saint Livres[2]	3,500*	–	–	Switzerland
Grotta del Castelletto di Mezzo (M. Ischia – A. Borsato, 2004)	3,000[a]*	–	–	Italy
Creux Bastian[2]	2,500*	–	–	Switzerland
Glacière de Saint George[2]	2,300*	–	–	Switzerland
Jaskinia Lodowa w Ciemniaku (W. Rygielski – W. Siarzewski, 1996; W. Siarzewski, 1994)	1,500*	–	5.0	Poland
Demänovská Ice Cave (A. Droppa, 1957a)	880*	440*	2.0*	Slovakia
Ľadová priepasť na Ohništi (Z. Hochmuth, 1995)	525*	–	–	Slovakia
Kungur Ice Cave (V. Andrejchuk, 1995)	350	500	–	Russia
Silická ľadnica (L. Rajman – Š. Roda – Š. Roda ml. – J. Ščuka, 1987)	340	–	–	Slovakia
Ľadová priepasť v Červených vrchoch (Z. Hochmuth, 1995)	200*	–	–	Slovakia
Barsa Ice Cave (G. Racoviță – B. P. Onac, 2000)	133	–	–	Romania

[1] http://www.eisriesenwelt.at
[2] http://www.lochstein.de/hoehlen/Ch/monlesi/monlesi.html
[3] http://www.mamilade.at/dachstein/rieseneishoehle/1006620-rieseneishoehle.html
[4] http://www.sat.dundee.adc.uk/marb/gsb/news/119.html
* estimated volume

– approx. 2 m, and the ice age – approx. 400 – 500 years. A. Droppa carried out his measurements and observations at the time when changes in the cave environment (including those related to the cave morphology) connected with a discovery of the Demänovská Cave of Peace (the years 1950 – 1952) took place. As a result of those changes, the ice filling of the cave underwent considerable degradation (V. Benický, 1957; A. Boček, 1954; A. Droppa, 1957a; J. Otruba, 1957, 1971; J. Halaš, 1984). According to J. Otruba (1957, 1971) and A. Droppa, there was more ice in the cave before 1950 ('an area of permanent ice was moved further to the south than now'). The above-mentioned information is too general to serve as the basis for the assessment of a size of the bottom ice in the cave at that time. Between the years 1957 and 2005, no exact data related to the surface area and volume of the ice in the cave have been published, either. J. Halaš (1983, 1984) and

J. Otruba (1957, 1971), the main explorers of the cave, focused on the description of the atmospheric and lithological environment of the cave as well as the conditions of its ice formation. In the years 1970 – 1982, J. Halaš (1984) performed the estimation of the size of the ice filling in the cave. However, he did not present any exact data in the studies available to the authors, and he only described an extent of the ice formation in the cave with the use of the terms ‘lots’ and ‘little’.

Due to the unique character of the ice filling of the cave and its sensitivity to all changes which occur in its environment, including those resulting from making the cave available to tourists – approximately 100 000 tourists per year (Ľ. Nudzíková, 1997 – 2004; Ľ. Nudzíková – Ľ. Gaál, 2005), the quantitative description of the ice monolith is indispensable and crucial. This necessity is confirmed by the fact that 50 years later, since the moment of the considerable ice degradation in the cave, its ice filling size has not returned to the volume observed before 1950 (J. Otruba, 1957, 1971). For that reason, among other things, the research work that is carried out at the moment aims at the determination of changes to the volume and limit of the ice monolith with a maximum of accuracy possible to be reached. In the future, it will also provide further information on functioning of the climatic and ice environment of the Demänovská Ice Cave.

RESEARCH METHODOLOGY

The research, which served for the calculation of a cubature of the ice filling in the cave, started in March 2005. Due to the cost and size of the ice monolith, a georadar was not used. The georadar had been used before by other researchers to carry out measurements of the ice thickness in the Dobšinská Ice Cave (J. Géczy – Ľ. Kucharič, 1995). After the other measurement methods were identified, the decision was finally taken to make bore-holes in the ice. On 15 March 2005 scout boring was performed a few times, in order to assesses the equipment performance, a quality of the results obtained and to estimate the time needed for the realisation of the whole task. The tests resulted in the improvement of the equipment and the drilling method. The proper drilling was performed on 21 and 22 May 2005 (Photo 1). For the drilling, a drilling machine with a power of 1,100 Watt and a folded drill with a joint length of 5.12 m were used. The drill consisted of 4 threaded rods, each with a length of 1.22 m and a hardened drill intended for wood with a length of 0.24 m. Total 82 bore-holes were performed (Fig. 2), with a joint length of 68 m. Each drilling was carried out in stages for the reason of the necessary cleaning of the drill. The drilling was carried out until the rocky floor of the chamber was reached. A depth of a bore-hole (the ice thickness) was read from a calibrated drill. A measuring error did not exceed 0.5 cm. The proper drilling was performed at the time when the volume of the ice monolith in the cave happened to be the greatest (the authors have been conducting the observation of the ice in the cave for two years).

Two months later (i.e. on 27 July 2005), levelling of the bottom ice surface was performed with the use of a water-level 20 m long and a levelling staff with a height of 2.9 m. The levelling was started from a selected point in the Štrkový dóm chamber (level ’0’ of a relative height). In relation to the selected point, levelling in 91 points was performed (Fig. 2). A maximum measuring error did not exceed 5 cm.

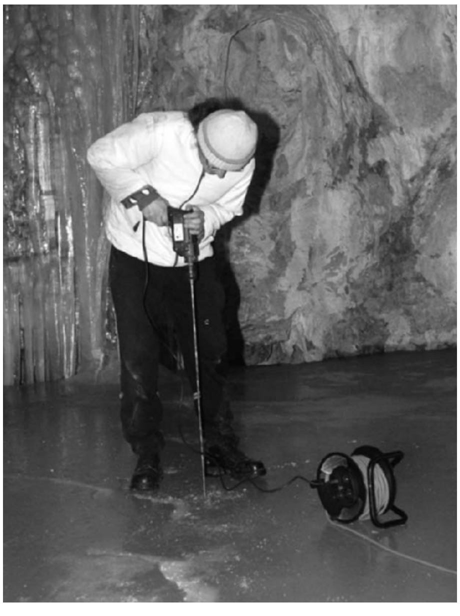

Photo 1. Demänovská Ice Cave – drilling in the Kmeťov dóm (21. 5. 2005). Photo: T. Sawiński

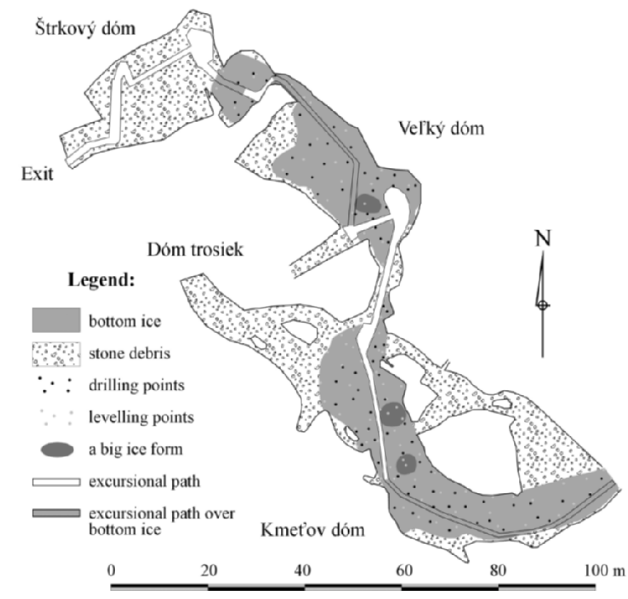

Fig. 2. Demänovská Ice Cave – location of drilling (21. – 22. 5. 2005) and levelling (27. 7. 2005) points

The drilling and measurement results obtained were subject to elaboration with the use of the data spatial interpolation method. Within a wide range of the stochastic and deterministic methods, an accurate interpolator (which returned a value measured in a given point) was looked for and which was not characterised by a tendency to generate the "bull's eye" effects. Finally, the ordinary point *kriging* method was chosen, which has been often applied in the geographical and geological sciences (N. A. C. Cressie, 1991). This algorithm is an accurate interpolator and it allows to approximate concentrations of the thicker ice (the dome) with the use of the nugget effect. *Kriging* is a geostatistical method based on the assumption that the points located closer to each other are more similar to each other than the ones located further (G. Matheron, 1963). The same method was applied to estimate hypsometry of the ice monolith surface area.

Using of the possibilities of the *kriging* method and the tools possessed by a 'SURFER 8 software', the total volume and surface area of the ice monolith in the cave were calculated.

RESULTS

The bottom ice permanently covers the floor of the following three chambers (Fig. 2, 3, 4 and 5) in the Demänovská Ice Cave: Kmeťov dóm, Veľký dóm and Štrkový dóm (the eastern part). During the research conducted by J. Halaš (1984) as well as by A. Droppa (1957a) and J. Otruba (1957, 1971) before, the permanent occurrence of the ice was observed in the Kmeťov dóm and Veľký dóm chambers, and a seasonal occurence (of the ice forms) was observed in the following chambers and corridors: Štrkový dóm, Medvedia chodba, Čierna galéria, Belov dóm, Halašov dóm, Dóm pagod as well as at the entrance to the cave (Figure 1). At present, the bottom ice streches out for approximately 150 metres, however, it does not form a continuous ice cover (Fig. 3, 4 and 5).

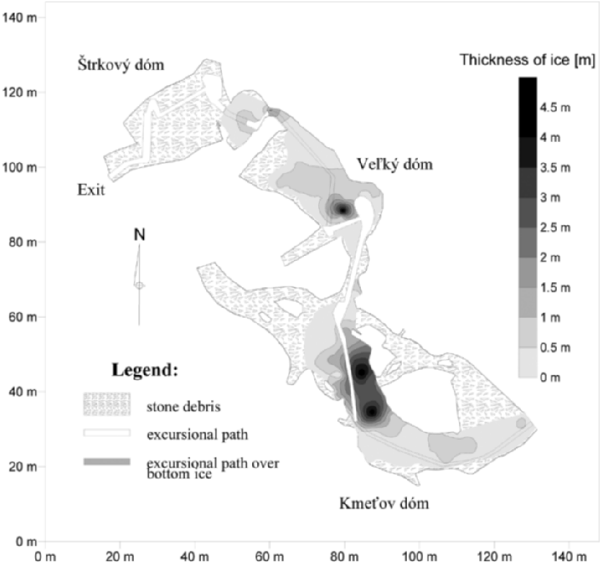

Fig. 3. Demänovská Ice Cave – thickness of bottom ice (21. – 22. 5. 2005)

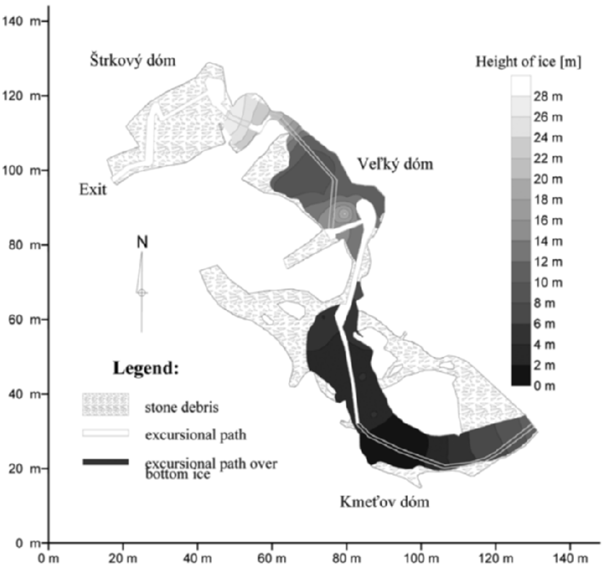

Fig. 4. Demänovská Ice Cave – hypsometry of bottom ice surface (27. 7. 2005)

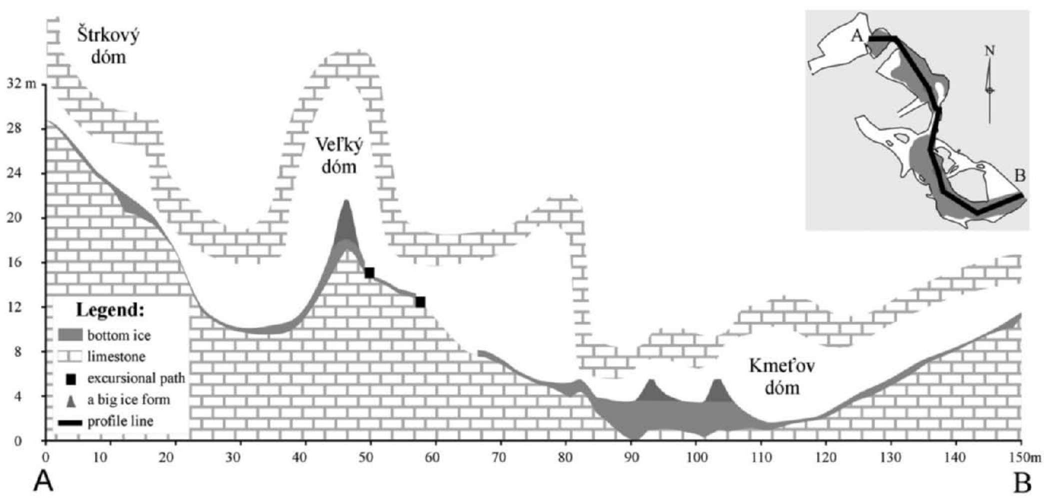

Fig. 5. Demänovská Ice Cave – cross section (27. 7. 2005)

Two stalagnates (ice columns) (Photo 2) and one stalagmite, as perennial forms, form an integral whole with the bottom ice. They have been included in all calculations and properly indicated on the attached maps (Fig. 2 and 5). On the basis of the observations related to alternations of their shapes, it was noticed that this part of the ice columns which was preserved after the ablation period it raised at a height of approximately 1.5 m over the bottom ice surface. It formed a dome-shaped form created from the place from which the freezing water spread. In spite of the loss of ice in the ablation period, the stalagmite preserved its height of approximately 3 m. Drilling was carried out in the direct surroundings of these forms. It was assumed for the purpose of the calculations that (approximate) ice thickness at the place where the above-mentioned forms occurred is a sum of the thickness of ice under the form and a height of the form.

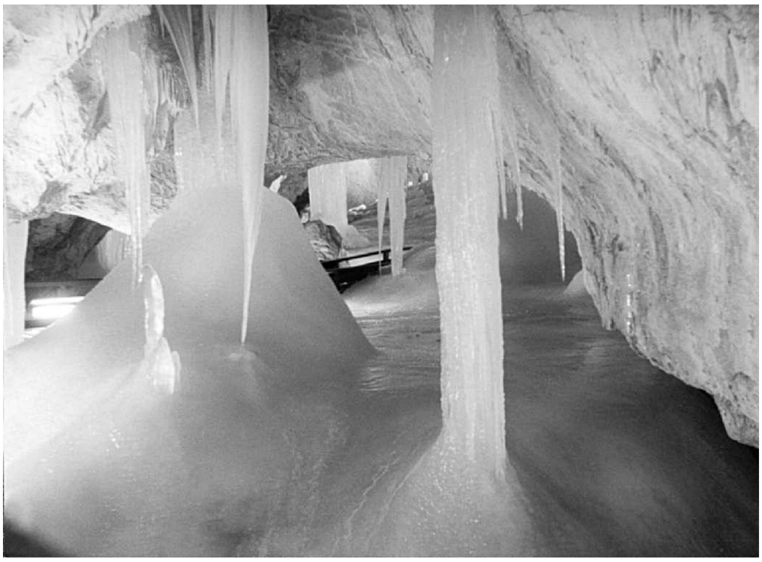
Photo 2. Demänovská Ice Cave – bottom ice in the Kmeťov dóm. Foreground (on the left): 1 from 2 ice coloumns. Photo: T. Sawiński

During every evaluation and calculation of the variability of the ice formation in the cave, the results of all those activities must be taken into account that have been taken up by the user in order to preserve the ice. They have been applied since the time of the sudden loss of ice caused by the above-mentioned changes to the morphology of the cave. In order to stop further the degradation of the ice, the Demänovská Ice Cave was separated from the warmer Demänovská Cave of Peace, and the frozen Kmeťov dóm chamber from the warmer Dóm trosiek chamber, respectively. During the freezing weather, an old entrance to the cave is opened in order to support its cooling. The chambers covered with ice are supplied with water (apart from natural dripping) by means of a network of sprinklers. Snow is also brought into the cave in order to seal the crevices through which warm air enters. The above-mentioned activities are crucial for the present limit and morphology of the ice monolith surface.

Most of the accumulated ice occurs in the Kmeťov dóm chamber (Fig. 3, 4 and 5; Photo 2), which has the bast conditions for its formation. The chamber has a shape of a caving (Fig. 5) in which cold air accumulates flowing down into the cave interior thanks to gravitation (A. Droppa, 1957a; J. Halaš, 1984; J. Otruba, 1957). At the time when the drilling was carried out, the bottom ice covered a surface area of 840 m^2, and its volume amounted to 727 m^3, which constituted 70 % of the total volume and 60 % of the ice monolith surface area, respectively. The average thickness of ice here amounted to 0.87 m. For a section of approximately 20 m, in central and northern parts of the Kmeťov dóm chamber, the bottom ice creates a thick concentration with an ice depth of over 2 m (Fig. 5). Within a relatively small surface area of this place, over half of the total mass of the monolith is accumulated here (Tab. 2). In the remaining part of the chamber, i.e. within 74 % of its surface area covered with ice, a layer of ice with a depth up to 1 m and a volume of merely 31 % of the whole ice mass occurs. In case of unpredictable warming caused by the natural or anthropogenetic factors, the main core of the ice mass has a chance to remain untouched. In central and northern part of the room, a channel 26 m long was cut out in the past in which a tourist route was routed (J. Knap, 2000). The volume of the ice cut out was estimated for approximately 30 – 40 m^3.

Table 2. Demänovská Ice Cave – volume and area of bottom ice (21. – 22. 5. 2005)

Thickness of ice [m]	Volume [%]	Area [%]	Volume [%]	Area [%]
> 1	69	26	17	9
> 2	54	16	11	3
> 3	22	5	4	0,6
Chamber	Kmeťov dóm		Veľký dóm and Štrkový dóm	

The remaining part of the bottom ice occurred in the Veľký dóm and Štrkový dóm chambers (Fig. 3, 4 and 5). They are the rooms through which cool air flows towards the Kmeťov dóm chamber. The size and character of the flow is associated with the chamber morphology and the external weather conditions (A.

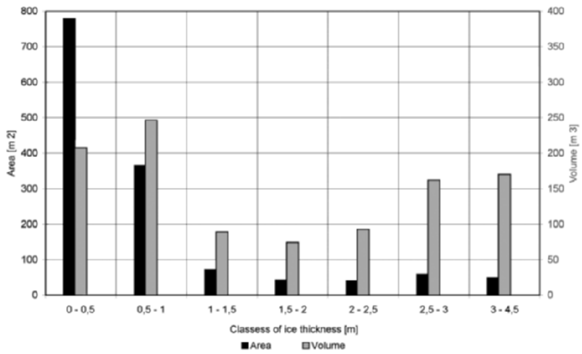

Fig. 6. Demänovská Ice Cave – area and volume of bottom ice in classes of thickness (21. – 22. 5. 2005)

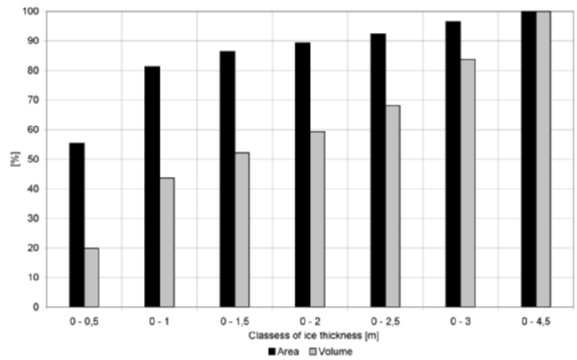

Fig. 7. Demänovská Ice Cave – cumulation area and volume of bottom ice (21. – 22. 5. 2005)

Droppa, 1957a; J. Halaš, 1984; J. Otruba, 1957, 1971). This was the main reason for which the ice in these chambers occupied a smaller surface area of 567 m^2 and it had a smaller volume of 315 m^3, and the average ice thickness amounted to 0.55 m. As much as 91 % of the surface area of these chambers was covered by a layer of ice with a depth up to z 1 m, in which 83 % of a volume of the ice that occurred in that part of the cave was accumulated (Tab. 2).

The bottom ice within the whole area of the cave occupied a surface area of 1407 m^2. Its volume amounted to 1042 m^3, and the average thickness – 0.74 m. The maximum depth of the drilling amounted to 3.03 m (Kmeťov dóm chamber), whereas the minimum depth amounted to 0.1 m. Over half of the surface area of the ice monolith in the cave was covered by a thin 0.5 m layer of ice which contained only 20 % of the total ice mass (Fig. 7). A layer of ice with a thickness over 1 m occupied only 19 % of the ice surface area, yet it contained as much as 56 % of its volume (Fig. 7). The actual and accumulated volume and surface area of the bottom ice related to the thickness classes are shown in figures (Fig. 6 and 7).

During the drilling, the layers of water with a thickness of even a few centimetres were found many times in each of three chambers. They occurred at the different depths, and their occurrence was associated with a distribution of the temperature gradient in the ice cover. Part or all of the water was likely to come from the floor ice ablation and the ice forms as well as from water infiltration in the warm season of the year. The water got into the interior of the ice monolith along the tourist route or at the junctions of ice and the rocky walls of the chambers.

At a few places located at the lowest level of the Kmeťov dóm chamber (Fig. 4 and 5), vacuum was found under the floor of the ice monolith. Its maximum height reached up to 0.4 m. The genesis of the vacuum is not known.

For two years, the authors have been carried out measurements related to the alternations of a limit of the ice monolith surface area and to the mass growth and loss on its surface. As the ice mass in the Demänovská Ice Cave is not subject to the translatory motion processes (J. Knap, 2000), the authors intend to reconstruct the status of ice formation present two years ago and to investigate its seasonal variability.

The results of the observations of the ice monolith limit carried out by the authors for two years have been compared to the information included in the studies of J. Otruba (1957, 1971). They have not proved his deliberations on the restoration of the original limit of the ice filling in the cave. One can conclude that the changes caused by interference in the morphological system of the cave were so significant that all actions undertaken later have not brought the expected effects.

SUMMARY

Bottom ice is a fundamental, unique component of an environment in the Demänovská Ice Cave, and is a valuable material for research of borderline cryology and climatology. Research conducted nowadays has to join and explain interdependences in the natural – glacial and speleoclimatic – processes with regard to human impact on cave's environment in view. Special importance was attached to precise and accurate measurements of thickness and volume of the bottom ice since it is a characteristic and most stable feature of the ice filling in the cave. To achieve it the drilling of the bottom ice and levelling of its surface was conducted. Spatial differentiation of thickness and hypsometry of bottom ice was obtained by a used method of interpolation: kriging, and tools from 'SURFER 8 software' were used for every calculations, which are confronted in tabels and on figures.

The area of the bottom ice in Demänovská Ice Cave totals to 1,407 m^2, of which the volume is 1,042 m^3, average thickness is 0.74 m, and maximum thickness is 3.03 m. More than 50 % of the area of the whole monolit of the bottom ice in the cave is occupied by a thin ice layer of 0,5 m in dimension which makes up 20 % of it's mass (Fig. 7). Bottom ice above 1 m thick, takes up only 19 % of the area and as much as 56 % of the whole ice mass.

In the Demänovská Ice Cave, bottom ice is unequally distributed, what is connected to morphology of the cave (A. Droppa, 1957a; J. Halaš, 1984; J. Otruba, 1957). The most of bottom ice occurs in Kmeťov dóm (Fig. 3, 4 and 5; Photo 2). It is made of 70 % of the whole volume and 60 % of the complete area of the ice monolith in the cave. In central and north part of Kmeťov dóm, ice monolith forms a thick concentration with thickness above 2 m. On this relatively small area, this concentration accumulates over 50 % of all mass of bottom ice (Tab. 2). The rest of the bottom ice is observe in Veľký dóm and Štrkový dóm where bottom ice 1 m thick almost completely fills both chambers (Tab. 2). Characteristics features of bottom ice monolith in the Demänovská Ice Cave are layers of water within and empty spaces in some areas under the bottom ice.

Compared with the results of research conducted systematically in the past two years, this calculations will help to investigate seasonal and yearly changes in the bottom ice's volume in the cave. They will also help to evaulate activities, undertaken in order to mantain ice feeling in the cave's environment.

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KVANTITATÍVNA CHARAKTERISTIKA PODLAHOVÉHO ĽADU V DEMÄNOVSKEJ ĽADOVEJ JASKYNI

S ú h r n

Podlahový ľad je základnou a dôležitou súčasťou prostredia Demänovskej ľadovej jaskyne. Predstavuje cenný materiál na kryologický a klimatologický výskum. Súčasný výskum sa realizuje s cieľom vysvetliť vzájomné závislosti medzi prirodzeným zaľadnením a speleoklimatickými procesmi, ako aj antropogénnymi vplyvmi na jaskynné prostredie. Zvláštny význam sa kladie na presné merania hrúbky a výpočet objemu podlahového ľadu, pretože ide o charakteristickú a najstabilnejšiu vlastnosť ľadovej výplne v jaskyni. Pre tento účel sa uskutočnilo vŕtanie podlahového ľadu a nivelizácia jeho povrchu. Priestorová diferenciácia hrúbky a hypsometria podlahového ľadu sa zistila využitím metódy interpolácie *kriging*. Pre všetky výpočty, ktoré sú uvedené v tabuľkách a grafických výstupoch, sa použili nástroje softwaru SURFER 8.

Celková plocha podlahového ľadu v Demänovskej ľadovej jaskyni je 1407 m^2, objem ľadu 1042 m^3, priemerná hrúbka ľadu 0,74 m, maximálna hrúbka ľadu 3,03 m. Viac ako 50 % plochy celého monolitu podlahového ľadu v jaskyni predstavuje vrstva hrubá 0,5 m, ktorá tvorí až 20 % jeho masy (obr. 7). Podlahový ľad hrubší viac ako 1 m, zaberá len 19 % plochy a 56 % celej ľadovej masy.

V Demänovskej ľadovej jaskyni je podlahový ľad rozložený nerovnomerne, čo súvisí s morfológiou jaskyne (A. Droppa, 1957a; J. Halaš, 1984; J. Otruba, 1957). Najviac podlahového ľadu sa vyskytuje v Kmeťovom dóme (obr. 3, 4 a 5; foto 2). Tvorí 70 % celého objemu a 60 % celej plochy ľadovej výplne v jaskyni. V strednej a severnej časti ľadový monolit vytvára masívnejšiu vrstvu s hrúbkou viac ako 2 m. Na tejto relatívne malej ploche uvedená koncentrácia dosahuje viac ako 50 % celej masy podlahového ľadu (tab. 2). Zvyšný podlahový ľad sa vyskytuje vo Veľkom dóme a Štrkovom dóme, kde v hrúbke 1 m takmer kompletne vypĺňa dná oboch priestorov (tab. 2). Charakteristickou vlastnosťou podlahového ľadového monolitu v Demänovskej ľadovej jaskyni sú vrstvy vody v dutinách v niektorých oblastiach pod podlahovým ľadom.

V porovnaní s výsledkami výskumu realizovaného systematicky v priebehu uplynulých dvoch rokov tieto výpočty pomôžu posúdiť sezónne a ročné zmeny objemu podlahového ľadu. Taktiež pomôžu zhodnotiť antropogénne aktivity s cieľom udržať ľadovú výplň v jaskyni.