MORPHOLOGY OF ICE SURFACE IN THE DOBŠINÁ ICE CAVE

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Abstract: The Dobšiná Ice Cave is one of well-known limestone ice-filled caves in the world. It presents a typical depression pocket-like large cavity with a uninterrupted stagnation cold air and freezing of seeping precipitation waters. The permanent wide-ranging and voluminous ice body of the cave is featured by several long-lasting and ephemeral forms. The long-lasting forms consist of supraglacial ice-deposited, ablation and compounded ice-deposited/ablation forms, intraglatial ablation forms deepened into ice surfaces of artificial tunnels, also sporadic subglacial ablation forms. The ephemeral supraglacial ice-deposited and ablation forms are observed seasonally during and after phases of intense seepage of rainfalls or snow-melting waters into the cave through overlying fractured and karstified limestone beds with a high permeability. The genetic and morphological classification and basic description of these ice forms are given in the paper.

Key words: ice-filled cave, cave ice surfaces, ablation forms, Dobšiná Ice Cave, Slovakia

INTRODUCTION

The Dobšiná Ice Cave belong to the most important ice-filled cave in the world. From the point of view of cave glaciation existing research activities were oriented mainly to climatic conditions and processes for deposition and stability of ice fill. But the morphology of ice surface was the sporadic object of glaciological research of the cave. Several remarkable ice morphological features are partially characterized by P. Bella (2003, 2005). The main aim of presented paper is the integral characterization and classification of various morphological and genetic forms of ice block surface in the cave.

DOBŠINÁ ICE CAVE: GENERAL DATA

The Dobšiná Ice Cave is located in the southern part of Slovak Paradise National Park within the Spiš-Gemer Karst (the nothern direction from the Dobšiná town). The altitude of its entrance is 969 m a. s. l. The cave was formed by erosion and corrosion of sinking water of palaeo-river Hnilec in the Middle-Triassic Steinalm and Wetterstein limestones of Stranená nappe. Its length is 1483 m and vertical range of 112 m.

From the genetic point of view the Dobšiná Ice Cave presents the part of larger Stratená Cave System long more than 21,9 km. At the end of Tertiary and during the Lower Quaternary both caves were presented by one united cave that were divided by subsequent breakdown and collapse below the Duča collapsed doline. The upper parts of Dobšiná Ice Cave at ca. 945 m a. s. l. relate to the larger cave level originated during the end of Tertiary. Probably in the Middle Quaternary in connection with the origin of Duča collapsed doline and breakdown interruption the original connecting cave passage also the depression pocket-like big cavity (70 m deep) were formed by collapse of rocky floor or roofs among lower cave levels. The cave glaciation is the result of cold air stagnation and freezing of seeping precipitation waters into the cavity (Tulis & Novotný 1989, Novotný & Tulis 1996).

Original rocky fluvial forms in the glaciated part of the cave are remodelled by breakdown and frost weathering. The upper non-glaciated parts are presented by horizontal passages and halls with fluvial oval shapes and ceiling channels or flat ceilings, and residues of fluvial sediments. Some non-glaciated cavities are located also in the lower part of the cave (Dry Dome, Dripstone Cellar).

The ice part of Dobšiná Ice Cave is located at 920 – 950 m a. s. l., below the alpin climatic zone. The area of the cave is included to the moderately cool subregion (July ≥ 12 °C to < 16 °C) and very humid (900 to 1000 mm) (in sense of Lapin et al. 2002, Faško & Šťastný 2002). Well-known ice-filled caves (Eisriesenwelt, Dachstein-Rieseneishöhle) in Austrian Alps are situated in high-mountain positions. The ice part of remarkable Scărişoara Cave in the Bihor Mts. (Romania) is located from 1,100 to 1,120 m a. s. l.

The ice fill in the Dobšiná Ice Cave occurs in various forms: floor ice, icefalls, ice stalagmites, columns and sublimation crystals. The surface of ice fill is ca. 9,770 m^2; its volume is more than 110,100 m^3. The maximal thickness of floor ice is 26.5 m, the average thickness is 13 m – determined by geophysical measurement (Géczy & Kucharič 1995, Tulis & Novotný 1995, Novotný & Tulis 1996). The floor ice decrease by melting at the contact with a rock basement. The assumed age of the oldest existing ice in the cave is 2,700 to 3,000 years (Tulis & Novotný 2003), but the newest results of dating of bat bones show the age only 1,250 years (Clausen et al. 2007). The ice body is moving from the cave entrance, Small Hall and Great Hall to the Ground Floor and Ruffiny´s Corridor (Lalkovič 1995), max. 2 to 4 cm per year (Tulis 1997).

The average air temperature in the glaciated Great Hall is –0,4 to –1,0 °C (in February –2,7 to –3,9 °C, in

August about +0,2 °C). The air temperature in lower parts of the cave is under the feezing point during all year. The air temperature in the non-glaciated parts is +0,8 to +3,5 °C. The Dobšiná Ice Cave presents a static-dynamic cave with a different winter and summer regime of air circulation. The colder air courses from surface to cave during winter season; the air course during summer season is contradictious (Petrovič & Šoltís 1971, Halaš 1989, Piasecki et al. 2004, 2005 and others).

The Dobšiná Ice Cave was discovered in 1870 and opened to the public in 1871. Its belong to the first electrically illuminated show caves in the world (from 1887, initial efforts began in 1881). During last years the number of visitors is ca. 105,000 persons per year (the cave is seasonally opened from May, 15 to September, 30).

From 2000, the Dobšiná Ice Cave is included in the World Heritage (in the framework of the extension of Slovak-Hungarian site *Caves of Slovak and Aggtelek Karst*).

SOME TERMINOLOGICAL AND METHODOLOGICAL NOTES TO THE STUDY OF ICE SURFACE IN GLACIER AND ICE-FILLED CAVES

Several ablation forms originated in consequence of dripping and flowing water or air circulation and convection are known in glacier and ice-filled caves. Moulins, intraglacial conduits, subglacial oval and scalloped tunnels, sublimation scallops and flutes, dripping holes, stream channels and other similar cave ablation forms are descripted in the existing literature (Curl 1966, Pulina 1982, Cigna & Forti 1986, Mavlyudov 1991, Pulina & Řehák 1991, Schroeder 1991, Eraso 1992, Lauritzen & Lundberg 2000, Bella 2002, Pulina, Řehák & Schroeder 2003 and others). However published mentions or descriptions on seasonally melting-freezing flat floor ice surfaces or ice lake (Racoviță & Onac 2000, Bella 2005, Shavrina & Guk 2005), ablation bevels (Bella 2005) or ablation flat ceiling (Mavlyudov 2005) are sporadic. In the framework of the classification of karstic phenomena presented by Cigna (1978) ablation features are included into hypokarstic phenomena.

Ice surfaces in glacier and ice-filled caves are featured by ice-deposited, ablation and compounded ice-deposited/ablation forms. The ablation is defined as a decrease of ice mass caused by natural and human processes. Physical ablation relate to snow and ice melting on a surface of glacier and runninig of melting water, snow and ice sublimation, evaporation of melting water, ice melting at the contact with sea or lake water, melting of glacier bottom at the contact with rock basement, internal melting of glacier. Mechanical ablation relate to blowing off a snow from glacier, marginal partition of glacier at the contact with sea water, loosening of snowslides from steep mountain glaciers (Jania 1997). Also some physical and mechanical anthropogenic forms are known in show ice-filled caves as the result of their development for tourism (Bella 2002).

From the point of view of spatial position in glaciers supraglacial, intraglacial (englacial) and subglacial ablation caves are distinguished. In the context this categorization of glacier caves, also supraglacial, intraglacial and subglacial ablation forms deepened into ice bodies of ice-flled caves can be classified.

Kiver and Steele (1975) descripted the firn caves formed by sub-ice fumaroles and warm air currents beneath ice filling the summit volcanic craters of Mount Reiner in the Cascade Mountains (Washigton, USA). They distinguish geothermal ablation caves and atmospheric ablation caves.

Natural cave ablation forms are caused by geothermal and atmospheric processes, also by fracturing of glacier or gravity ice block movement as results of mechanical ablation in sense of Jania (1997). Some ablation forms in show ice-filled caves are produced by human impacts or activities. Therefore cave anthropogenic ablation forms originated by physical or mechanical ablation are specific morphological features of cave ice surfaces.

From the point of view of the duration of ice formations their long-lasting forms and ephemeral forms can be differentiated. The long-lasting forms in main morphological features remain for several years, ten, hundred or more years, but ephemeral forms mostly hold on only for one or several annual seasons.

DOBŠINÁ ICE CAVE: ICE SURFACE MORPHOLOGY CAUSED BY NATURAL PROCESSES AND CAVE DEVELOPMENT FOR TOURISM

Several types of ice surface forms are distinguished on the basis of long-term observations icluding annual phases of intense seepage od atmospheric waters. In the framework of multistage classification these criterions are used: duration, spatial position in the ice body, genetic process/processes and morphogical shape of ice form.

1. LONG-LASTING FORMS OF ICE SURFACES

1.1. SUPRAGLACIAL ICE-DEPOSITED FORMS

1.1.1. Forms originated by freezing of water film or trickling water

a) *ice subhorizontal floor* – presented by the largest ice surface in the cave, the original flat floor in the Great Hall is remodelled by one-side deposition of ice (see 1.3.1.);

b) *ice evenly inclined or cascaded slopes* – visibled between the ice flat floor of Small Hall and the ice subhorizontal floor of Great Hall;

c) *ice evenly inclined or cascaded tongues* – formed in lines of collected water flowing, the ice tongue inclined from the Small Hall to the Hell or the Ground Floor is related to artificial outflow channels cut into the ice floor along the tourist path in the Small Hall;

d) *small ice tongues (half-conic or medusoid) on steep rock walls* – lead downward or hanging from karstified tectonic fissure (Ground Floor);

e) *icefalls/ice curtains* – formed at the end of ice body (Great Curtain) or hanging from karstified tectonic fissures (Small Hall);

1.1.2. Forms originated by freezing of dripping water

a) *ice stalagmites and mounds* – conical stalagmites and bell-shaped mounds formed below karstified tectonic faults or cracks (Small Hall, Great Hall);

b) *ice stalactites* – formed mostly in same places as ice stalagmites;

c) *ice columns* – formed below the vertical karstified chimneys controlled by tectonic faults (Great Hall, Small Hall);

1.2. SUPRAGLACIAL ABLATION FORMS

1.2.1. Physical ablation forms

1.2.1.1. Forms originated by air circulation and ice sublimation

a) *sublimation large scallops and hollows in ice walls* – deepened into steep ice walls (Ruffiny´s Corridor, Small Curtains in the Small Hall) and sides of artificial notches of tourist path cut into the ice floor and ice walls;

b) *sublimation steep ice walls* – several or more than ten metres high smooth ice walls in the lower glaciated part of the cave (Great Curtain, Ruffiny´s Corridor), here and there slightly dissected by sublimation large scallops and hollows;

c) *ablation windows and smaller holes* – deepened into the residue of Niagara Formation in the upper part of Great Hall and into the Small Curtain in the Small Hall;

d) *ablation ice irregular protrusions* – the sculptural residue of Niagara Formation and other similar horn-like ice formations;

e) *ablation oval mound-shaped elevations* – very low and wider hillock-like elevations protuted from floor ice in the nort-estern part of Great Hall caused by air circulation between the Great Hall and the Collapsed Dome;

1.2.1.2. Forms originated by stagnant water

a) *ablation bevels at the edge of flat ice floors* – formed by melting of ice caused by waters of intermittent shallow lakes during phases of intense percolation of atmospheric waters in the Collapsed Dome. Ablation bevels, mostly more than 1 meter high, were extended downwards after gradational ablation lowering of flat ice floor (the intermittent supraglacial lake is only several centimeters deep). They are not dissected by water-level notches but in deveral places ones are features by differently inclined smaller partial surfaces. The direction of their inclination is to the centre of flat floor ice surface. The inclined partial smaller surfaces are probably related to phases of different ablation intensity (Bella 2005).

From the morphological point of view ablation bevels at the edges of flat floor ice surfaces are very similar with *planes of repose* (Lange 1963) and *Facetten* (Kempe 1970, Rainboth 1971, Kempe et al. 1975 and others).

The ablation bevels at the edge of flat ice floor in the Collapsed Dome, Dobšiná Ice Cave. Photo: P. Bella

The ablation bevels in the Collapsed Dome, Dobšiná Ice Cave. Photo: P. Bella

Considering the shallow supraglacial lake the origin of ablation bevels in consequence of the thermic gradient of water to a different ablation intensity between lake water-level and lake floor is contentious (dimensionally different contact with ice surface during cooling up to freezing of water, more intense melting effect at a water-level of lake than at its floor).

The ablation bevels between the Collapsed Dome and the Great Hall are dissected into several smaller oval elevations by sublimation caused by air movement.

1.2.1.3. Anthropogenic forms

a) *melting depressions near electric spotlights* – negative anthropogenic impact caused by electrical illumination in the Great Hall and some other places near the tourist path;

1.2.2. Mechanical ablation forms

1.2.2.1. Anthropogenic forms

a) *artificial notches of tourist path cut into the ice floor and ice walls* – negative anthropogenic impact but in several cases necessary for a cave development for tourism, the distinct artificial notches are marked between the Small Hall and the Great Hall, between The Great Hall and the Ruffiny´s Corridor, also in the Groun Floor between the Ruffiny´s Corridor and the Great Curtains (the past deep artificial notch led from the cave entrance alongside the Small Hall to lower glaciated parts, excavated in the beginnig of seventies of the last century, was later markedly enlarged by ablation of air sublimation; from this reason it was artificially repeatedly glaciated in the second part of nineties – Bobro et al. 1995b, Zelinka 1996);

1.3. SUPRAGLACIAL COMPOUNDED ICE-DEPOSITED/ABLATION FORMS

1.3.1. Forms originated by stagnant melting-freezing water

a) *flat ice floors* – developed in cave parts where the changes of the phases of intense seepage of atmospheric waters, lake accumulation and stagnation of atmospheric waters with melting and feezing of ice are repeated, ones are located on top positions in the Small Hall (ca. 90 m^2) and on lower barrier slope or foot positions of ice body at the contact of ice-filled and non-ice-filled cave parts in the Collapsed Dome (ca. 430 m^2).

Originally the flat ice foor in the lower position was evident also in the Great Hall. Pelech (1879) wrote about the flat ice surface of 1,726 m^2 used for summer skating. Also several old postcards show the ice flat surface with skaters. During next growing up of floor ice, the flat ice surface was changed to the surface inclined from places below karstified chimneys – main sources of atmospheric waters seeping into the cave – to lower outflow articial channels along the tourist path. These artificial channels present deepened barriers against covering the tourist path by young ice layers. The vertical positions of ice surfaces on the both sides of tourist path are different. The lower position of ice surface is between the tourist path and the rock wall; the higher position of ice surface is between the tourist path and the ice surface inclined from the main sources of atmospheric water seeping.

1.4. INTRAGLACIAL ABLATION FORMS

1.4.1. Physical ablation forms

1.4.1.1. Forms originated by air circulation and ice sublimation

a) *sublimation large scallops and flutes on ice walls of artificial tunnels in the ice block* – two tunnels between the bend of tourist path above the Hell and the Great Curtain and between the Ground Floor and the Ruffiny´s Corridor are characterized by tube morphology for air movement (more intense air movement is evident in constricted tube places), the origin of sublimation scalloped and fluted walls and ceiling of artificial tunnels is influenced also by air movement caused by movement of visitors (Bobro et al. 1995a), the asymmetric shape of sublimation scallops correspond with the direction of air movement through these artificial tunnels (Piasecki et al. 2005);

Ablation sublimation large scallops and flutes in the artificial tunnel between the Great Curtain and the Ruffiny´s Corridor, Dobšiná Ice Cave. Photo: P. Bella

b) *sublimation ceiling pockets in the artificial tunnels cut into the ice block* – shallow oval ceiling plate- or bowl-shaped hollows originated by small air turbulency in the tunnel inclined from the bend of tourist path above the Hell to the Great Curtain;

1.4.1.2. Anthropogenic forms

a) *melting ceiling cupola above the electric spotlight in the artificial small hall cut into the ice body* – deeper ceiling kettle-shaped hollow, the result of negative anthropogenic impact in the atrificial cavity called Chapel near the Ruffiny´s Corridor;

1.4.2. Mechanical ablation forms

1.4.2.1. Anthropogenic forms

a) *artificial ice tunnels in the ice block* – cut out during the cave development for tourism (between the Ruffiny´s Corridor and the Ground Floor, between the steep slope inclined to the Hell and the Great Curtain).

From the point of view of cave climatology these tunnels are used as a routes of air circulation (Piasecki et al. 2005). Their walls and ceiling are remodelled and enlarged by ice sublimation (Bella 2003).

1.5. SUBGLACIAL ABLATION FORMS

1.5.1. Physical ablation forms

1.5.1.1. Forms originated by air circulation and ice sublimation

a) *sublimation cavities at the contact of ice and rock wall* – the cavity with sublimation ice crystals under the Great Curtain and the narrow slit-shaped cavity in the Ruffiny´s Corridor (several centimetres to max. 1 meter wide; Strug, unpubl. information) originated and enlarged by ice sublimation between ice and rock surface. The courses of air movement from lower underglaciaced cave parts to up (in the first case through underlying debris from unknown underground hollows, in the second case probably from the adjacent Dry Dome) is demonstrated by coating of sublimation ice crystals formed on the rock wall or ice surface above these subglacial cavities.

For the present natural processes of basal melting of the ice block in the Dobšiná Ice Cave were not more detailed studied. Broadly similar climatic conditions for dynamics of ice block are in the Scărişoara Cave where the ablation of the base of ice block is due to melting generated by geothermal flux and sublimation due to the circulation of cold and dry air under the ice block (Perşoiu 2004, 2005).

Spasmodically the upper parts of narrow slit-shaped cavity in the Ruffiny´s Corridor are filled by new ice in consequence of water flowing on the ice surface inclined to rock wall.

2. EPHEMERAL FORMS OF ICE SURFACES

They originated mostly in the upper glaciated parts of the cave (Entrance Passage, Small Hall, Great Hall, Collapsed Dome) with less thick overlying rocks, more karstified tectonic faults or another structural discontinuities, and seasonal phases of intense seepage water from melting snow or rainfalls.

Ice-deposited forms are usually formed at the end of winter and are remained during spring partially to the beginning of summer. Physical ablation forms are formed mostly during summer and are remained to the end of winter. After they are filled and covered by new ice. Anomalies of ice stratigraphy (depressions filled by newer ice) are related to former ablation forms. Descripted ablation forms were observed mainly in summer and autumn 2002 and winter 2002/2003 after very intense rainfalls season in summer 2002.

2.1. SUPRAGLACIAL ICE-DEPOSITED FORMS

2.1.1. Forms originated by freezing of water film or trickling water

a) *ice curtains* – hanging from karstified tectonic fissures or subhorizontal bedding-planes (Small Hall, Collapsed Dome);

2.1.2. Forms originated by freezing of dripping water

a) *ice stalagmites* – stick stalagmites in the entrance collapsed part of the cave and in the Small Hall;

b) *ice stalactites* – mostly conical stalactites hanging from fractured a frost weathered roof in the entrance collapsed part of the cave, in the Small Hall and Collapsed Dome; ice stalactites in the entrance cave part are covered by sublimation ice crystals during the end of wintwer and at the begining of spring;

2.2. SUPRAGLACIAL ABLATION FORMS

2.2.1. Physical ablation forms

2.2.1.1. Forms originated by dripping water

a) *ablation eguttation pits* – according to the intensity, energy and temperature of dripping waters shallow plate pits, deeper bowl-like pits, well-like pits are deepened into the ice floor of Small Hall or other upper glaciated parts of the cave; ablation outflow small channels lead downward from biger egutattion pits;

b) *ablation eguttation more-pits depressions* – composed from several adjacent well-like pits, they are featured by linear or quasi radial (star-shaped) formations (Small Hall, the upper part of Great Hall, the inclined floor ice above the Hell);

c) *ablation pinnacle karren* – residues of ice stalagmite broken by intense dripping waters in the Small Hall;

Ablation eguttation bowl-like pits in the Great Hall, Dobšiná Ice Cave. Photo: P. Bella

Ablation eguttation more-pits depression in the Small Hall, Dobšiná Ice Cave. Photo: P. Bella

2.2.1.2. Forms originated by dripping, stagnant and slowly running water

a) *ablation shallow pans* – shallow ice floor plate-shaped depressions (resembled with kamenitzas) originated on horizontal to subhorizontal ice surfaces with slowly running water (Small Hall), small inflow and outflow channels on opposite sides of the depressions evidence an effect of flowing waters, flat bottom and steep walls of the depressions are the result of repeated melting and freezing waters (small ice lakes), in many cases the origin of ablation shallow pan is iniciated by ablation eguttation pit located on the route of small runnel;

b) *ablation eguttation kettle-holes* – deeper ice floor depressions (resembled with potholes) originated in places of intense seepage of atmospheric waters in the upper part of Great Hall, outflow channel leads from lower side of the depression;

Ablation pans in the Small Hall, Dobšiná Ice Cave. Photo: P. Bella

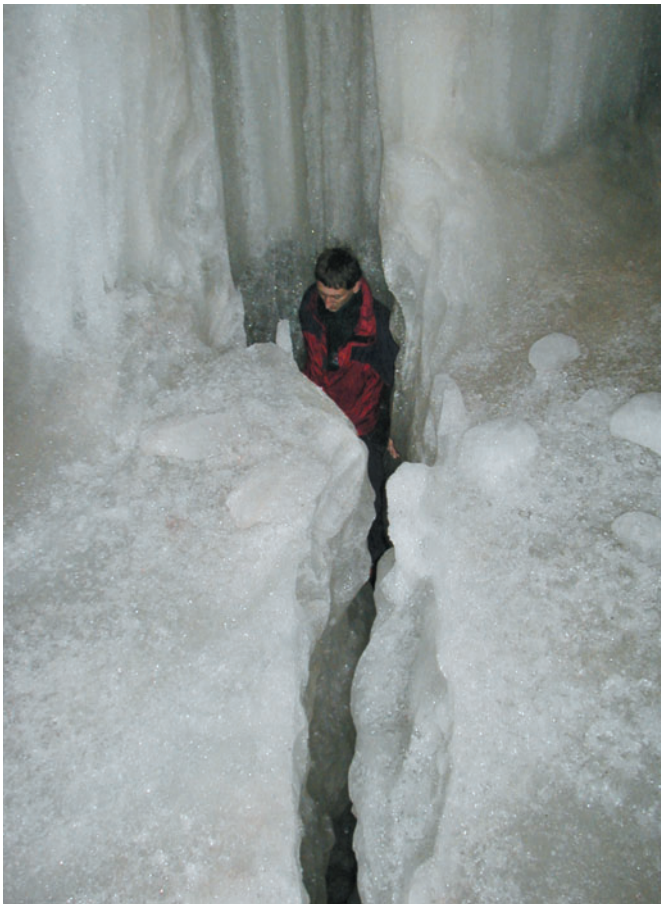
Ablation eguttation kettle in the Great Hall, Dobšiná Ice Cave. Photo: P. Bella

2.2.1.3. Forms originated by intense dripping or steep running water

a) *ablation eguttation well-like depressions* – ca. 1.3 to 1.8 metres deep depressions with steep walls originated below intense karstified vertical chimneys in the Small Hall and Great Hall, their lower side of upper perimeter is cut down to bottom by outflow partially meandering channel;

b) *ablation eguttation well-like depresions at the contact with a rock wall* – deepened into ice inclined slope above the Hell, these contact ablation depressions are downward narrowed along rock walls, ouflow channels are not developed;

c) *ablation vertical half-tube grooves on ice columns* – occasional forms deepened into ice columns originated below intense karstified vertical ceiling chimneys (Great Hall);



Ablation eguttation well-like depression with an outflow channel in the Great Hall, Dobšiná Ice Cave. Photo: P. Bella

2.2.1.4. Forms originated by less or more concentrated flows of running water

a) *ablation rinnenkarren* – originated on the steep walls of artificial notch of tourist path cut into the ice floor between the Small Hall and the Great Hall, visibled also on the lower part of Great Curtain near the terrace of tourist path;

b) *small shallow meandering channels on a flat ice floor* – originated in the Collapsed Dome;

c) *ablation outflow channels from eguttation well-like depressions and larger kettle-holes* – deep from several centimetres to ca. 1.5 m, characterized by linear or meandering morphology, occasionally remarkabled mostly in the Great Hall;

Ablation meandering outflow channel from an eguttation kettle in the Great Hall, Dobšiná Ice Cave. Photo: P. Bella

2.2.1.5. Forms originated by freezing of stagnant water

a) *loaf-shaped ice bulge with radial cracks* – sporadic several centimeters gibbous and more wider elevation on the flat ice floor in the Small Hall, caused by expanded volume of freezing water in the deepest place of shallow supraglacial lake (or in the larger dripping/eguttation pan);

2.3. MECHANICAL ABLATION FORMS

2.3.1. Anthropogenic forms

a) *artificial outflow channels cut into the ice floor along the tourist path* – against covering the tourist path by new ice layers (Small Hall, Great Hall, the steep ice slope inclined from the Small Hall to the Hell, Ruffiny´s Corridor).

CONCLUSIONS

The spectrum of various ice surfaces in the Dobšiná Ice Cave is presented. These long-lasting and ephemeral supraglacial ice-deposited, ablation and compounded ice-deposited/ablation, intraglacial ablation forms and subglacial ablation forms are classified according to the durability, genetic and morphological features in connection with existing relevant terminology and theoretical-methodological approaches. Intraglacial and subglacial ablation phenomena formed by running water are not known in the cave. Several ice-deposited and ablation forms are originated and controlled by anthropogenic impacts related to the cave development for tourism.

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