DEVELOPMENT AND DEGRADATION OF ICE CRYSTALS SEDIMENT IN DOBŠINSKÁ ICE CAVE (SLOVAKIA)

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Abstract: This article presents the genesis and course of the development of the ice crystals deposit in the Dobšinská Ice Cave. The results of the periodical observations and surveys of the range area of the different forms of sublimation ice have been compared to the research results of the air movement spatial structure in the cave and the changeability of the thermal and humidity conditions in the cave and its environment. The results of the rock thermal efficiency surveys carried out in the years 1980 – 1984 have been used. The time and space – related diversity of the ice crystals range area has been shown against a background of the cave air exchange diagrams. The deposit development and degradation have been divided into six stages and described.

Key words: speleoclimatology, ice crystals deposit, air moving, rock temperature

INTRODUCTION

In July 2002, following the several years' break, the complex research of the ice and speleoclimatic phenomena in the Dobšinská Ice Cave was resumed. The ice crystals deposit is one of the important components of its ice environment (Krenner J. S., 1874, Droppa A., 1957, Petrovič Š., Šoltís J., 1971, Halaš J., 1980, Rajman L., Roda Š., Roda Š. jr, Ščuka J., 1985, Strug K., Piasecki J., Sawiński T., Zelinka J., 2004). The abundant and stable development of the deposit and, then, its melting make it act as a natural controller of the steam content in the cave air. Simultaneously, the deposit growing and degradation process, which changes in time and space illustrates well the phenomena of the cave air movement dynamic.

The ice crystals deposit sublimation depends directly on the extent of the rock cooling, surface and dripstone ice in the cave chambers, an intensity of the air flow between the cave and its surroundings, as well as the course of the air movement inside the cave system. These factors together with the thermal and humidity aspect of the air volumes that are subject to movement determine the place of the crystals settling and their durability (Pulina M., 1971, Halaš J., 1980). In the Dobšinská Ice Cave, the ice crystals deposit occurs in the whole area of its icy part (Strug K., Piasecki J., Sawiński T., Zelinka J., 2004). The deposit develops both the forms of the continuous, compact ice crystals covers of considerable sizes and the ice crystals covers whose crystals are less compact and have smaller sizes, as well as clusters of the single crystals. The specific feature of this phenomenon is an occurrence of clusters of the long-lasting crystals that have been created through growing of the new crystals on the partly-degraded old forms. They form layers with a thickness > 50 cm. The crystals grow on a rock slab and the chamber walls, where they cover the largest surface areas, as well as on the bottom ice and ice speleothems. At the front part of the cave, the crystals develop one of the two deposit forms i.e. rime crystals. The ice crystals of white frost are a type of deposit that occurs all over the cave. In the individual cases, they reach the sizes up to 25 cm. The crystals with sizes up to 0.5 cm occupy the largest surface areas.

The regular observations and surveys of the ice crystals deposit were commenced in March 2003 (Strug K., Piasecki J., Sawiński T., Zelinka J., 2004). The research concentrated on charting of the deposit range and compactness, measurement of the crystal sizes in accessible places, measurement of the deposit growth speed, and observations of changes to the crystal structures. Total 19 chartings were performed. The measurements were carried out every two months on average which enabled identification of the deposit development and degradation dynamic.

DESCRIPTION OF THE RESEARCH AREA

The Dobšinská Ice Cave is located in the Spiš-Gemer Karst. An entry opening to the cave is situated at a height of 969 m above sea level, on the north–west slope of the Duča karst massif, 130 m above the bottom of the River Hnilec valley. The cave was created in Neogene as a result of the paleo–Hnilec erosive activity in the Middle Triassic Steinalm and Wetterstein limestones of the Duča massif (Tulis J., Novotný L., 1989). In respect of its genesis, the cave constitutes part of the Stratenská Cave system. At present, the Dobšinská Ice Cave is not connected to the said system. Separation of the caves probably occurred in Pleistocene as a result of collapse of part of the cave ceilings (Novotný L., 1995). As a result of the collapse, the Duča collapse was created, which separates the Dobšinská Cave from the Stratenská Cave, and the entrance collapse in the Dobšinská Cave. The creation of the collapses resulted in activation of intense air exchange between the cave and its surroundings. As a result, the conditions appropriate for the cave icing were created. The morphogenetic processes and the ice monolith development in the cave formed a system of corridors and chambers with a length of 1 232 m and delevelling of 113 m (Tulis J., Novotný L., 1989). In the cave, the cave ice forms the bottom in the Small Hall, Great Hall, Collapsed Dome, Icefall, Great Curtain, Underground Floor and Ruffiny's Corridor chambers. Ice does not occur in the Hell, Stalactic Cellar, Dry Dome, Dripstone Hall and White Hall chambers (Fig. 1.). Currently, a surface area of the iced parts of the cave amounts to 9 772 m^2. Ice volume is estimated at 110 132 m^3. An average ice thickness amounts to approximately 13 m, and its greatest thickness – 26.5 m, respectively (Tulis J., Novotný L., 1995).

The average monthly air temperatures in the iced part of the Dobšinská cave alternate from 0 °C to -10 °C (Halaš J., 1986, Halaš J., 1989). In the summer half year (V-X), the air temperature alternates w from 0 °C to 1.5 °C. In the winter, the air temperature in the cave alternates with the changes to the temperature of the surroundings (Kožáková G., 2002). Air relative humidity alternates in a similar way. In the summer, the air is close to the saturated conditions, whereas in the winter, a decrease in humidity up to 75 % is noted (Droppa A., 1960). Throughout the year, the alternation of the two meteorological parameters is strictly associated with a thermal gradient between the cave and its surroundings. A size and direction of the gradient vector is a stimulator of a type of the air movement in the cave chambers. Simultaneously, in the summer half year, the ice filling of the cave stabilizes the alternations of the temperature and humidity inside the cave.

AIR MOVEMENT

Based on the data collected in the course of the research on the air movement in the cave (coming from the years 2002 – 2006), the air exchange schemes have been prepared for the ice parts of the cave. Acoustic anemometers manufactured by METEK GmbH, a German

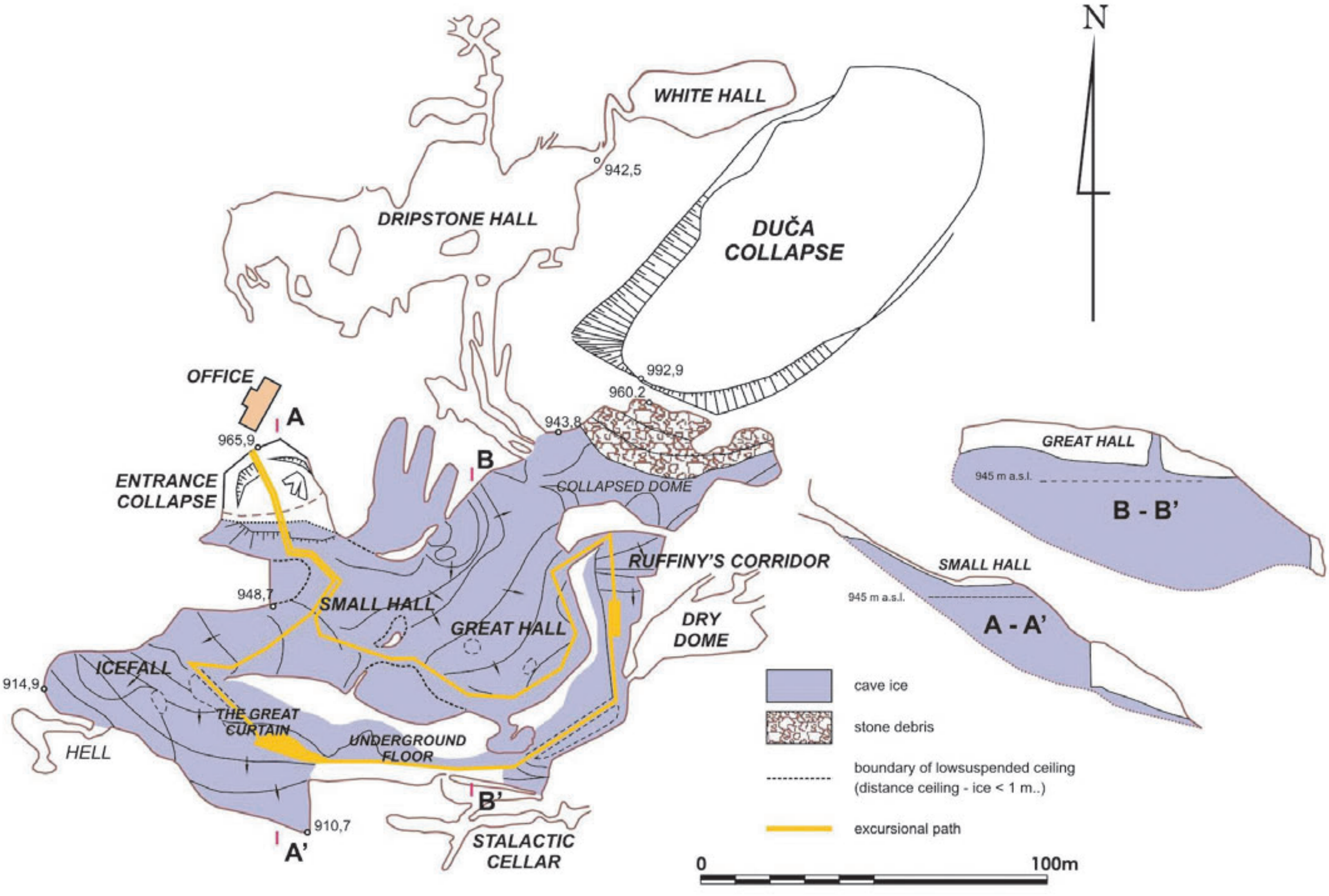


Fig. 1. Dobšinská Ice Cave – the scheme and cross sections

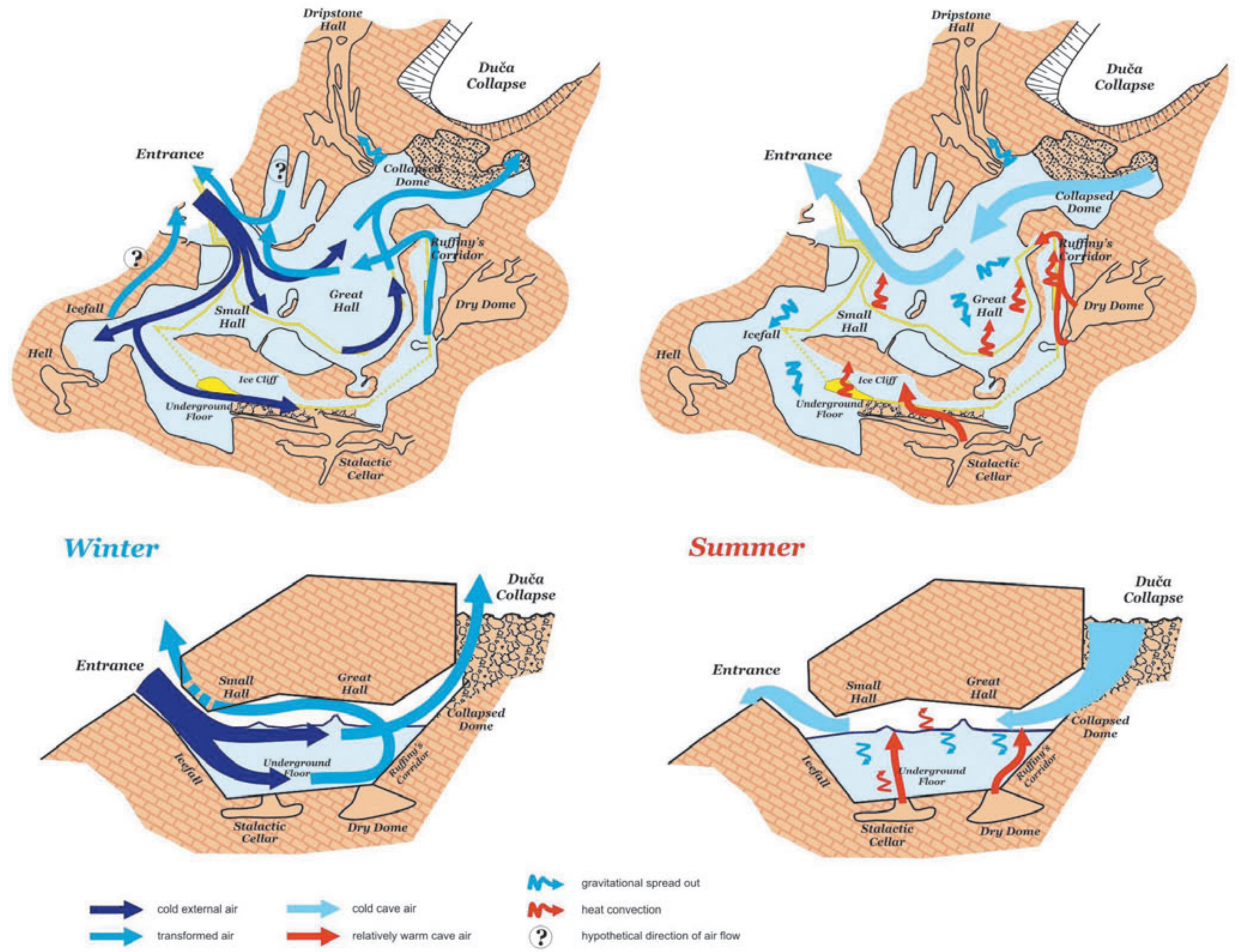


Fig. 2. The scheme of the course of summer and winter air exchange on icy parts of the Dobšinská Ice Cave

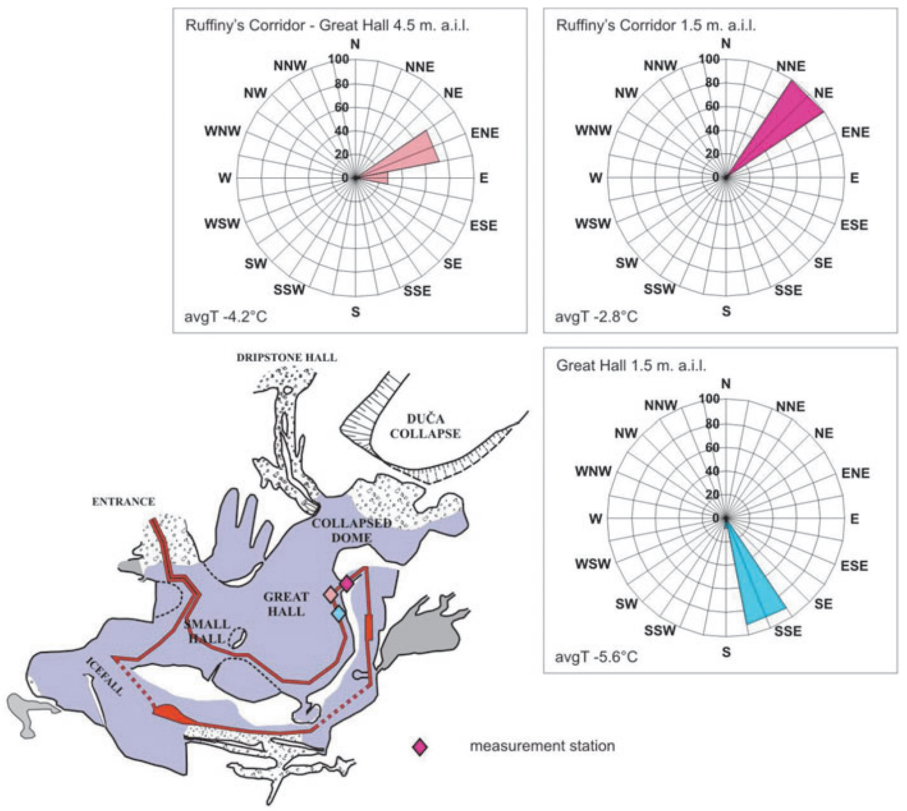


Fig. 3. The frequency of the direction of air flow between Ruffiny's Corridor and Great Hall (February 2006)

company, have been applied for the purpose of the air movement recording.

On the basis of the results collected, it has been found that the course of air exchange is influenced by the following factors (Piasecki J., Zelinka J., Pflitsch A., Sawiński T., 2004, Piasecki J., Sawiński T., Zelinka J., 2005):

- inflow of cold air into the cave interior in the cold half year;
- activation of a winter or summer phase of "the thermal air current effect";
- transfer of heat between the particular areas of the cave throughout convection movements and air flows;
- heat exchange processes between the components of the cave environment.

There is a clear seasonal diversity in the course of the above-mentioned processes. As a result of the

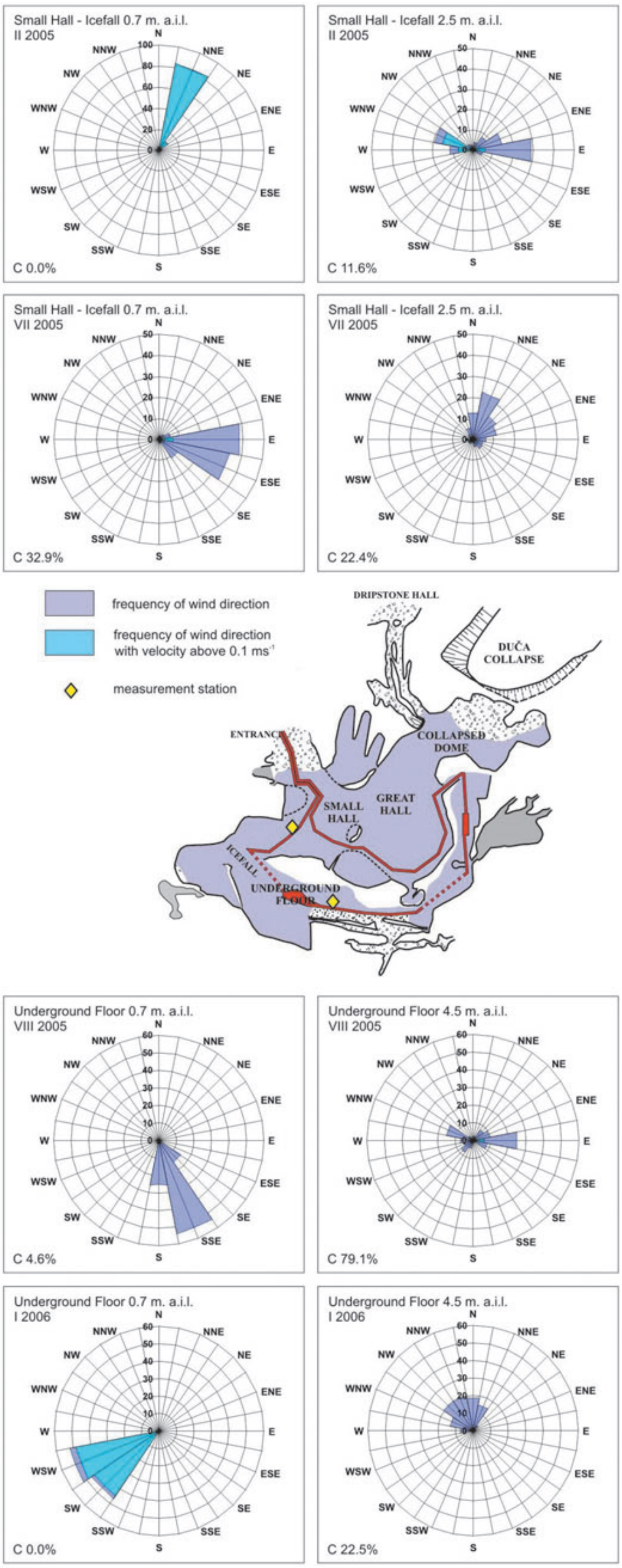


Fig. 4. The Frequency of the direction of air flow measured at points between Small Hall and Icefall (0.7 m a.i.l. and 2.5 m a.i.l.) and in Underground Floor (0.7 m a.i.l. and 4.5 m a.i.l.) in chosen summer and winter months

diversity, there are two main types of air exchange present in the Dobšinská cave system i.e. the winter air exchange and the summer one (Fig. 2.). In the winter, intensive winter inflow of the cold air from outside into the cave takes place through the main entrance opening. In the cave area where the entrance opening is located, the cold air divides into two streams. One of them flows down to the lowest parts of the cave through the Icefall, and then, it flows towards the Ruffiny's Corridor. The second stream flows through Small Hall towards the Great Hall (Fig 2.). The outside air in the streams is subject to gradual transformation as it gets warmer in the relatively warmer air inside the cave. The extent of transformation is different for the two streams. During the measurements carried out in February 2006, the air with a temperature from -9 to -12 °C that flew into the cave got warmer up to -5 °C in the Great Hall, and -3 °C in the Ruffiny's Corridor, respectively. As a result of the temperature difference, the air that underwent greater transformation and flew through the lower part of the cave, flew into the chamber located higher. The corridor that connected the chamber of the Ruffiny's Corridor to the Great Hall fulfilled the role of the chimney (the chimney effect), through which the inflow occurred (Fig. 3.). The same scenario with the same transformation of the air flow takes place every year. At the same time, it was not found whether the colder air that filled in the Great Hall in winter flew under an influence of gravitation to the Ruffiny's Corridor. On the basis of the results of the air movement measurements which were carried out at an outlet of the Ruffiny's Corridor, it is assumed that the air stream that leaves the Corridor moves, under the ceiling of the Great Hall, towards the Small Hall. Neither was the similar phenomenon of "the chimney effect" observed in the Icefall area (Fig. 4.). The inflow of the transformed warmer air from the Underground Floor and the Hell to the Small Hall is likely to be blocked by the external air flowing inside throughout the whole section of the Icefall. This indicates that, in the winter time, the flow of air through the lowest parts of the cave has a nature of a circulation with a strictly determined direction, and it is driven by the continuous inflow of the cold external air into the cave (Fig. 4.).

The second outside air stream flows between the Small and Great Halls and the Collapsed Dome in the upper parts of the cave (Fig. 5., 6.). The cave air in the Collapsed Dome flows into clefts in the rock debris, which connects the Dome with the bottom of the Duča karst collapse situated on the surface (approximately 30 m above). An outflow of the relatively warmer cave air through the clefts in the bottom of the Collapsed Dome observed each winter indicates that the rock debris plays the role of the chimney, which sucks the cave air outside.

In spite of the very intensive inflow of the air into the Collapsed Dome in the winter it does not cause an equally intensive exchange of air between the Dome and those neighbouring parts of the cave which are not covered with ice. The air temperature monitoring carried out in the Dripstone Hall (from 2001 on) has shown that an average air temperature amounts to

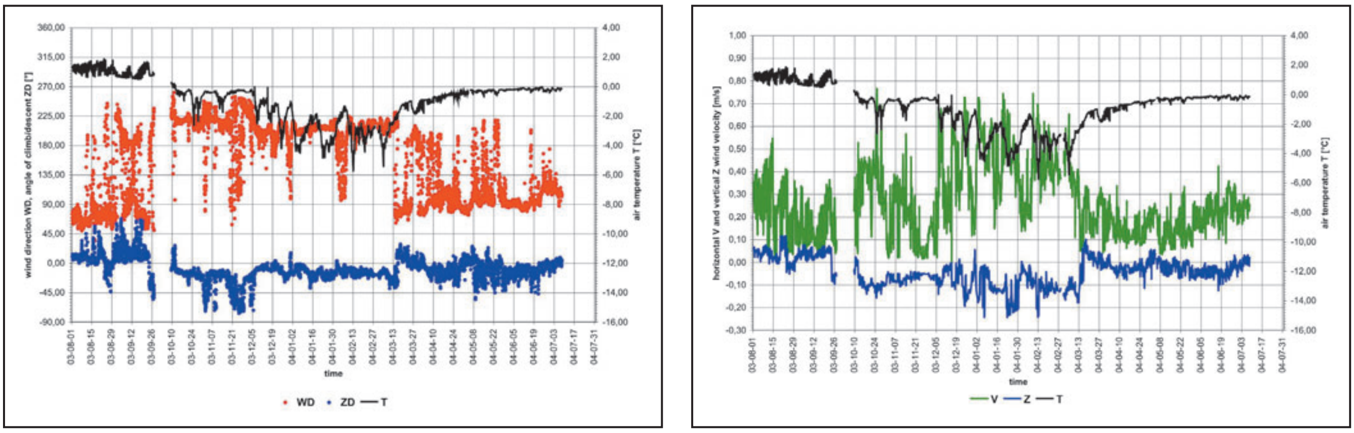


Fig. 5. Seasonal changes of air flow parameters in the period of August 2003 and July 2004 measured at point between Collapsed Dome and Great Hall a) The direction of air flow, climb/descent angle and the air temperature; b) The horizontal and vertical velocity and the air temperature;

+3.1 °C there, and its amplitude does not exceed 0.5 °C in a year. The observations of changes to a range of the ice forms that form in a corridor which connects the Collapsed Dome to the Dripstone Hall indicate that a maximum range of the 0 °C isotherm reaches only an outlet of this corridor in the Dripstone Hall. It is assumed that the corridor morphology fulfils the role of a controller of the air inflow into the Dripstone Hall and accelerates transformation of this air to a temperature higher than 0 °C.

In the winter time, there are two air streams in the vertical section of the part of the cave with the opening, which control the exchange of air between the cave and its surroundings (Piasecki J., Sawiński T., Zelinka J., 2005; Fig. 6.). In part of the cave over the bottom, the cool external air flows continuously into the cave. Its movement is characterized by a considerable speed (as fast as 1 ms^{-1}) and stable direction, and its temperature is close to a temperature outside the cave. At a distance of a few metres from the opening, the inflow air layer has a thickness up to 1.5 m. In parallel, in the part of the cave under its ceiling, a continuous flow of air from the interior of the cave towards the entrance opening takes place. A temperature of the air that flows in the said part is higher, and its periodical fluctuations

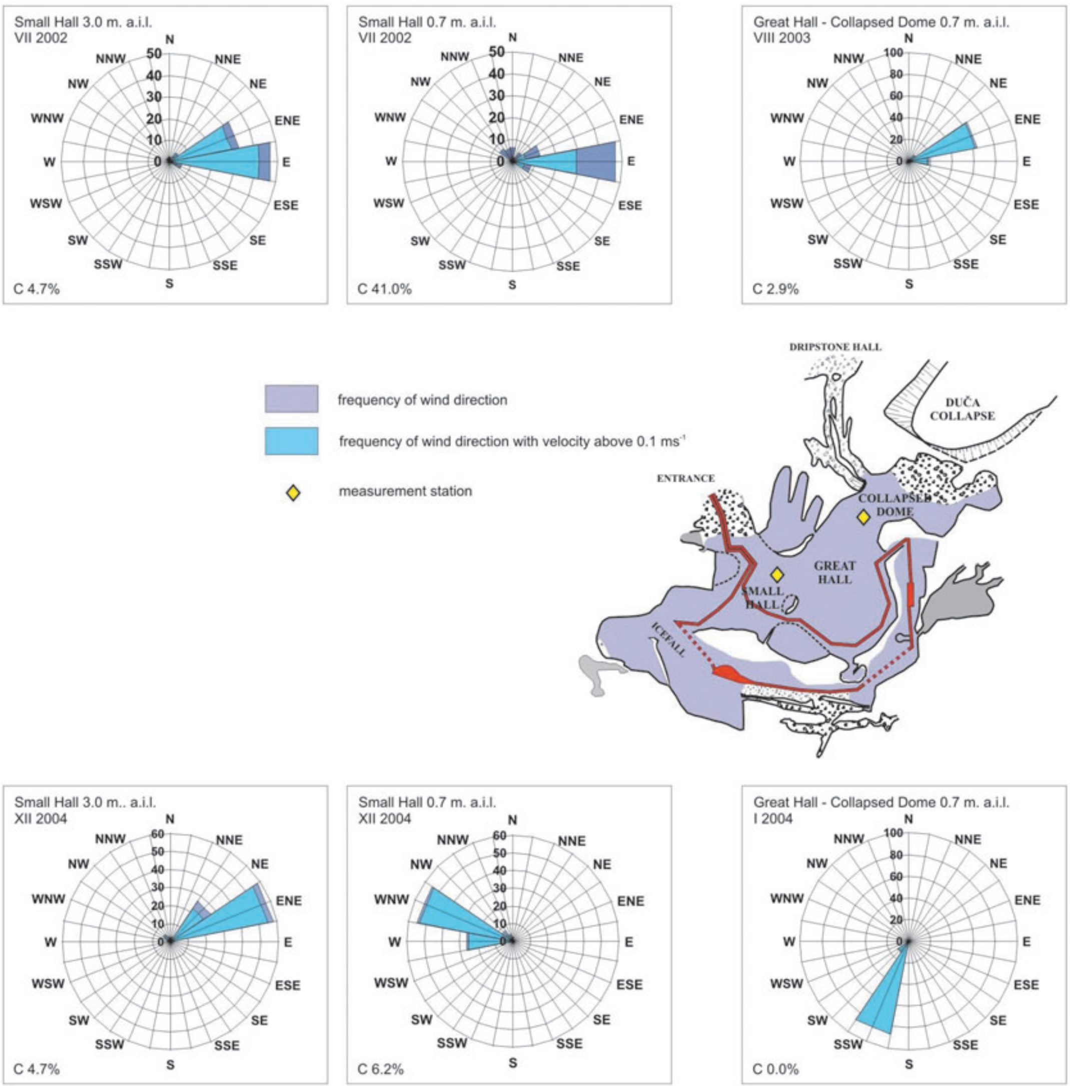


Fig. 6. The Frequency of the direction of air flow measured at points in Small Hall (0.7 m a.i.l. and 3.0 m a.i.l.) and between Great Hall and Collapsed Dome (0.7 m a.i.l.) in chosen summer and winter months

are smaller than in the part over the cave bottom. Also the air movement speed is clearly lower (lower than 0.3 ms^{-1} on average). The research that has been carried out so far does not show a direct winter air flow from the Collapsed Dome and the Icefall towards the Small Hall. Therefore a conclusion can be drawn the air stream under the ceiling observed in the chamber is associated with the air that flows into the Great Hall from the Ruffiny's Corridor.

The external air flows into the cave through the whole profile of the main entrance opening of the cave. The external air does not allow the warmer air under the ceiling to flow outside. In addition, the ceiling in the passage between the Small Hall and the entrance to the cave is suspended low which is in favour of the blockage. As a result, the air under the ceiling finds the way outside through clefts and low empty spaces that are adjacent to the Small Hall and the entrance to the cave (Fig. 2.). The said air outflows were identified during the anemometric measurements and observations of the deposit ice crystals grow on the protruding parts of the walls and the cave bottom. It is likely that the air coming from the neighbouring parts of the cave without ice also flows through the above–mentioned clefts and empty spaces. It is indicated by the ice crystals which forms on the rock walls and ceiling of the spaces located below the bottom of the Small Hall.

In the summer time, the air exchange in the chambers of the upper level of the cave is influenced by the summer phase of the chimney effect (Piasecki J., Sawiński T., Zelinka J., 2005). In this period, the air flows from the rock debris in the Collapsed Dome, through the Great Hall and the Small Hall, to the exit from the cave (Fig. 2., 5., 6.). The cool cave air flows outside through the entrance opening, which is considerably higher than the cave interior. This movement is driven by the difference of temperatures between the cave surroundings and the cleft space in the rock debris which connects the Collapsed Dome to the Duča collapse (Piasecki J., Sawiński T., Zelinka J., 2005). The difference causes a relatively heavier cool air to settle inside the rock debris and „pushes" the air outside the cave. This movement is possible thanks to the difference of a relative height of the collapse bottom (which lies higher) and the collapse edge with the entrance opening to the cave.

The air exchange between the upper and the bottom levels of the cave is much less intensive in the summer than in winter, and it does not have the distinct features of a circulation. It is driven mainly by flow of the air out of the cave parts without ice (Stalactic Cellar, Dry Dome; Fig. 2., 4.). The outflow is activated at the same time as the summer air stream in the upper level chambers. It can be assumed that it is associated with the summer phase of the chimney effect. The main routes of the air outflow from the bottom chambers of the cave lead through Ruffiny's Corridor and the ice cliff zone in the Underground Floor (Fig. 2.).

A supply of heat delivered together with the infiltrating and freezing water, and the water of anthropogenic origin is an additional factor that activates the air exchange in the cave. The water supply effect is particularly important in spring and at the beginning of summer when the cave interior is cooled down after winter. The freezing water warms the air in the part over the bottom up to a temperature of approximately 0 °C. The air rises thanks to convection and flows out to the upper level chambers. A similar effect is caused by electric power supplied for lighting and the presence of tourists in the cave. In parallel, the air movement associated with energy exchange between the cave rock, ice and air develops. It consists in the slow air movements such as air settling or flowing down as a result of gravitation (Piasecki J., Zelinka J., Pflitsch A., Sawiński T., 2004).

In the course of the air movements in autumn and spring, there are some temporary situations with the temporary changes to the course of air exchange between the cave and its surroundings and in the cave itself. The winter type air exchange occurs by turns with the summer type of air exchange (Fig. 7.). A specific type of air exchange can remain for a few days or alternatively, air exchange may occur with 24 hours rhythm. A shift from one type of air exchange to the second type is associated with a temporary change of the relation between an air temperature outside the cave (T_{ext}) and an average temperature of the rock debris interior and the chimneys that connect the cave to the surface (T_{int}). In the case of $T_{ext} > T_{int}$, the summer phase of the thermal air current effect and

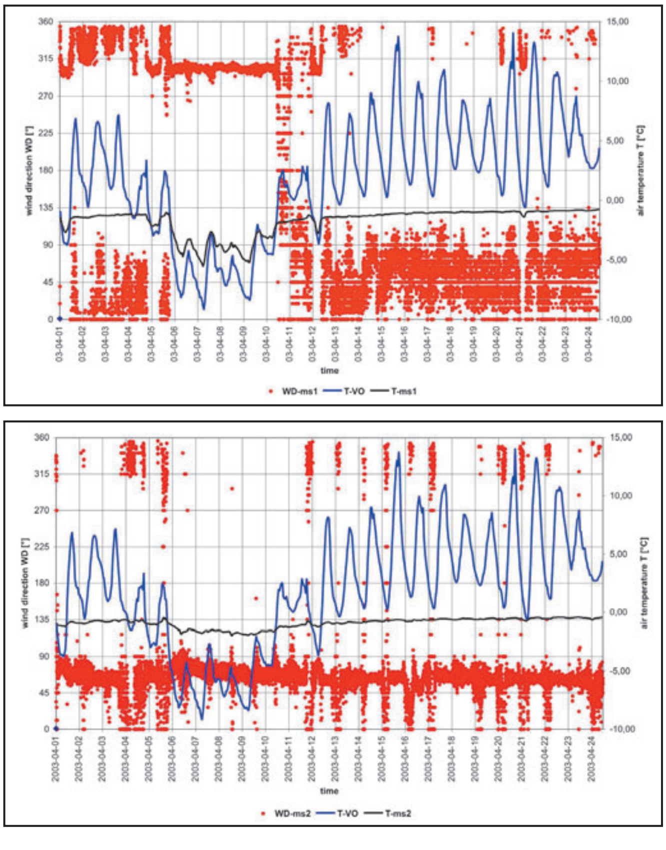
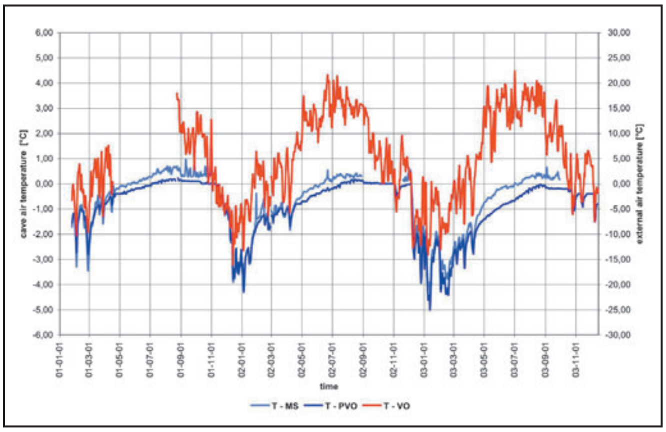


Fig. 7. The temporary changes of air exchange course measured in April 2003 at measurement points localised in Small Hall area on the height of 0.7 m a.i.l. (a) and 3.0 m a.i.l (b) against air temperature changes inside (T-ms1, T-ms2) and outside (T-VO) the cave

the summer type of air exchange activate. In the period when $T_{ext}<T_{int}$, the winter phase develops and the winter type of air exchange. The measurements of temperature of the air flowing out of the rock debris in the Collapsed Dome have shown that T_{int} takes the values from 0 ° to 1 °C.

During the winter type of air exchange, the course of temperatures inside the cave becomes like the course of temperatures outside the cave (Fig. 8.). In this time, the considerable fluctuation of air humidity occurs. When the warmer weather occurs in the winter time, the temperature and humidity of air in the cave get stabilized. When the summer type of air exchange develops, a continuous growth of the temperature and humidity of air in the cave proceeds. It is associated with an inflow of the transformed air out of the depths of orogenic belt into the cave and gradual transformation of the air that fills in the cave in the conditions of weaker ventilation. In July, a temperature in the cave stabilizes at a level close to 0 °C. Earlier (generally in June) air humidity reaches 100 % (Fig 8b.). In the warm half year, the daily and periodical fluctuation of temperature is associated with the presence of tourists in the cave. Stability of the summer speleoclimatic conditions lasts until the first frost, when the winter type of air exchange activates.



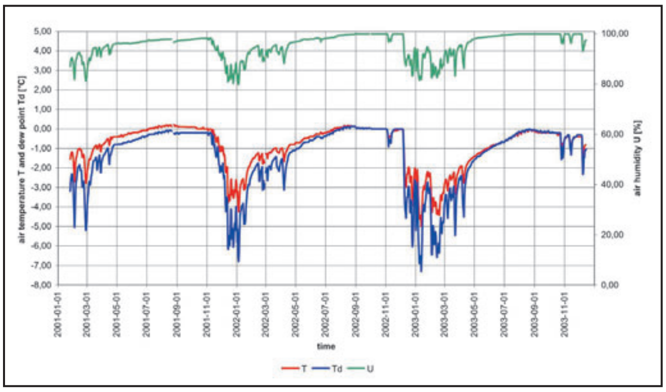


Fig. 8. The course of changes of temperature and relative air humidity of cave's air in the years 2001 – 2003:
a) The course of air temperature changes at measurement points in Small Hall (T-MS) and Great Curtain (T-PVO) against air temperature changes outside the cave (T-VO);
b) The course of air temperature (T), dew point (Td) and relative humidity (U) of air in Great Curtain

ICE CRYSTALS DEPOSIT

SCHEME OF THE ICE CRYSTALS DEVELOPMENT

The extensive documentary material collected, has enabled preparation a simple scheme of the ice crystals development and degradation in the Dobšinská ice cave. Due to the lack of the current date on the rock temperature, the recorded data from the years 1980 – 1984 published by J. Halaš (Halaš J., 1986) have been used. For the purpose of the elaboration, it has been assumed that in both periods i.e. the present one and at the beginning of the 80s, the process of cooling and heating of the cave rocks had a similar course. The diversity of the rock temperature in the cave is directly associated with the course of the air exchange without the cave. The intensive winter inflow of the cool air into the cave causes freezing of the rock, especially in the chambers at the low level, whereas in the summer, the air stream that flows from the Collapsed Dome through the chambers of the upper level heats that zone. The convection lifting of the warm air from the lower level of the cave and the settling and downflow of the cold air from the chamber located higher cause that this area gets warmer to the least extent.

Based on the average monthly temperatures of air (T_{air}) and the rock surface (T_{rock}) from the years 1980 – 1984 (Tab. 1.), the difference $\Delta = T_{air} - T_{rock}$ has been calculated for the particular months. If T_{air} and T_{rock} are lower than 0 °C, the non-negative values of the Δ difference determine an average potential period of the ice crystals creation in the cave. These results have been compared to the information on the spatial temperature diversity. On the basis of that, three zones have been sectioned off that differ from each other in respect of the course of the rock temperature and favourable conditions for the ice crystals creation. The first zone covers the part of the cave where the opening is located (Fig. 9., Tab. 1.). In the above-mentioned zone, an average monthly temperature of the rock surface changes from 5.2 °C in January to +5.3 °C in July which is the most strongly associated with the changes to a temperature of the surroundings. Energy convectivity in the orogenic belt plays an important role within the area of the zone. Ice crystals are created here in the winter time and the first months of spring. The second zone covers the chambers of the upper level of the cave (Fig. 9., Tab. 1.). An average monthly temperature of the rock surface reaches there minimum in February (-2.6 °C in the Small Hall, -2.8 ° C between the Great Hall and the Collapsed Dome), and maximum (+0.1 °C) at the end of summer and the beginning of autumn (September – October). Non-negative temperatures of the rock surface occur within this zone from August to October. The ice crystals deposit is formed from January to the middle of summer. The third zone covers the chambers of the lower level of the cave covered with ice (Fig. 9., Tab. 1.). The lowest temperature of the rock surface occurs there in February (-3.4 °C), the highest (-0.3 °C) – in September and October, respectively.

Tab. 1. The average monthly temperatures of air and of rock surface (after Halaš J., 1986) as well as the temperature difference between air and rock surface. The blue colour indicates the values which potentially promoted the making of ice crystals sediment.

	T	MONTHS											
		I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
MEASUREMENT POINT 1 ENTRANCE	AIR	-5,30	-4,90	-1,63	0,83	3,23	4,50	5,65	5,30	4,73	3,36	-0,24	-3,20
	ROCK	-5,15	-5,10	-1,83	0,30	2,65	4,23	5,23	5,33	5,23	3,64	0,30	-2,66
	Δ	-0,15	0,20	0,20	0,53	0,58	0,28	0,43	-0,03	-0,50	-0,28	-0,54	-0,54
MEASUREMENT POINT 2 SMALL HALL	AIR	-2,28	-2,85	-1,93	-1,08	-0,53	-0,13	0,08	0,18	0,23	0,18	-0,60	-1,36
	ROCK	-2,33	-2,63	-2,00	-1,23	-0,78	-0,30	-0,15	0,03	0,13	0,10	-0,58	-1,20
	Δ	0,05	-0,23	0,08	0,15	0,25	0,18	0,23	0,15	0,10	0,08	-0,02	-0,16
MEASUREMENT POINT 3 GREAT HALL/ COLLAPSED DOME	AIR	-2,40	-3,10	-1,95	-1,08	-0,58	-0,20	-0,08	0,03	0,15	0,10	-0,66	-1,54
	ROCK	-2,60	-2,80	-1,88	-1,28	-0,75	-0,35	-0,23	-0,03	0,10	0,06	-0,52	-1,36
	Δ	0,20	-0,30	-0,08	0,20	0,18	0,15	0,15	0,05	0,05	0,04	-0,14	-0,18
MEASUREMENT POINT 4 RUFFINY'S CORRIDOR	AIR	-2,55	-2,83	-1,93	-1,50	-0,78	-0,38	-0,10	0,05	0,05	-0,04	-0,70	-1,68
	ROCK	-2,40	-2,75	-1,90	-1,55	-1,08	-0,78	-0,60	-0,25	-0,13	-0,06	-0,70	-1,52
	Δ	-0,15	-0,08	-0,03	0,05	0,30	0,40	0,50	0,30	0,18	0,02	0,00	-0,16
MEASUREMENT POINT 5 JELLY FISH	AIR	-3,00	-3,40	-2,35	-1,73	-0,98	-0,60	-0,48	-0,35	-0,23	-0,22	-0,96	-1,94
	ROCK	-2,98	-3,40	-2,23	-1,90	-1,25	-0,75	-0,65	-0,50	-0,25	-0,28	-0,82	-1,80
	Δ	-0,02	0,00	-0,13	0,18	0,28	0,15	0,18	0,15	0,03	0,06	-0,14	-0,14
MEASUREMENT POINT 6 ICEFALL	AIR	-3,63	-3,93	-2,58	-1,90	-0,90	-0,48	-0,38	-0,25	-0,13	-0,16	-1,12	-2,18
	ROCK	-3,38	-3,40	-2,70	-2,05	-1,20	-0,70	-0,53	-0,35	-0,25	-0,34	-0,92	-2,08
	Δ	-0,25	-0,53	0,13	0,15	0,30	0,23	0,15	0,10	0,13	0,18	-0,20	-0,10

In this zone, the potential period of the crystals formation lasts from the end of winter to autumn.

The above-mentioned settlements compared to the results of charting of the deposit range (Fig. 10.) and the results of the air movement measurements have served for the determination of six stages of the creation and destruction of the ice crystals in the Dobšinská Ice Cave.

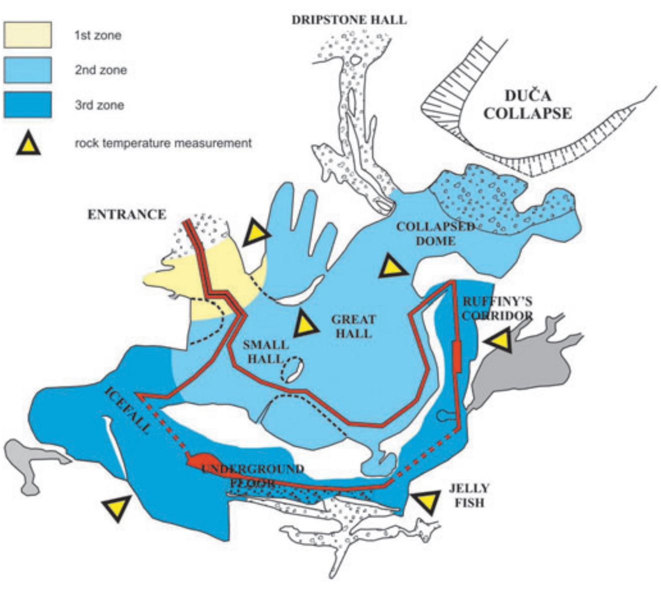


Fig. 9. The division of the cave on zones in terms of potential conditions of ice crystals sediments formation

STAGE I.

The first stage commences from the first frost and is characterized by gradual cooling of the cave associated with the activation of the winter type of air exchange in the cave. The chill moves forward in the orogenic belt from the entrance opening inside the cave. In this period, the rock inside the cave is not cooled down enough (Tab. 1.). This condition is not to the advantage of the ice crystals creation. The first layers of the deposit are formed only in those places where the warm cave air flows onto the surface (Fig. 11a.). Simultaneously, disappearance of the remaining crystals at the back of the cave moves forward as a result of the ice sublimation in contact with the inflowing cool and relatively dry external air (Fig. 11b.). The end of this stage is in January.

STAGE II.

At this stage of the deposit development, the rock walls of the front part of the cave (the Small Hall and the chamber adjacent to it) are already cooled down enough for the process of the gradual growth of the crystals to intensify (Tab. 1. Fig. 11a.). Continuous intensive supply of the air from the back of the cave, for which an air stream under the ceiling is responsible flowing from the Ruffiny's Corridor through the Great and Small halls towards the exit (Fig. 2.), works in favour the deposit growth. In the zone where the opening is located, the boundary for the ice crystals

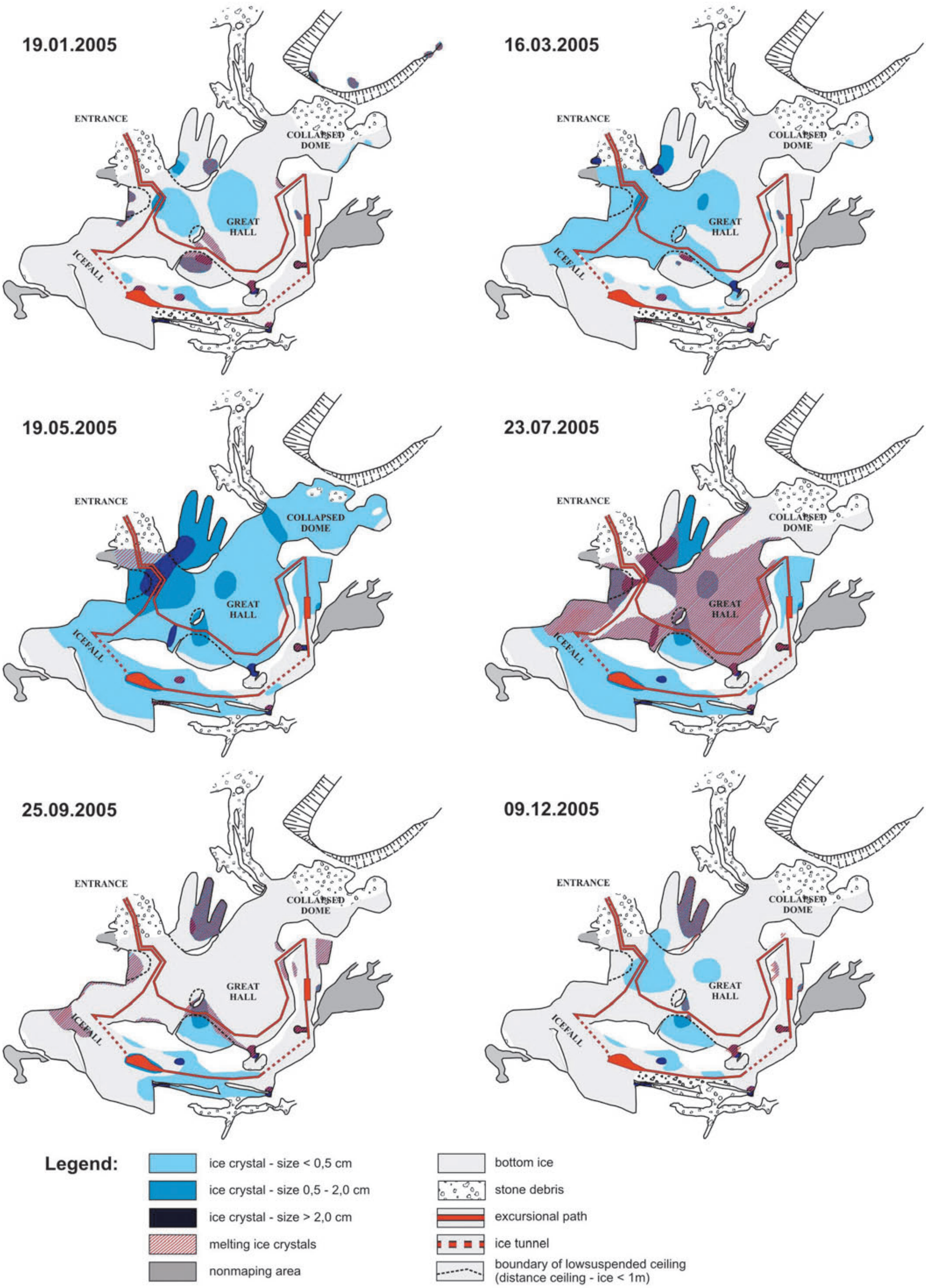


Fig. 10. The course of development and the degradation of ice crystals sediment in Dobšinská Ice Cave in 2005

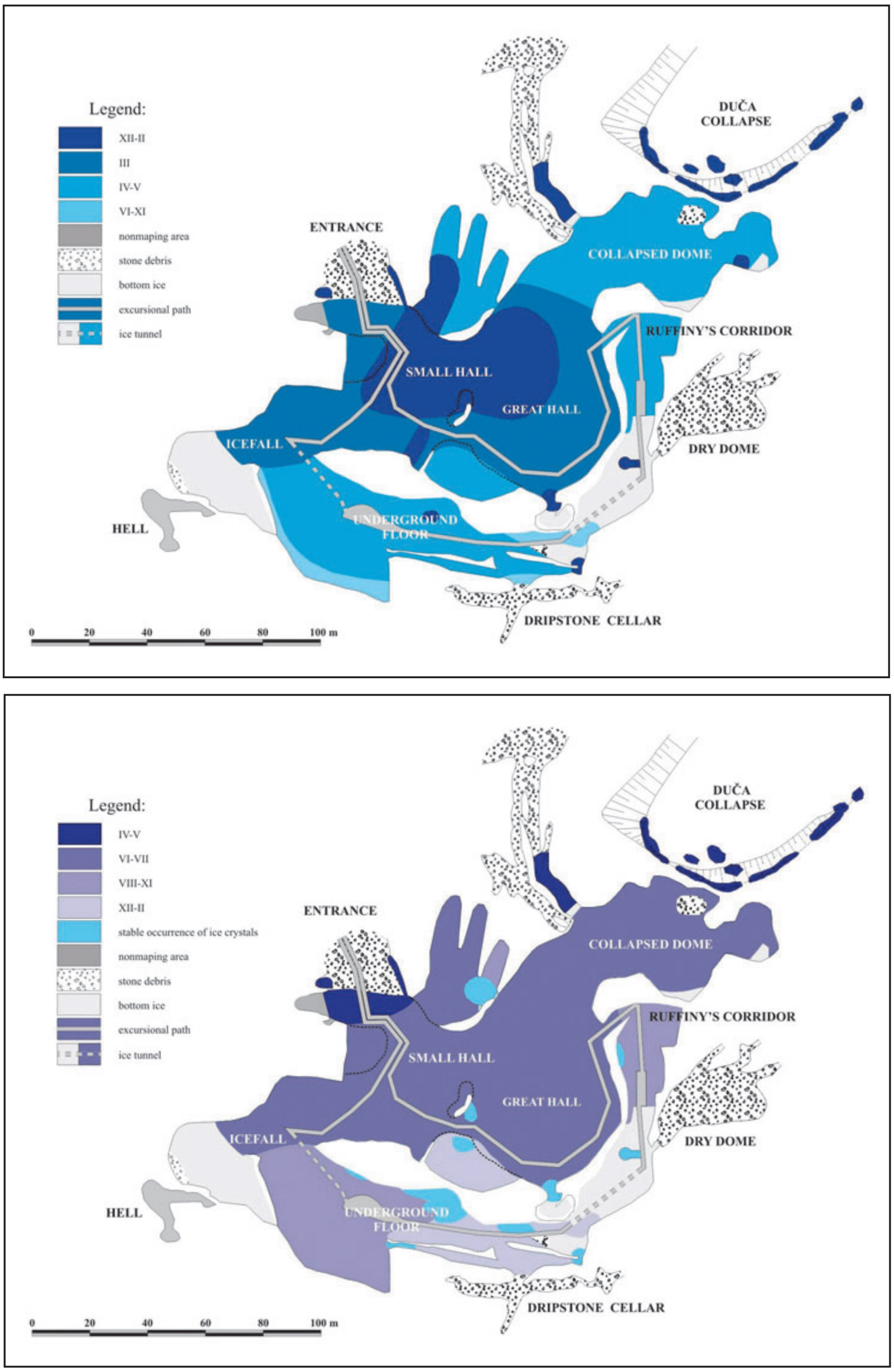


Fig. 11. The scheme of development (a) and degradation (b) of ice crystals sediment in Dobšinská Ice Cave

development is routed along lowering of the ceiling between the Small Hall and the cave exit. The reason for its forming is blocking of the cave air outflow through the intensive inflow of the external air. As a result, the cave air finds escape through the side clefts where it joints the air that flows from the Dripstone Hall. Development of the crystals in the chambers located on the north side of the Small Hall (which are adjacent to those parts of the cave that are not covered with ice) is partly associated with the outflow of warm air from the Dripstone Hall. The second zone of the crystals growth develops in a corridor that connects the Dripstone Hall and the Collapsed Dome.

The crystals which are created at this stage of their development reach considerable sizes and usually form compact covers of large thickness. The pace of an increase of the ice crystals range corresponds to the pace of the cave cooling. The boundary of the deposit determines a zone in which a rock temperature is lower than a temperature of silver frost for the cave air.

STAGE III.

The beginning of the third stage of the ice crystals deposit formation is in a period of the warmer weather in the second half of winter (March). It is enough warm for the activation of the summer type of air exchange with an active flow of air stream from the Collapsed Dome to the Small Hall and the entrance opening (disappearance of the cave air outflow blocking effect). As a result, the whole zone from the Small Hall to the exit, which is cooled down to the great extent, gets covered with crystals (Fig. 11a.). The range of the ice crystals deposit also gradually increases in the Great Hall. Their growing is supported by the considerable cooling down of the area after the winter (Tab. 1.), and a continuous supply of the transformed cave air from the Ruffiny's Corridor (with an active winter phase), or from the Collapsed Dome (with the summer type of air exchange).

The development of the ice crystals in the Icefall zone (Fig. 11a.) is associated with the stopping of flow of the air from the upper level of the cave to its lower level when the summer type of air exchange activates within the cave area. In the chambers of the lower level, the air that stagnates is subject to the gradual transformation and becomes wetter and wetter (Fig. 8b.). Its contact with the rock which is cooled down to the great extent intensifies the process of the sublimation ice settling. The phenomenon is the most intensive in the Icefall, an area which is cooled down to the greatest extent in winter. A periodical supply of energy released during the melt water infiltration is likely to make some contribution to the ice crystals development in this part of the cave. The Icefall is located relatively close to the surface of the orogenic belt therefore excess of the infiltration water from the Small Hall flows down the Icefall at the same time. The heat which comes from this water heats and saturates the air layer over the ice surface with steam. The air lifted as a result of the convection phenomenon cools down at the contact with the rock and intensifies the sublimation process (in this period, the rock temperature in the Icefall zone amounts to approximately -3 °C). It is likely that the similar phenomenon occurs in the other parts of the cave however its intensity is low.

STAGE IV.

The fourth stage lasts from April to May. It is characterized by the ice crystals development within the whole cave area (Fig. 11a.) caused by the stabilization of the summer type of air exchange. The cooler weather periods occur occasionally in the early spring. The rare cases of the external air inflow do not considerably influence a tendency for a gradual growth of temperature and humidity of the cave air. Its transformation is intensified by a continuous inflow of the wet and relatively warm air flowing out of the rock debris in the Collapsed Dome and the cave air from the chambers of the Dry Dome and the Stalactic Cellar which are not covered with ice. In this process, a contribution of energy and humidity released from the infiltrating melt water increases. In the still very cold interior of the cave, there are optimum conditions for development of the ice crystals deposit. However, a low dynamic of the air exchange within the area of the lower level chambers of the cave causes that the crystals that are formed there have small sizes and often do not create compact covers. Simultaneously, in the zone where the opening is located and in the rock debris adjacent to the Duca Collapse, destruction of the deposit takes place (Fig. 11b.). This process is directly associated with the thermal conditions outside the cave and a growth of temperature in this part of the orogenic belt. Stopping of the inflow of cool air to the Dripstone Hall causes gradual degradation of the crystals within its whole area.

STAGE V.

From June to July, gradual degradation of the ice crystals occurs within the area of the upper part of the cave (Fig. 11b.). In this time, the rock debris that connects the Collapsed Dome to the Duca Collapse is gradually heated as a result of a continuous flow of the warm air sucked out of the outside. At the same time, as a result of thermal conductivity and energy exchange, the rock temperature in this part of the cave grows (Tab. 1.). The process of heating of the orogenic belt and the cave inside is accelerated by the precipitation water infiltration and an additional supply of heat from the anthropogenic sources. The combined operation of the above-mentioned factors commences, and then, intensifies the ice crystals cover degradation.

STAGE VI.

Stage VI lasts from August to November. At this stage, the crystals disappear almost everywhere in the cave. In spite of the still prevailing potential conditions for the crystals formation in the chambers at the lower level of the cave (Tab. 1.), the crystals start to slowly disappear there, too (Fig. 11b). It is influenced by the gradual heating of this part of cave and acceleration of the crystals melting as a result of heat supply from the tourist traffic. The deposit degradation covers the area of the Icefall, the Underground Floor, and the Ruffiny's Corridor where the platforms on which the tourists stop for a few or more minutes are located.

From June to November (Stage V and VI), the crystals are still formed in the lowest, most isolated and coolest parts of the cave (Fig. 11a.). These zones have a very low ceiling and are located aside the main chambers of the cave, the isolated chambers and deep rock clefts. The isolation and morphology of these zones prevent a supply of heat brought in during the air exchange in the cave and the heat emitted by the tourists and the light sources. The crystals that are formed in these zones build up their covers which last for the all the year round. Durability of the covers often results from its considerable thickness (from a thickness of 0.5 m). Every year, only the surface layer of the growing new crystals is subject to melting. They form e.g. at cleft outlets through which warmer air flows into the parts of the cave covered with ice from the rock vacuum located at the end of the orogenic belt (e.g. in the vicinity of the Stalactic Cellar).

SUMMARY

In the area of the Dobšinská Ice Cave covered with ice, an occurrence of the sublimation ice crystals deposit is a typical and permanent phenomenon. The deposit forms extensive ice covers with diversified crystal sizes and age. Formation and destruction of the ice crystals have six stages which differ from each other in respect in respect of a scope of influence of the main causative factors which favours a growth or fading of the cave deposit. The factors have been put in the order of their influence on the course of the deposit evolution and are as follows:

- exchange of air between the cave and the surroundings, and inside the cave (which regulates cooling of the orogenic belt in the cave);
- extent, pace and range of the orogenic belt cooling or heating;
- size and changeability of intensification of the melt and precipitation water infiltration in the cave in time;
- volume of the anthropogenic energy supply.

The specific features of the air movement in the Dobšinská Ice Cave are shaped through the development of the winter or summer phase of the thermal air current. An occurrence of this effect depends on the cave morphology. In consequence, the air flow in the cave is characterized by periodical and spatial structural diversity, which facilitates the exchange of energy and steam inside the cave system. The exchange accelerates the process of transformation of the inflowing air and the cave air, and thus influences the development or degradation of the ice crystals covers.

Three zone have been sectioned off within the cave area, which differ from each other in respect of the thermal conditions of the rock walls which influence the ice crystals formation. As a criterion for sectioning off these zones, a difference of temperatures between the rock surface and air has been assumed. The zones are as follows: the zone where the opening is located, the zone of the upper level of the cave, and the chambers of the lower level covered with ice. In each of these zones, the period of the greatest development of the ice crystals deposit comes in a different time and depends on the extent of the rock cooling down. The ice crystals deposit is formed when a stream of energy is directed from the air to the rock or another filling of the cave if $T_{air}>T_{rock}$, and T_{air} and $T_{rock}<0$ (T_{air} – air temperature, T_{rock}.- rock temperature). Destruction of the deposit occurs if $T_{air}>0$ and T_{rock} is equal to the temperature of ice crystals. The crystals are not formed in a period in which the flow of energy takes place from the walls to the air that fills in the cave if $T_{air}<T_{rock}$, and T_{air} and $T_{rock}<0$. In the conditions when $T_{air}>T_{rock}$, and T_{air} and $T_{rock}>0$, the liquid deposit condenses.

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