

NCKRI SYMPOSIUM 4 Proceedings of the 6th International Workshop on Ice Caves

National Cave
and Karst Research Institute
400-1 Cascades Avenue
Carlsbad, New Mexico 88220

ISBN 978-0-9910009-4-4

2014

NCKRI SYMPOSIUM 4

Proceedings of the 6th International Workshop on Ice Caves

Edited by: Lewis Land



National Cave and Karst Research Institute

www.nckri.org

NATIONAL CAVE AND KARST RESEARCH INSTITUTE
SYMPOSIUM 4

6TH INTERNATIONAL WORKSHOP ON ICE CAVES

August 17 through 22, 2014
Idaho Falls, Idaho, USA

EDITORS:

Lewis Land
New Mexico Bureau of Geology and Mineral Resources,
and National Cave and Karst Research Institute;
New Mexico Institute of Mining and Technology

Zoltan Kern
Institute for Geological and Geochemical Research, Hungarian Academy of Sciences

Valter Maggi
Environmental Sciences Department, University of Milano-Bicocca

Stefano Turri
GeoSFerA



Published and distributed by

National Cave and Karst Research Institute

Dr. George Veni, Executive Director

400-1 Cascades Ave.
Carlsbad, NM 88220 USA
www.nckri.org

Peer-review: Editors of the Proceedings Volume of the 6th International Workshop on Ice Caves

The citation information:
Land L, Kern Z, Maggi V, Turri S, editors. 2014. Proceedings of the Sixth International Workshop on Ice Caves, August 17-22, Idaho Falls, Idaho, USA: NCKRI Symposium 4. Carlsbad (NM): National Cave and Karst Research Institute.

ISBN 978-0-9910009-4-4

TECHNICAL PROGRAM CHAIRS

George Veni
National Cave and Karst Research Institute

Andreas Pflitsch
Ruhr University Bochum

Produced with the assistance of the University of South Florida - Tampa Library.

IWIC SPONSORS:

US National Park Service through Craters of the Moon National Monument and Preserve and Timpanogos Cave National Monument

Cover Photo: Booming Ice Chasm was recently discovered in Canada and is possibly the largest ice cave known in North America. It is one of the caves examined in the enclosed paper, *Stable Isotope Composition of Perennial Ice in Caves as an Aid to Characterizing Ice Cave Types,* by Chas Yonge. Photo courtesy of Francois-Xavier De Ruydts.

CONTENTS

Organizing Committee ..... *v*

Foreword ..... *vi*

Ice Cave Processes

Numerical modeling of formation of a static ice cave—Ningwu Ice Cave Shanxi, China
Shaohua Yang and Yaolin Shi *7*

Can glacier in ice cave cut U-shaped valley—a numerical analysis
Shaohua Yang and Yaolin Shi *12*

The influence of karst topography to ice cave occurrence—example of Ledena Jama in Lomska Duliba (Croatia)
Nenad Buzjak *17*

Ice connected processes in the morphology of the cave—an example from Snezna Jama, Slovenian Alps
Andrej Mihevc *24*

Study of multiyear ice in Medeo Cave (north Ural)
Yuri Stepanov, Bulat Mavlyudov, Alexandr Tainitskiy, Alexandr Kichigin, and Olga Kadebskaya *25*

New research in cave Ledenica in Bukovi Vrh on Velebit Mt. in Croatian Dinaric karst
Mladen Garašic *31*

Characterization of two permanent ice cave deposits in the southeastern Alps (Italy) by means of ground penetrating radar (GPR)
Renato Colucci, Daniele Fontana, and Emanuele Forte *33*

On the mechanism of the naturally-formed ice spikes
Hi-Ryong Byun and Chang-Kyun Park *40*

Stable isotope composition of perennial ice in caves as an aid to characterizing ice cave types
Chas Yonge *41*

Glacier Caves

Internal drainage of glaciers and its origin
Bulat Mavlyudov *50*

The Sandy Glacier cave project: The study of glacial recession from within
Eduardo Cartaya *59*

Climate, Microclimates, and Cave Ice

Time, money and melting ice: Proposal for a cooperative study of the world's cave ice in a race against climate change
George Veni **65**

Analysis of selected climatologically observations of talus & gorge ice caves in New England
David Holmgren and Andreas Pflitsch **68**

Some new potential subterranean glaciation research sites from Velebit Mt. (Croatia)
Neven Bocic, Nenad Buzjak, and Zoltán Kern **72**

Climate study in an abandoned auto tunnel in Alaska, USA
Andreas Pflitsch and David Holmgren **77**

Schellenberger ice cave (Germany): A conceptual model of temperature and airflow
Christiane Meyer, Andreas Pflitsch, David Holmgren, and Valter Maggi **82**

Ice cave monitoring at Lava Beds National Monument
Katrina Smith **88**

The MONICA (Monitoring of ice within caves) project: A multidisciplinary approach for the geophysical and paleoclimatic characterization of permanent ice deposits in the southeastern Alps
Renato Colucci, Emanuele Forte, Barbara Stenni, Marco Basso Bondini, Mauro Colle Fontana, Costanza Del Gobbo, Daniele Fontana, Doriana Belligoi, Valter Maggi, and Marco Filipazzi **93**

Bridging the work of field scientists and the needs of data re-users
Antonia Rosati and Lynn Yarmey **95**

Ice caves on extraterrestrial bodies: What are the prospects for speleogenesis and detection?
Penelope Boston **96**

ORGANIZING COMMITTEE

Workshop Co-Chairs
- George Veni, Ph.D., National Cave and Karst Research Institute
- Andreas Pflitsch, Ph.D., Ruhr University Bochum

Advisors
- Valter Maggi, Ph.D., Environmental Sciences Department, University of Milano-Bicocca
- Aurel Persoiu, Ph.D., Department of Geography, University of Suceava

Proceedings Managing and Assistant Editors
- Lewis Land, Ph.D., New Mexico Bureau of Geology & Mineral Resources and National Cave and Karst Research Institute
- Zoltan Kern, Ph.D., Institute for Geological and Geochemical Research, Hungarian Academy of Sciences
- Valter Maggi, Ph.D., Environmental Sciences Department, University of Milano-Bicocca
- Stefano Turri, Ph.D., GeoSFerA - Studio Associato di Geologia

Field Trips
- Andy Armstrong, National Park Service
- Scott and April Earl, Idaho Cave Survey
- Andreas Pflitsch, Ph.D., Ruhr University Bochum

Hotel/Conference Facilities
- George Veni, Ph.D., P.G., National Cave and Karst Research Institute

Public relations
- Suzanna Langowski, National Cave and Karst Research Institute

Program with Abstracts
- Bonny Armstrong, National Park Service

Website
- Jill Orr

Logo
- Mark Rabin, Websnare, Inc.

Registration/Treasurer
- Debbie Herr, National Cave and Karst Research Institute

FOREWORD

Welcome to the Sixth International Workshop on Ice Caves (IWIC VI) in Idaho Falls, Idaho, USA. The National Cave and Karst Research Institute is pleased to host the first IWIC to meet outside of Europe, which will include speakers from over half a dozen countries in Europe, Asia, and North America. The conference setting in this mountainous region of the northwestern United States will provide conference participants with multiple opportunities to visit ice caves, including two trips to Craters of the Moon National Monument. This is also the first IWIC to examine ice in lava tube caves.

A number of different topics relating to cave ice will be addressed during this workshop, but a recurring theme will be the impact of global climate change on ice caves around the world. The last presentation on Monday evening will specifically address the need for increased international research in this area, and will be followed by an open discussion of efforts to acquire funding for future collaborative research.

We wish to thank the organizers of the conference, particularly co-chairs George Veni and Andreas Pflitsch, and our field trip leaders, Scott and April Earl and Andy Armstrong. I would also like to acknowledge the support and assistance of my co-editors and reviewers, Zoltan Kern, Steffano Turri, and Valter Maggi.

Thank you for your participation, and for your contributions to this year's proceedings; and please enjoy your visit to Idaho Falls.

Lewis Land
Proceedings volume editor

Edited by:

Lewis Land
New Mexico Bureau of Geology and Mineral Resources
and the National Cave and Karst Research Institute;
New Mexico Institute of Mining and Technology.

Zoltan Kern
Institute for Geological and Geochemical Research
Hungarian Academy of Sciences

Valter Maggi
Environmental Sciences Department, University of Milano-Bicocca

Stefanno Turri
GeoSFerA

National Cave and Karst Research Institute

NUMERICAL MODELING OF FORMATION OF A STATIC ICE CAVE – NINGWU ICE CAVE, SHANXI, CHINA

Yaolin Shi
No.19A Yuquan Road
Beijing 100049, China, shyl@ucas.ac.cn

Shaohua Yang
No.19A Yuquan Road
Beijing 100049, China, yangshaohua09@sina.com

Abstract
Ningwu Ice Cave in Shanxi province, China, is the largest Ice cave in China. We use Finite Element Method（FEM) to model the process of heat transfer in the ice cave. We not only calculate thermal conduction in spring, summer and fall, but also calculate the convective heat transfer in winter by introducing an equivalent thermal conductivity of cave air. Our computation shows that the ice cave can be formed within a decade, and reach a stable cyclic state in few centuries. Our calculation also shows that if people set a trap door at the ice cave entrance, especially in winter, the cave ice then cannot be convectively cooled down in winter and will melt within less than 40 years. This is probably happening in some scenic ice caves in China.

Introduction
Ningwu Ice Cave (38º57' N and 112°10' E, elevation 2121m) is located in the shady slope of Guancen Mountain in Ningwu County, Shanxi Province, China (Shao et al., 2007). The cave is bowling-like, with only one opening upwards, therefore, a typical static cave (Luetscher and Jeannin, 2004). It extends downward from the ground to a depth of about 85m. The widest part is in the middle with a width of 20m. Above the depth of 40m, there are only layered ices, and there are lots of ice bodies along the wall below the 40m (Fig. 1). The outside of the ice cave keeps a temperate climate. The annual average temperature is 2.3°C (Meng et al., 2006). The external mean annual temperature is 2.3°C (Meng et al., 2006), without any ice preservation on the mountain area.

Some Chinese researchers suggest a "cold source" beneath the cave may explain the existence of the ice cave (Chen, 2003). Temperature usually increases with depth at a geothermal gradient about 1-3°C/100m or so (Hu et al., 2001), and there have been persistent heat flows from the deep crust to the surface. Even if there was a cold region somehow formed, it will be heated up under the effect of geothermal flux. Reversal of geotherms can occur only in cases of existence of advective heat transfer due to crustal movement or ground water flow (Shi et al., 1987). However, as long as the motion stops, it will return to normal geothermal gradient under the heating of terrestrial heat flow. There must be a sustainable mechanism to remove the heat from underneath and ensure the maintenance of the ice cave.

The main reason for formation of ice caves is due to air convection in winter to cool down the cave. In spring, summer and fall, heavy cold air sinks in the cave, and no natural thermal convections occurs. Conduction is the main form for heat transfer. Thermal conductivities of either rock or air are quite low and the conductive heat transfer is very inefficient, therefore, the temperature rise in the ice cave in the three seasons is quite limited. In winter, although the temperature inside the ice cave is low, the outside air temperature is even lower. The air in the ice cave is lighter than the air outside the entrance. It could become gravitationally unstable, and thermal convection could occur. External very cold air flows into the cave to cool it down, removes the heat from the cave and reduces cave temperature below 0°C. Since the convective heat transfer is much more efficient than the conduction heat transfer, the heat transferred out of the cave in the a few winter months is comparable to the heat transferred into the cave year around.

We intend to apply numerical simulation tools to explore the formation and preservation of a special static cave of Ningwu Ice Cave. FEM (Finite Element Method) is used to calculate heat transfer process due to thermal conduction and air convection in order to quantitatively interpreting the formation and preservation mechanism of ice bodies in Ningwu Ice Cave. The results will be instructive to scientifically manage the usage of natural tourism resources.

Principle of numerical modeling
For numerical modeling, the basic equation of heat transfer is given as:

$$c\rho(\frac{\partial T}{\partial t}+u\nabla T)=k\nabla^2 T \qquad (1)$$

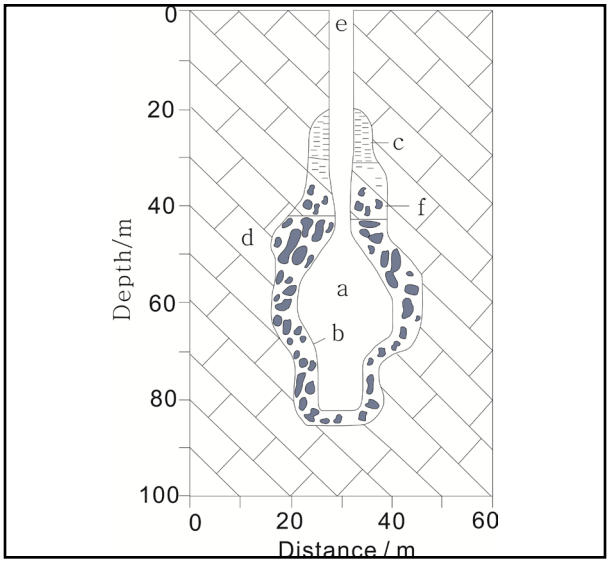






Figure 1. *(A). Cross section of Ningwu Ice Cave a. Air, b. Massive ice body c. Horizontal layered ice body d. Surrounding rocks (limestone) e. Entrance of ice cave f. Fracture of surrounding rock g. (from Meng et al., 2006); (B)(C)Picture of the inside of the ice cave.*

Where c is the specific heat, ρ is density, T is temperature, t is time, k is thermal conductivity, u is the velocity of air flow. The difficulty in the problem is that the air convection may be turbulent and the velocities are not known. Therefore, the convective heat transfer term cannot be directly calculated. However, it is well known that in natural convection case, the overall heat transfer due to convection will be Nu times greater than the purely conduction case. Nu is the Nusselt number, and can be determined from experiments and/or numerical calculations. An equivalent thermal conductivity of air (Nu times greater than the true conductivity) can be introduced in the thermal conduction equation to calculate the effective heat transfer due to convection in the winter (Schmeling & Marquart, 2014).

Ningwu ice cave can be approximated by an up-right circular tube. For such up-right circular tube, Nu can be calculated as:

$$Nu_m = C(Gr \cdot Pr)_m^n \quad (2)$$

Nu_m is the Nusselt number, the subscript m represents for the arithmetic mean temperature of the boundary layer; Gr is the Grashof number, Pr is the Prandtl number; both can be calculated from material properties (Table 1) and specific cave geometric shapes. C and n are constants. After a series of calculations, for Ningwu ice cave:

$$Nu = 11000(0.0740\Delta T)^{1/3} \quad (3)$$

The annual average temperature outside Ningwu ice cave is about 2.3°C (Meng et al., 2006) and the average daily temperature (from 1957 to 2008) is obtained from Wuzhai meteorological station, which is the station closest to the ice cave. By making an elevation correction, we then obtain the annual temperature variation outside the ice cave (Fig. 2) which is assigned as the upper surface boundary condition. The mean value of geothermal gradient in the area is 2.0°C/100m (Li, 1996). Based the thermal gradient, temperature boundary conditions are assigned to the both sides of the model. Heat flow boundary condition is assigned for the bottom boundary. The terrestrial heat flow value is the product of geothermal gradient times the thermal conductivity of the limestone wall rock. The initial condition is assumed to be the normal thermal gradient. The calculation, then, simulates the formation process of the ice cave.

In the finite element computation, in every time step (1 day in our calculation), it is judged from difference

Table 1. *Material properties.*

Material	Heat Conductivity (W/m.K)	Density (Kg/m3)	Specific Heat (kJ/kg.K)
Limestone	2.7	2500	0.84
Ice	2.23	916.5	2.05
Mixture	2.465	1708.25	1.445
Air	0.0243	1.293	1.005
Water	0.58	1000	4.2

between the bottom temperature of the cave and air temperature outside the cave whether convection would occur or not. If no convection occurs, the true thermal conductivity of air will be used. If convection should occur, the equivalent thermal conductivity will be used for the cave air.

Results of computation

Figure 3 shows the evolution of temperature at the bottom of the ice cave from a normal geothermal gradient. It can be regarded as the process of formation of ice cave. Internal temperature of the cave drops rapidly in the first decade, then its drop slows down gradually and, at last, it tends to become stable cyclic. The permanent ice (cave temperature below 0°C year round) can be formed only after 5 years.

Figure 4 shows the cave temperature annual fluctuations when the process has lasted a time of two centuries, long enough to be evolved to a stable cyclic state. The amplitude of temperature variation is about

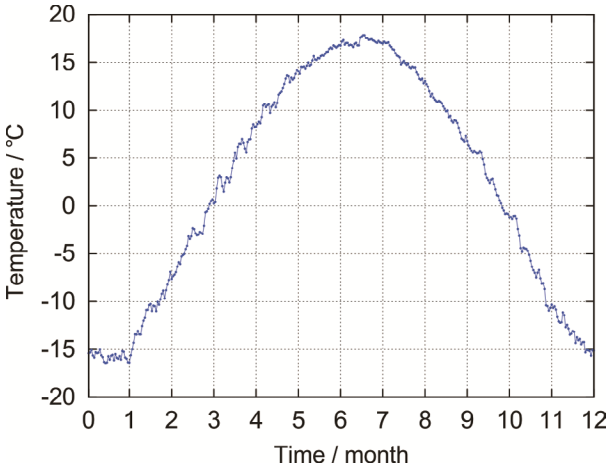


Figure 2. *Averaged daily temperature (1957-2008) outside the Ice Cave.*

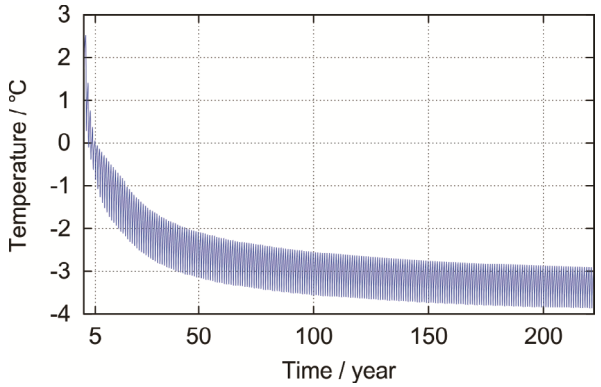


Figure 3. *Variation of temperature at bottom of the cave during the formation process of the ice cave.*

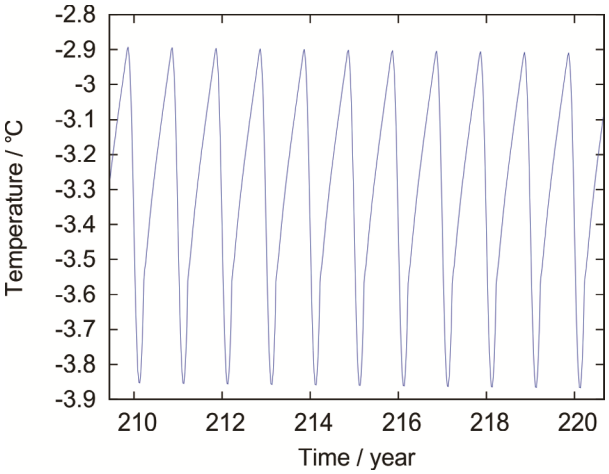


Figure 4. *Cave temperature at stabilized stage.*

1°C (from -3.9°C to -2.9°C). Ningwu ice cave has been open to tourists. Therefore, the cave temperature has been disturbed. By our actual measurement on June 5, 2012, the lowest internal temperature of ice cave was -1.5°C. And through the record in literature, the actual measured internal temperature of ice cave goes between -1.0°C (Meng et al., 2006), -4°C and -6°C (Gao et al., 2005). The difference of actual measured results may be caused by difference in measuring method and differences in measuring time and position. The cave temperature presents annually periodic variation. It increases in spring, summer and fall and rapidly decreases in winter because efficiency of heat conduction in spring, summer and fall is much more ineffective than convective heat transfer in winter.

Figure 5 shows the spatial temperature distribution around ice cave in summer. It is apparent that even in summer, a significant part of the cave and its surrounding rocks are under 0°C.

The ice body in the ice cave will melt if there is no air convective heat transfer in winter, such as to build a seal door at the entrance to prevent air flowing into the cave. The temperature variation is shown in Figure 6. It takes about 20 years to start the melting of ice at the bottom of cave, but requires 37 years to thaw the ice body completely. Because the melting of ice absorbs significant amount of latent heat (334kJ/kg), the heat to melt 1kg ice is sufficient to raise the temperature of 1kg limestone by 397.6°C.

Discussion and Conclusion

There is no dating of age of neither the cave nor the ice in the cave. The age of the cave and the age of the ice body are different. Formation of the cave cavity could be old and in a warmer climate. The formation of the ice body in cave is in a process much later when the saccate cave was formed and the climate became cold enough. Actually, in the present climate, our numerical modeling suggested that the year-round ice body can be formed within a decade.

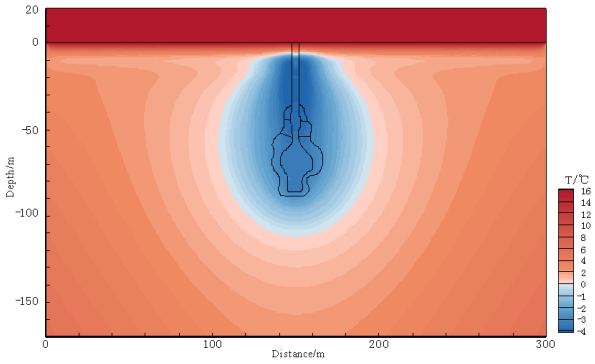


Figure 5. *Temperature Distribution around Ice Cave in Summer.*

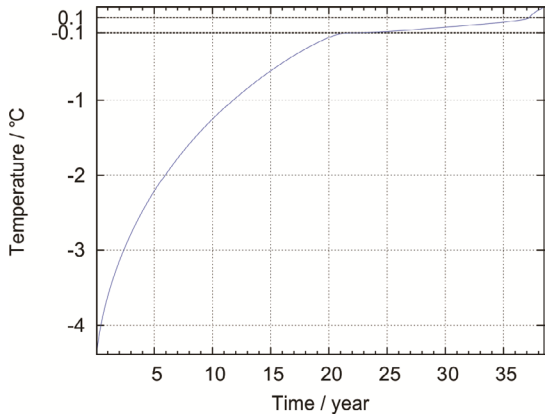


Figure 6. *Temperature variations in the cave if a trap door is installed at the entrance of Ningwu ice cave to prevent air convection in the winter.*

If a trap door is set at the cave entrance, as some other park in China has done for "protection" of the ice cave at night during tour season and the entire winter when the cave is closed to tourist, it actually blocks the air convection in winter; therefore, cold air cannot bring out the heat in the cave and accumulation of heat flow from the surface and from deep crust will finally lead to the melting of ice body in the cave. Our computation shows that it only takes less than 40 years to completely melt the whole ice body in the cave. It suggests that scientific management is important for sustainable usage of natural tourism resources. Otherwise, a good intention, such as to install a trap door to completely seal the entrance for protection, will actually destroy the natural wonder in several decades.

In summary, our finite element computation shows numerical simulation reveals more clearly the mechanism of formation and preservation of Ningwu ice cave. It is shown that the controlling factor for formation and sustainment of ice body in the cave are air natural convection in winter. Under current temperature and geothermal gradient at Ningwu area, starting from a normal geothermal temperature, winter air convection can cool down the cave beneath frozen point within a decade. The cave temperature will decrease gradually to a stable cyclic state. Under the stable cyclic state, the amplitude of annual temperature variation in the ice cave is within 1°C. If the air convective heat transfer is stopped, all ice body in the cave will be completely melted within about 40 years. These analyses are important for sustainable management of the ice cave as a tourism resource.

Acknowledgements

This research is supported by NSFC Project 41174067 and the CAS/CAFEA international partnership Program for creative research teams (No.KZZD-EW-TZ-19).

References

Chen S. 2003. Cave Tourism Science. Fuzhou: Fujian People's Publishing House.

Gao L, Wang X, Wan X. 2005. Analysis of Ice Cave Formation in Ningwu Shanxi. Journal of Taiyuan University of Technology 36: 455-458.

Hu S, He L, Wang J. 2001. Compilation of heat flow data in the China continental area (3rd edition): Chinese Journal Geophysics 44(5): 611-626.

Li Q. 1996. Some characteristics of the geothermal distribution in Shanxi rift zone. Earthquake Research in Shanxi 1: 26-30.

Luetscher M, Jeannin P. 2004. A process-based classification of alpine ice caves. Theoretical and Applied Karstology 17: 5-10.

Meng X, Zhu D, Shao Z. 2006. A discussion on the formation mechanism of the "Ten-Thousand-Year-Old Ice Cave" in Shanxi Province. Acta Geoscientica Sinica 2: 163-168.

Schmeling H, Marquart G. 2014. A scaling law for approximating porous hydrothermal convection by an equivalent thermal conductivity: theory and application to the cooling oceanic lithosphere. Geophysical Journal International 197 (2): 645-664.

Shao Z, Meng X, Zhu D, Yu J, Han J, Meng Q, Lv R. 2007. Detection for the spatial distribution of "Ten Thousand Ice Cave" in Ningwu, Shanxi Province. Journal of Jilin University(Earth Science Edition) 5: 961-966.

Shi Y, Wang C-Y. 1987. Two-dimensional modeling of the PTt paths of regional metamorphism in simple overthrust terrains. Geology 15 (11): 1048-1051.

CAN GLACIER IN ICE CAVE CUT U-SHAPED VALLEY - A NUMERICAL ANALYSIS

Shaohua Yang
No.19A Yuquan Road
Beijing 100049, China, yangshaohua09@sina.com

Yaolin Shi
No.19A Yuquan Road
Beijing 100049, China, shyl@ucas.ac.cn

Abstract
U-shaped valleys are widely found in ordinary glaciers. There are a few huge ice caves in which ice body extends nearly 1km and becomes a glacier in the cave. Can glacier in an ice cave cut the cave and form a U-shaped valley? We use numerical simulation method to study the possibility if a U-shaped valley could exist or not in an ice cave before carrying out costly field work. Our calculation does simulate the formation of U-shaped valley in ordinary glaciers, but the ice cave glacier is too small in size, so that it is not likely to form U-shaped valleys in the lifetime of the cave. Water erosion is the decisive factor in producing the cave.

Introduction
A U-shaped valley, with steep sides and a flat bottom, is formed by the erosion of alpine glaciation (Johnson, 1970; Boulton, 1974). There are a few huge ice caves in which ice body extends nearly 1km and becomes a glacier in the cave, such as Eisriesenwelt Ice Cave in Austria, the largest ice cave of the world. Flow structures both basal and internal can be observed (Hausmann and Behm, 2011). Can glacier in an ice cave cut the cave and form a U-shaped valley? It is an interesting question. The bottom of an ice cave is covered by ice. Geophysical methods could be used to explore the base of glacier, but it usually is not an easy job. Therefore, we use numerical simulation method to study the possibility if a U-shaped valley could exist or not in an ice cave before carrying out costly field work.

Methods
We use a Cartesian coordinate with x-axis across the glacier, z along the glacier, and y perpendicular to the x-y plane pointing up (Figure 1a). Figure 1b is longitudinal glacier profile. α is downglacier slope. We developed a 3D ice flow model coupled with an erosion process. The flow model calculates the velocity field by solving the continuity equation (1) and the Stokes equation (2) for viscous flow.

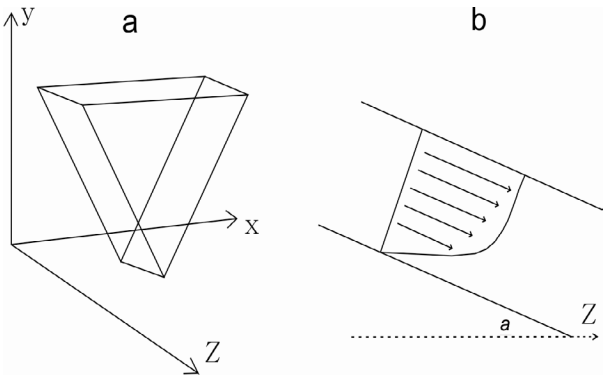


Figure 1. *(a) Initial valley geometry and coordinate system used in the simulations. (b) Longitudinal glacier profile*

$$div(\vec{v}) = 0 \tag{1}$$

$$\frac{\partial \sigma'_{ij}}{\partial x_j} - \frac{\partial P}{\partial x_i} + \rho g_i = 0 \qquad \text{i, j=1,2,3} \tag{2}$$

Where $\vec{v}$ is the velocity vector; *i* and *j* are coordinate indices; x_i and x_j are spatial coordinates; σ'_{ij} is deviatoric stresses tensors; P is pressure; ρ is density; g_i is the i-th component of the gravity vector. For the first order calculation, Newtonian law of viscous friction showed as equation (3) is used.

$$\sigma'_{ij} = 2\eta \hat{\varepsilon}_{ij} \tag{3}$$

Where η is viscosity; $\hat{\varepsilon}_{ij}$ is the deviatoric strain rate tensors. Glacial flow is treated as a non-Newtonian fluid

for the more exacter calculation, and Glen's flow law is used as a constitutive relation. Glen's flow law is showed as below:

$$\dot{\varepsilon} = A\sigma^n \tag{4}$$

Where σ is dominant shear stress; $\dot{\varepsilon}$ is corresponding shear strain rate; A is flow parameter; n is creep exponent.

At the glacier base (y = GB(x)), we introduce the basal sliding by linearly relating the sliding speed u_b to the shear stress acting on the bed τ_b (Weertman, 1964),

$$u_b = -c\tau_b = -c\left(\frac{\partial GB}{\partial x}\tau_{xz} + \tau_{yz}\right) / \sqrt{1+\left(\frac{\partial \mathrm{GB}}{\partial x}\right)} \tag{5}$$

The complex nature of the glacial erosion has not allowed the development of physically complete models for processes such as glacial abrasion, plucking. But we can couple the ice flow model with an erosion model by introducing a quadratic function of the sliding speed for the calculation of the erosion rate. This assumption for the erosion law represents the general form of the abrasion law proposed by Hallet (1979). In this paper, erosion rate normal to the bedrock surface was calculated as equation (6). Where C is an erosion constant equal to 10^{-4} a m^{-1} (Harbor, 1992).

$$E = Cu_b^2 \tag{6}$$

Result - The formation process of an ordinary U-shaped valley

We prescribe a V-shaped cross section with maximum ice thickness of 480m, surface width of 1200m, and downglacier slope of 4° (Figure 2) as the initial glacier and valley geometries. We employ a 3D FEM (Finite Element Method) to solver the Stokes equation with Newtonian law of viscous friction.

Figure 2 shows glacial valley evolution from an initial V-shaped pre-glacial profile computed with the 3D model for different times. The mechanism for such process is shown in Figure 3. Figure 3a, the three graphs in the left column, shows V_y, V_z and erosion rate in the valley respectively at time t = 10ka. The velocity at both

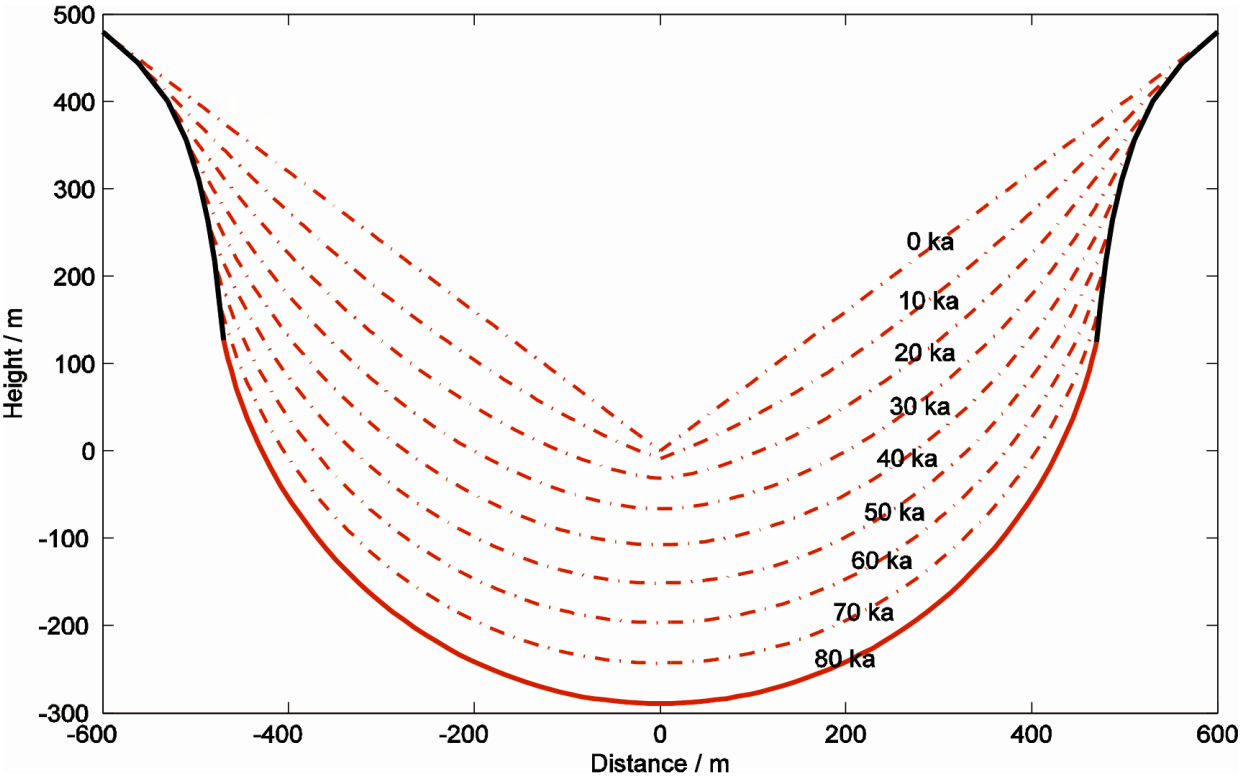


Figure 2. *Glacial valley evolution from an initial pre-glacial profile computed with the 3D model for different times.*

edge of the V-shaped valley is most small, and velocity reach maximum at the center upper part of the glacier. The velocity gradient, however, is largest at the central part of the two edges, and smallest at the bottom of the V-shaped valley and the edge at the top of glacier. The velocity gradient is proportional to the shear strain rate and shear stress. Therefore, largest erosion rate occurs at the central part of two edges of the valley as shown in the bottom figure of Figure 3a. Difference between erosion rates at the center of edge and that at the bottom at the valley prompt the transition from the initial V-shaped valley gradually to a U-shaped valley after dozens of kiloyears.

Figure 3b, three graphs in the right column shows similar figures at the time t=30ka when the valley approaches a U-shaped valley. The overall pattern of velocity distribution of V_y and V_z are similar to those at time 10ka. However, the velocity gradients are different. The difference in velocity gradient between the bottom and edges becomes more and more small, so are the erosion rates as shown in bottom of Figure 3b. At t=10ka, the maximum erosion rate is nearly 60 mm/a at the central part of valley edges, but only 10 mm/a at the valley bottom. The difference is 50mm/a. However, at t=30ka, this difference is reduced to less than 20mm/a. If the erosion continues, at t=60ka the difference is only

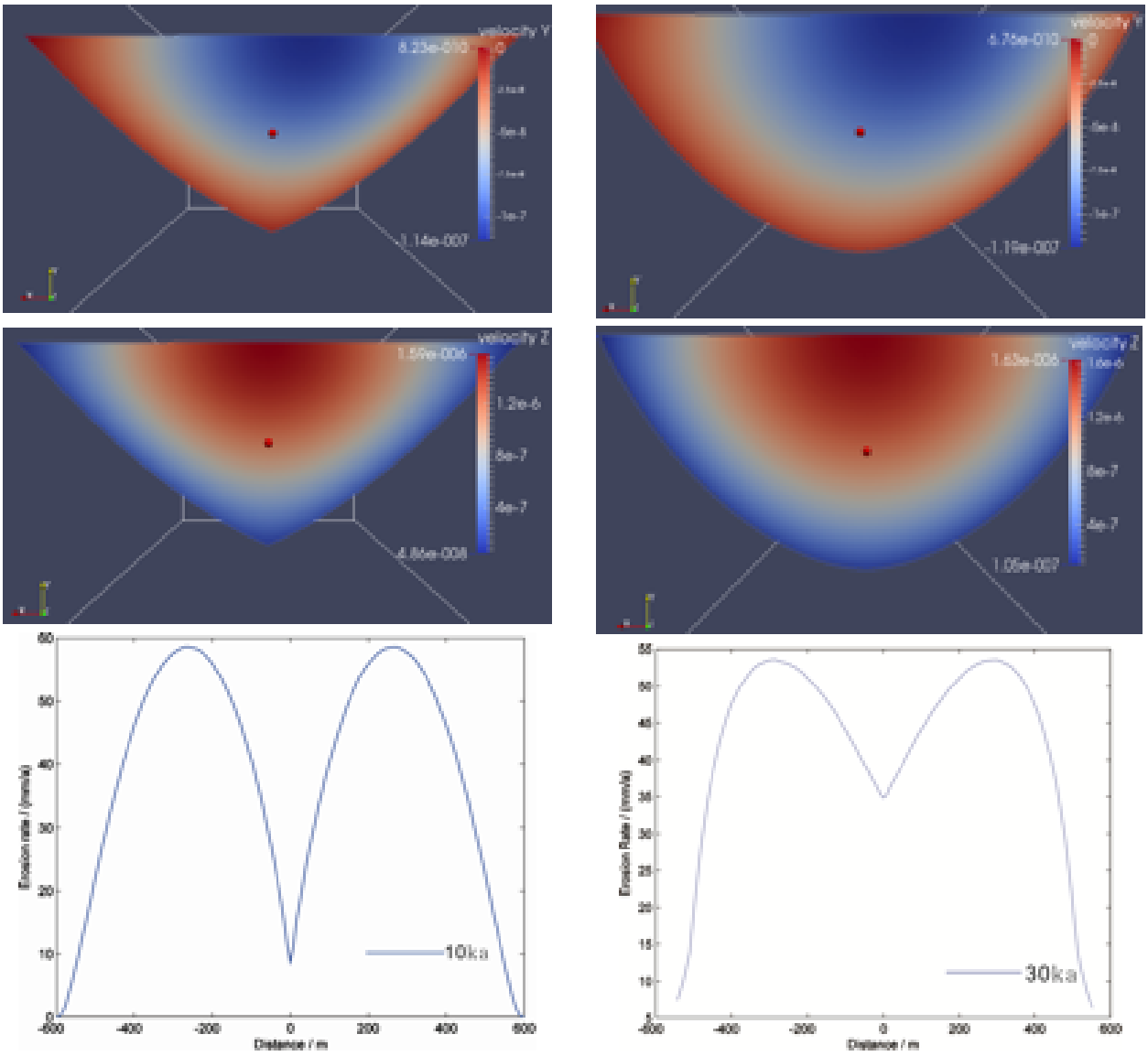


Figure 3. *(a) (b) Cross-glacier variation of V_y, V_z (Unit: m/s) and erosion rates for times t=10 and 30 ka, respectively.*

about 3 mm/a. That means, the U-shape is stabilized, and the valley cut deeper and deeper, but the U-shape keeps almost unchanged at this stage. These results are in agreement with 2-D analysis of Seddik, Greve et al., 2009.

Results - The erosion process in an ice cave

Glaciers in ice caves are much smaller in size in comparison with ordinary glaciers. We prescribe a V-shaped cross section with maximum ice thickness of 8m, surface width of 20m, as the initial glacier and valley geometries. Models of downglacier slope of 4° and 40° are calculated for comparison.

Figure 4 shows the cross-glacier variation of V_y, V_z and glacial shape at time t=50,000 years. The left column is for α=4°and the right column is for α=40° respectively. Although the patterns of velocity distribution are similar to the large size glacier of Figure 3, the magnitude of velocity is much smaller, For α=4° case, the largest velocity is as well as velocity gradient are only about

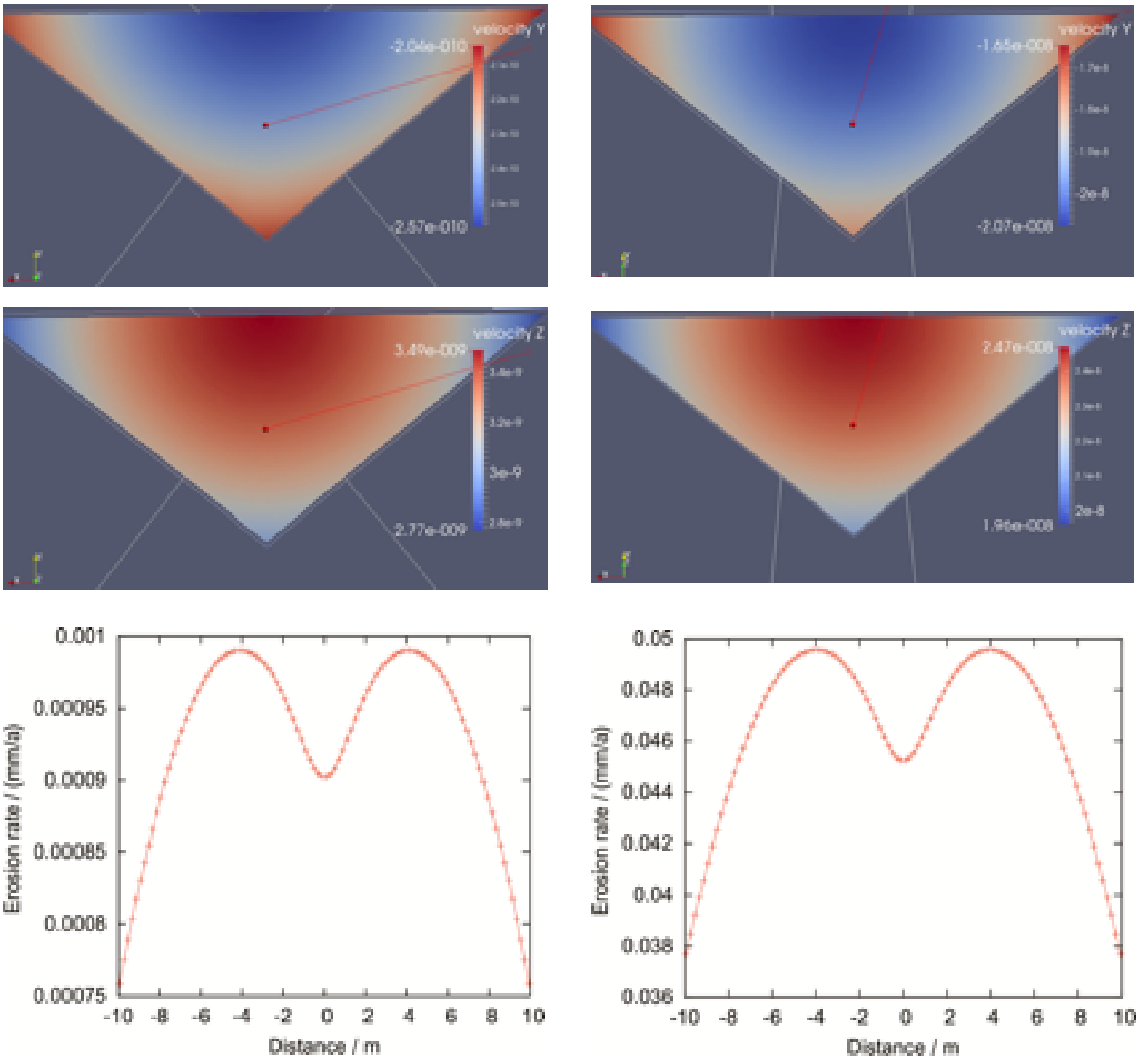


Figure 4. *Cross-glacier variation of V_y, V_z (Unit: m/s) when t=50,000 year; Glacial valley evolution from an initial pre-glacial profile. a. α = 4°; b.α =40°*

1/1000 of those of the large scale glacier of Figure 3. The erosion rate in ice cave is smaller about 50,000 times than erosion rate of U-shaped valley. In another word, if it is need 1 ka, an enough small time, to form a U-shaped valley of ordinary glacier, it has to take about 50 Ma to form a U-shaped valley in ice cave. It is a time too long for the life of cave. For the case of α=40°, both the velocity and the velocity gradient are 10 times greater than that of α=4°. However, the erosion rate is still too small for U-shape valley formation in the life time of a cave.

Discussion and Conclusion

The size of glacier is very important for obtain enough erosion rate to form U-shaped valley. In an ice cave glacier, the size is too small to reach sufficient erosion rate to form U-shaped valley. Before the ice cut the U-shaped valley, the cave may have been reformed by actions of leakage water. Steep slopes may increase erosion rate, but still too small for ice cave glacier.

From the numerical analysis, it is suggested that U-shaped valley is not likely to be able to form in ice caves.

Acknowledgement

This research is supported by NSFC Project 41174067 and the CAS/CAFEA international partnership Program for creative research teams (No.KZZD-EW-TZ-19).

References

Boulton, G. S. 1974. Processes and patterns of glacial erosion, in Coates, D.R., ed. Glacial geomorphology: Binghamton, New York, State University of New York, p. 41-87.

Harbor, J.M. 1992. Numerical modeling of the development of U-shaped valleys by glacial erosion. Geological Society of America Bulletin 104: 1364-1375.

Hallet, B. 1979. A theoretical model of glacial abrasion. J. Glaciol 23: 39-50.

Hausmann H, Behm M. 2011. Imaging the structure of cave ice by ground-penetrating radar. The Cryosphere 5: 329–340.

Johnson, A. 1970. Physical processes in geology. San Francisco, California, Freeman, Cooper & Co, 577p

Seddik, Greve, et al.. 2009. Numerical simulation of the evolution of glacial valley cross sections. arXiv preprint arXiv 9: 1-14

Weertman J. 1964. The theory of glacier sliding. J. Glaciol 5: 287-303.

THE INFLUENCE OF KARST TOPOGRAPHY TO ICE CAVE OCCURRENCE - EXAMPLE OF LEDENA JAMA IN LOMSKA DULIBA (CROATIA)

Nenad Buzjak
University of Zagreb, Faculty of Science,
Department of Geography
Marulićev trg 19/II
Zagreb, Croatia, nbuzjak@geog.pmf.hr

Dalibor Paar
University of Zagreb, Faculty of Science,
Department of Physics
Bijenička 32
Zagreb, Croatia

Vinka Dubovečak
Speleological Society Velebit
Radićeva 23
Zagreb, Croatia

Neven Bočić
University of Zagreb, Faculty of Science,
Department of Geography
Marulićev trg 19/II
Zagreb, Croatia

Abstract

The research of cave microclimate in general contributes to a better understanding of physical and chemical processes in complex karst geoecosystems. Special challenges for researchers are ice caves. The ice contains various fossil, geomorphological and chemical records of the past that can be used for research of former processes or creating climate profiles for paleoenvironmental research. Also, the "pressing need" is to study ice caves due to the significant ice loss that has been documented for the ice caves worldwide (Kern and Perşoiu, 2013).

This preliminary report is a part of the long-term project dedicated to the research of deep caves on Velebit Mt. and pointed to the influence of the large karst depression microclimate to cave microclimate, e.g. ice and snow accumulation. The one year study using T/RH data loggers was conducted in Lomska duliba valley (Velebit Mt.) known for frequent temperature inversion and low air temperature, and in partially ice-snow filled Ledena jama (Ice shaft) located at valley's bottom. The main research was focused on the entrance part of Ledena jama, where the dynamics (accumulation and melting) of perennial ice and snow is significant.

Introduction

All caves with perennial ice and snow in Croatia are situated in Dinaric Mountains. In Croatia they are not of high altitude (up to 1813 m a.s.l.) but are characterized by mosaic of meso- and microclimates. Such climate diversity is, among other relevant factors (like geographical position, altitude etc.), influenced by diverse relief, karst terrain roughness and border position between Adriatic Sea (as the source of warm and humid air) and Pannonian Basin (as the source of cold air masses in winter period). Most of the lower mountain belts (<1500 m a. s. l.) have temperate humid climate with warm summer (Köppen climate type Cfb), and higher parts have humid boreal climate (type Df). Mean annual air temperature (MAAT) in the area around 1000 m a.s.l. is 5.5°C and in the highest parts MAAT=3.5°C. The coldest months are January and February (MMAT=-2 to -5°C) and the warmest one is July (MMAT=12-16°C; Zaninović et al., 2008). But even in the lower altitudes, where larger karst depression (dolines, uvalas, karst poljes) acting as a cold air traps, there are often air temperature inversions documented (Antonić et al., 1997; Buzjak et al., 2011; Horvat, 1952-53; Vrbek et al., 2010). Mean annual precipitation above 1000 m a.s.l. ranges between 1500-3500 mm/y (Zaninović et al., 2008). With altitude rise there is a snow ratio rise in total precipitation.

The study area

Velebit Mt. is the longest and the most spacious Croatian mountain. It is a part of Dinaric karst belt and extends in N-S and NW-SE (Dinaric) direction, making important physiognomic, relief, climate and biogeographical barrier between continental and Mediterranean parts of Croatia. Due to the prevalence of carbonate beds of well-developed secondary and tertiary porosity there is deep karst developed, with all types of surface and subterranean karst forms. The research area is located in the region of Northern Velebit National Park. Up to year 2013 there were 362 (mostly vertical) caves recorded (Dubovečak et al., 2013; Mudronja, 2011; Železnjak

and Mudronja, 2012). This area is widely known among cavers and researcher for deep vertical caves (Bakšić and Paar, 2006; Bočić, 2005; Bočić, 2006; Kuhta and Bakšić, 2001). Three of them are deeper than 1000 m: Lukina jama-Trojama system (-1431 m, the deepest one in Croatian part of Dinarides), Slovačka jama (-1320 m) and Velebita (-1026 m). Many of up to now discovered caves (132) of Northern Velebit contains accumulations of perennial ice and snow recorded to the depths of several hundred meters (Buzjak et al., 2010). Their characteristics are object of a study involving speleological, microclimate, physical, hydrological and geomorphological researches (Paar et al., 2013a, 2013b).

Research history

The first record of the research of Ledena jama, by the Croatian Speleological Society cavers, dates back to the 1962. They explored and mapped entrance chamber up to the depth of about 50 m where they were stopped by the ice and snow plug. The descents into the ice plug holes and below it were successful in 1992 and 1993 when Croatian and Slovakian cavers intensively explored this area. In 1996 cavers reached the bottom, and map was finalized in 1997 (Jelinić, 2001). During the expedition in 1997 there was one of the most serious accidents in recent Croatian caving history when one caver was heavily injured by the ice- and rockfall. Due to the extreme risks connected with ice melting, ice- and rockfalls in deeper passages shaft was avoided and not explored or visited anymore.

First records about Ledena jama microclimate were collected during the botanical, microclimate and ecological researches in 1995 and 1996 (Buzjak, 2001; Vrbek and Buzjak, 2000). During 1995 cavers sampled the ice cores and organic material used for dating (Jelinić et al., 2001). Further analyses, calculations of accumulation and melting rate were performed by Kern et al. (2008). Additional dating of organic material from Ledena jama and comparison with Lukina jama was done by Paar et al. (2013a, 2013b).

Methods

The climate data for surface parameters were obtained from the Main meteorological station Zavižan (Croatian Meteorological and Hydrological Service). It is the highest permanent meteorological station in Croatia, 1594 m a.s.l. (Fig. 1). It is located 6.2 km NW from Ledena jama. Microclimate parameters (T and RH) for Ledena jama and Lomska duliba were measured with Hobo U23-001 RH/Temp (Onset Computer Corporation) and Oakton RH/TempLog (Metex Corporation Limited) data loggers. For the research 8 loggers on different loactions were used. For this preliminary report we selected most representative data from 2 loggers. The surface logger was installed at the bottom of Lomska duliba - on the edge of the entrance to Ledena jama (1235 m a.s.l.). It was mounted on a trunk (N exposure) below treetop and 200 cm above bare surface. The logger in lateral passage in Ledena jama (Fig. 1 and 2) was mounted at the depth of -45 m below the surface, on the thin plastic cork to avoid direct contact with a cave wall and possible direct thermal interactions. The logging intervals were set to 30 and 60 minutes.

Geological and geomorphological settings

Lomska duliba is a large elongated depression (14 km^2, 120 m deep) shaped during Pleistocene as a glacial valley formed by Lomski glacier. During Holocene it is slightly reshaped by karst and periglacial processes. It was developed along Lomski fault and therefore elongated in the direction of WNW-ESE. The area is built of well karstified Upper and Middle Jurassic limestones and dolomites and Paleogene limestone breccias (Velić and Velić, 2009). In the entrance part of Ledena jama Pleistocene and Holocene beds (mostly breccias and rock debris) are known. These beds are the result of glacial erosion and accumulation by the Lomski glacier and recent Holocene periglacial processes (Bognar et al., 1991; Bočić et al., 2013).

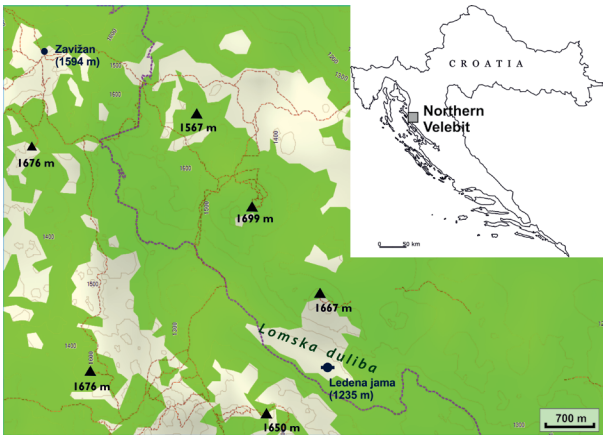


Figure 1. *Location map of Northern Velebit in Croatia and measuring points: Zavižan Meteorological Station and Ledena jama.*

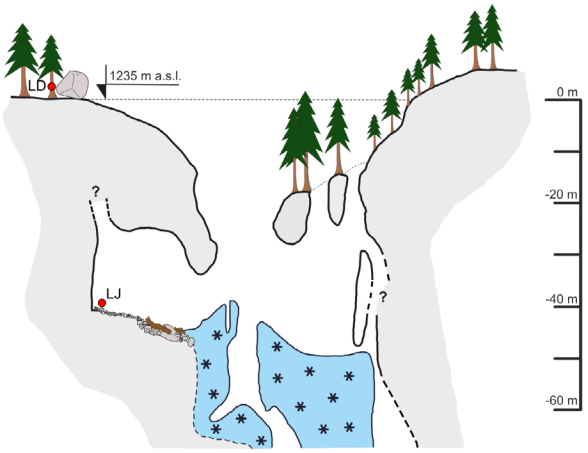


Figure 2. *Locations of data loggers (LD=Lomska duliba, LJ=Ledena jama). Map source: Jelinić 2001.*

Ledena jama is located in the SW part of the bottom of Lomska duliba valley. It is a knee-formed vertical cave (shaft) consists of large vertical passages and chambers interconnected with shorter narrower horizontal passages. The attractive, funnel-like entrance opens at the valley bottom (1235 m a. s. l; Fig. 3). The entrance is 50 m wide and 60 m long. Such a wide open entrance (area=3000 m^2) enables strong microclimate influence from the surface. Despite of dimension entrance part is shady and even during the summer most of the day protected from the direct sunlight.



Figure 3. *A - entrance to Ledena jama (photo S. Buzjak), B - the aerial view of ice-snow accumulation (photo V. Dubovečak).*

The entrance continues in a large (60x60 m) chamber, with 25 m long lateral horizontal passage. Total volume of this part is about 30000 m^3. At the depth of 50 m (1185 m a. s. l.) there is a chamber bottom consisting of snow, névé, firn and ice. It is a large cold body that has important cooling effect. The snow is allochthonous deposit that accumulates from outside the cave: directly from the precipitation and indirectly by sliding and collapsing from the steep slopes and trees around the entrance. The névé, firn and ice are autigenic deposits forming from deposited snow and by freezing of percolating water. This infilling reaches the depth of 90 m and separates the entrance part from the rest of the vertical passages and chambers. The total depth of Ledena jama is 536 m (bottom = 699 m a.s.l.; Fig. 4). In the chamber and passage there are geomorphological markers indicating frost weathering in the form of rock debris fallen from the passage walls and ceiling.

The snow and ice filling is very interesting as a microclimate modifier and as a "treasury" of scientific data. It is layered and contains various material of terrestrial origin (soil and rock particles, leaves, branches, animal bones, etc.). The estimated ice deposit age based on tritium (^3H) and radiocarbon (^{14}C) dating of ice and wood sampled from the ice, after Jelinić et al. (2001), and Paar et al. (2013a) is about 140-525 years. Kern et al. (2008), according to accumulation/melting rates, roughly estimated it to 105 years. Their research indicated that the winter precipitation has a more important role in the ice formation than the rain of summer half year.

Climate conditions

Due to the altitude range 1200-1700 m a.s.l. the highest areas of northern Velebit, including research area of Lomska duliba, are transition zone between the temperate humid climate with warm summer (Cfb), and humid boreal climate (Df). The transitional zone is discontinuous and highly modified by often change of the high peaks, ridges and deep karst depressions (mostly dolines) with often temperature inversion.

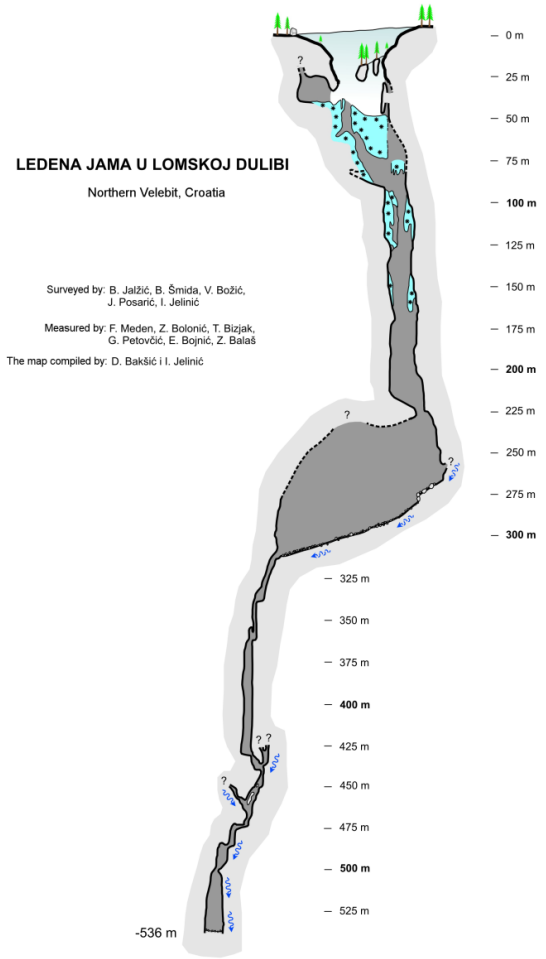


Figure 4. *The profile of Ledena jama in Lomska duliba (after Jelinić 2001).*

There is the highest Croatian meteorological station Zavižan (1594 m a. s. l.) that collects data since 1953. The data from Zavižan for the 10-year period (2003-2012) illustrates climate conditions enabling permanent snow accumulation and ice forming in mountain caves (Fig. 5). MAAT was 4.2°C. There are four months with MMAT below 0°C. Also the number of cold days (Tmin≤-10°C), icy days (Tmax<0°C) and frosty days (Tmin<0°C) should be taken into account. In total there was 2590 days (71%) with air temperatures ≤0°C and only 18 (0.5%) warm days (Tmax≥25°C).

The large karst depressions are known for low air temperatures due to the temperature inversion. Such a temperature distribution is the factor influencing snow accumulation and percolating water freezing. The cooling effect on Zavižan location is mostly influenced by the strong, dry and cold NE wind locally known as "bura" (int. *bora*; Grisogono and Belušić, 2009). Although it

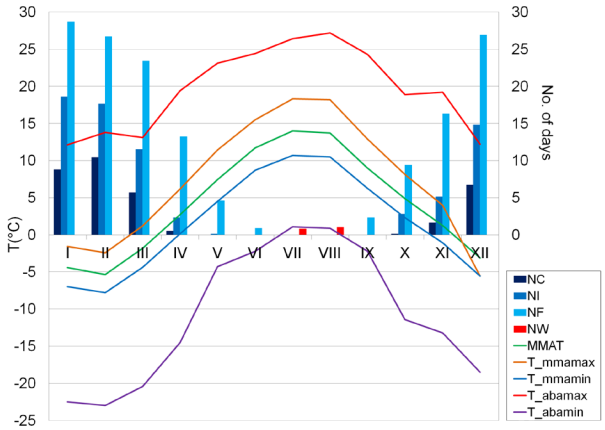


Figure 5. *Climate diagram of Zavižan, period 2003-2012. Legend: NC=number of cold days (T_{min}≤-10°C), NI=number of icy days (T_{max}<0°C), NF=number of frosty days (T_{min}<0°C), NW=number of warm days (T_{max}≥25°C), MMAT=mean monthly air temperature, T_mmamax=mean monthly max. air temperature, T_mmamin=mean monthly min. air temperature, T_abamax=absolute max. air temperature, T_abamin=absolute min. air temperature. Data source: State Meteorological and Hydrological Service.*

has no direct effect to isolated karst depressions it has a wider importance - during winter this air circulation transports colder air masses from the continental Croatia and Panonnian basin towards the warmer Adriatic coast. Therefore it is also an interesting feature for a study of local microclimate and possible influence on ice and snow accumulation in caves.

Due to the feeding of the cave from the infall snow and freezing meteoric, melting and percolation water, it is useful to analyze the precipitation (Fig. 6). The mean annual precipitation on Zavižan was 1838 mm/y, within range 1300-2400 mm/y. The MMP ranged from 68 mm (July) to >200 mm (November-December). The highest mean monthly amounts (>300 mm) were recorded in January and October-December, but with prevalent share of snow. In the observed period there was total of 1145 days with snow depth ≥30 cm (31% of total days counted). Such a thickness of snow cover is possible, besides winter months, also in the period from March (average 26 days) to May (average 2 days), and in November (average 3 days). The long term average number of days with snow is about 150-170. Maximum snow depths during winter is regularly >200 cm. The record values (>300 cm) are always recorded in March (March 21, 2013 = 322 cm).

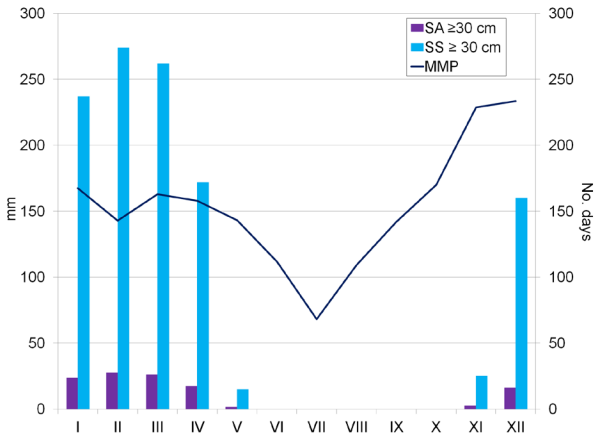


Figure 6. *Mean monthly precipitation (MMP) and amounts of snow cover on Zavižan (2003-2012). Legend: SA ≥30 cm=mean number of days with snow cover ≥30 cm, SS ≥30 cm=total number of days with snow cover ≥30 cm, MMP=mean monthly precipitation. Data source: State Meteorological and Hydrological Service.*

The amount and snow balance is important for Velebit ice caves with vertical entrances. It accumulates directly during falling, indirectly by sliding from the surrounding tress and slopes. As it melts it provides huge amounts of water that percolates underground and freeze in a cold cave environment.

Discussion

By the analysis of sample data for the period June 1 - September 29, 2013 it is obvious that Zavižan and Lomska duliba have similar trend in mean daily air temperatures (MDAT; Fig. 7). Lomska duliba has slightly lower values due to the often temperature inversion. In the observed period there were 61 days (50%) when MDAT was lower in Lomska duliba than on Zavižan. They are influenced by the terrestrial long wave radiation and cold air trap effect of Lomska duliba. The air temperatures were always above 0°C (range 4-21°C, MDAT=11.7°C), but obviously low enough to prevent fast and complete ice melting. The ice and snow in the shaft are protected since they are in the shade, due to albedo and cooling effect. The chamber air temperature ranges between 0.6 and 2.9°C (median=1.1°C). The environment important for ice mass balance is obvious from temperature amplitude=3.5°C (σ=0.6°C). During the winter there are very low air temperatures, and a lot of precipitation but mostly in the form of snow so the water intake is of small importance. But due to the large entrance and steep slopes around, there is a lot of snow accumulation in the cave. The snow on the surface can last till the April-May and in the case of slow melting there is a constant water infiltration into the cold cave environment. There are «warmer» periods in the cave when there is a melting process dominant. It is clearly observable form deep holes in the ice and reducing of the ice-snow body (Fig. 3B). According to the recent observations and after Kern et al. (2008) warm summer period is of less importance for ice accumulation and it›s critical because of melting. Melting is caused by higher ambiental air temperature and by the warm percolation water that infiltrates fast through highly porous epikarst zone into the cave. The entering of warmer air was not observed because it is prevented by the thick layer of denser, heavier and colder air marked by sharp thermocline some 20 m below the entrance line.

According to its morphology and the amount of ice-snow mass, Ledena jama could easily be classified as a typical static cave, but here presented microclimate observations and previous researches by Jelinić et al. (2001) and Kern et al. (2008) suggests that situation is a little bit more complicated. There is a system of inaccessible chimneys above and large spaces below the ice-snow plug that probably enabling air exchange through passages. One of the future research tasks will be to search for the causes of a temperature rise responsible for ice melting and quest for explanation of different trends and correlations between surface and cave air temperature like these observable in early and late summer (Fig. 7).

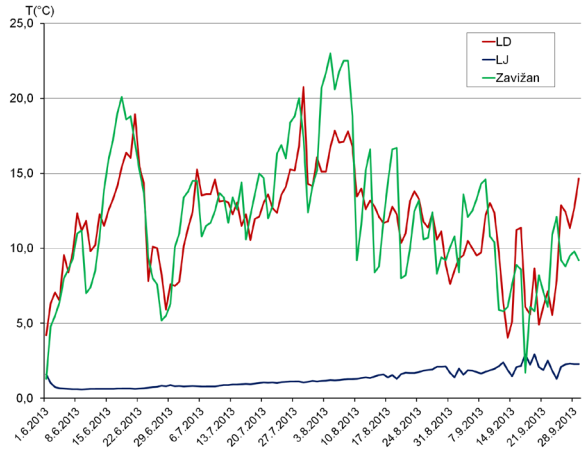


Figure 7. *Mean daily air temperatures (LD=Lomska duliba, LJ=Ledena jama). Data source for Zavižan: State Meteorological and Hydrological Service.*

Conclusion

Ledena jama in Lomska duliba is very promising site for research of ice cave microclimate and dynamics of ice-snow deposits. It is easy accessible, large in dimensions, and abundant in deposits connected with various geomorphological processes. Part of them is the result of paleo- and recent microclimate like rocks, sediments and organic material. Recent microclimate is highly interconnected with microclimate of Lomska duliba and local mesoclimate so they must be researched and analyzed as a unique system. Important microclimate factors shaping this interesting microclimate system are: geographical position, absolute and relative altitudes, microclimate diversity, geomorphological features, and morphometrical properties of Lomska duliba and Ledena jama. The geographical position and altitude provide climate environment (lower air temperatures, abundant precipitation) important for ice-snow accumulation and conservation. Lomska duliba as a karst depression has microclimate marked with often temperature inversions. Ledena jama has large shaded entrance with steep slopes that enables easy snow accumulation. But positive air temperature values and temperature variations (compared to surface values) indicate dynamic system that requires further data collection, observation and analyses. The plan for future research is to establish permanent meteorological sites for measuring T, RH and air circulation in the area of Lomska duliba and in Ledena jama. There are also opportunities for ice, water and organic matter sampling and dating.

Acknowledgments

The research was realized with the support of Ministry of Science, Education and Sports of Croatia, Project No. 119–1191306–1305: Geomorphological and geoecological research on Karst features in the Republic of Croatia, and 119-0000000-1299: Geomorphological mapping of Croatia. The authors would like to thank the Northern Velebit National Park and the Croatian Environmental Protection and Energy Efficiency Fund for supporting the study and to Suzana Buzjak for the assistance during fieldwork.

References

Antonić O, Kušan V, Hrašovec B. 1997. Microclimatic and topoclimatic differences between the phytocenosis in the Viljska ponikva sinkhole, Mt. Risnjak, Croatia. Hrvatski meteorološki časopis 32: 37-49.

Bakšić D, Paar D. 2006. Croatia and the Deep Caves of Northern Velebit. In: Oliphant J, Oliphant T, editors. Alpine Karst, Vol. 2. Cavebooks, Dayton. p. 105-124.

Bočić N. 2005. O morfologiji i postanku dubokih jama na Velebitu. Zimski seminar nastavnika geografije: Sažeci predavanja; 2005 Jan. 27-28; Zagreb, Croatia: Hrvatsko geografsko društvo. p. 42–46.

Bočić N. 2006. Najdublji speleološki objekti hrvatskog krša i njihove temeljne geomorfološke značajke. Međunarodni znan. skup "Akademik Josip Roglić i njegovo djelo", Zbornik radova; 2006 Apr. 19-22; Zagreb, Croatia: Hrvatsko geografsko društvo. p. 161–182.

Bočić N, Faivre S, Kovačić M, Horvatinčić N. 2013. Influence of the Pleistocene glaciations on karst development in the Dinarides – examples from Velebit mt. (Croatia). In: Filippi M, Bosák P., editors. Proceedings of the 16th International Congress of Speleology; 2013 July 21-28; Brno, Czech Republic: Czech Speleological Society. p. 170-172.

Bognar A, Faivre S, Pavelić J. 1991. Tragovi oledbe na Sjevernom Velebitu. Geografski glasnik 53: 27-39.

Buzjak N, Paar D, Bakšić D. 2010. Some characteristics of ice and snow caves in Croatia. In: Spotl C, Luetscher M, Ritting P, editors. Abstract volume of the 4th International Workshop on Ice Caves, Abstract volume; 2010 June 5-11; Obertraun, Austria: Technische Universität Wien. p. 8-9.

Buzjak N, Buzjak S, Orešić D. 2011. Florističke, mikroklimatske i geomorfološke značajke ponikve Japage na Žumberku (Hrvatska). Šumarski list 3-4: 127-137.

Buzjak S. 2001. Ekološka i floristička obilježja ulaznih dijelova jama i spilja u kršu Hrvatske (dissertation). Zagreb: University of Zagreb, Faculty of science, Division of biology, 162 p.

Dubovečak V, Rakovac M, Paar D, Žmegač A, Bakšić A. 2013. Speleološka ekspedicija "Sirena 2013", Izvješće o projektu, SO PDS Velebit, 58 p.

Grisogono B, Belušić D. 2009. A review of recent advances in understanding the meso- and microscale properties of the severe Bora wind. Tellus 61A: 1-16.

Horvat I. 1952-53. Vegetacija ponikava. Geografski glasnik 14-15: 1-25.

Jelinić I. 2001. Ledena jama u Lomskoj dulibi. Speleolog 46/47: 17-22.

Jelinić I, Horvatinčić N, Božić V. 2001. Ledena jama u Lomskoj dulibi. Senjski zbornik 28: 5-20.

Kern Z, Perşoiu A. 2013. Cave ice – the imminent loss of untapped mid-latitude cryospheric palaeoenvironmental archives. Quaternary Science Reviews 67: 1-7.

Kern Z, Bočić N, Horvatinčić N, Fórizs I, Nagy B, László P. 2008. Palaeoenvironmental records from ice caves of Velebit Mt. - Ledena pit and Vukušić ice cave, Croatia. In: Kadebskaya O, Mavludov B, Mikhail, P., editors. Proceedings of the 3rd International Workshop on Ice Caves: Proceedings; 2008 May 12-17; Kungur, Russia: Perm State University. p. 108-113.

Kuhta M, Bakšić D. 2001. Karstification Dynamics and Development of the Deep Caves on the North Velebit Mt. - Croatia: Proceedings of the 13th International Congress of Speleology; 2001 July 15-22; Brasilia, Brasil. p. 1-4.

Mudronja L. 2011. Speleološka ekspedicija "Lukina jama 2011", Izvješće o projektu, SO PDS Velebit, 33 p.

Paar D, Buzjak N, Sironić A, Horvatinčić N. 2013a. Paleoklimatske arhive dubokih jama Velebita. In: Marjanac L., editor. Knjiga sažetaka 3. znan. skup Geologija kvaratara u Hrvatskoj; 2013 Mar. 21-23; Zagreb, Croatia: HAZU. p. 39-40.

Paar D, Buzjak N, Bakšić D, Radolić V. 2013b. Physical research in Croatia's deepest cave system: Lukina jama-Trojama, Mt. Velebit. In: Filippi M, Bosák P., editors. Proceedings of the 16th International Congress of Speleology, Vol. 2; 2013 July 21-28; Brno, Czech Republic: Czech Speleological Society. p. 442-446.

Velić I, Velić J. 2009. Od morskih plićaka do planine: Geološki vodič kroz Nacionalni park Sjeverni Velebit. Krasno: NP Sjev. Velebit.

Vrbek M, Buzjak S. 2000. The ecological and floristic characteristics of Ledena jama pit on Velebit mountain - Croatia: Natura Croatic. 9(2): 115-131.

Vrbek M, Buzjak N, Buzjak S, Vrbek B. 2010. Floristic, microclimatic, pedological and geomorphological features of the Balinovac doline on North Velebit (Croatia). In: Gilkes R, Prakongkep N., editors. Proceedings of the 19th World Congress of Soil Science; Soil Solutions for a Changing World; 2010 Aug 1-6; Melbourne, Australia: IUSS. p. 9-11.

Zaninović K, Gajić-Čapka M, Perčec Tadić M. 2008. Klimatski atlas Hrvatske/Climate atlas of Croatia 1961-1990, 1971-2000. Zagreb: Državni hidrometeorološki zavod (DHMZ).

Železnjak R., Mudronja L. 2012. Istraživanja dubokih jama Nacionalnog parka Sjeverni Velebit, Izvješće o projektu, SO PDS Velebit, 40 p.

ICE-CONNECTED PROCESSES IN THE MORPHOLOGY OF THE CAVE – AN EXAMPLE FROM SNEŽNA JAMA, SLOVENIAN ALPS

Andrej Mihevc
Karst Research Institute ZRC SAZU
Titov trg 2
Sl – 6230 Postojna, SLOVENIA
Mihevc@zrc-sazu.si

Abstract

Cave ice in temperate climates is a result of cave morphology that enables cooling of the cave by efficient seasonal reversible ventilation in the presence of water and impacts the morphology of the cave. Besides the effects of the ice itself, seasonal oscillations of the temperatures around the freezing point cause rock shattering and cryoturbation, a sort of periglacial process which has even more important morphological effects on caves.

Snežna jama cave is about 1.6 km long in Raduha Mountain (2005 m elevation) in the Kamnik Alps, Slovenia. This cave, with its entrance at 1560 m, is a remnant of a large horizontal epiphreatic cave system. In the entrance part is a large body of ice which is the result of air circulation between the entrance and a chimney 150 m further inside. In this part of the cave temperatures seasonally drop far below the freezing point, maintaining ice formation. The morphological effect of the ice is small. The ice is stagnant and where it is recently melting the rocks are arranged chaotically. There are traces of frost shattering on the cave walls which are result of low winter temperatures.

The inner parts of the cave have a rather stable temperature around 4 ˚C, which is in accordance with the temperature of the surroundings. Under recent conditions no freezing is present. But there are numerous traces of frost shattering mostly and sediment creeping in the past. This indicates that in the past, the cave had another entrance at its far end. Well-developed patterned ground, vertically arranged slabs of shattered flowstone, and cones of debris all indicate freezing and thawing and not the existence of permanent ice.

By comparison of morphologies created by ice and by periglacial processes, the latter are more pronounced and extensive. Even if there had been bodies of permanent ice all traces of it would have been efficiently remodeled or destroyed by cryoturbation.

STUDY OF MULTIYEAR ICE IN MEDEO CAVE (NORTH URAL)

Y.I. Stepanov
Sibirskaya 78-a
Perm, Perm kraj, 614007, Russia, stepanov@mi-perm.ru

A.A. Tainitskiy
Sibirskaya 78-a
Perm, Perm kraj, 614007, Russia, tainickiy@mail.ru

A.V. Kichigin
Sibirskaya 78-a
Perm, Perm kraj, 614007, Russia

O.I. Kadebskaya
Sibirskaya 78-a
Perm, Perm kraj, 614007, Russia, icecave@bk.ru

B.R. Mavlyudov
Staromonetnij per. 29
Moscow, 119017, Russia, bulatrm@bk.ru

Abstract
The uniqueness of cave ice study lies in characteristic and simulation of continental climate and predictability of its changes. This study carried out GPR studies in a remote cave, Medeo. The cave is located in the territory of Srednevisherski area of North Ural folded zone carbon-bearing karst. The aim of the study was to examine the power and homogeneity of perennial ice formations. According to the results for the first time was defined the power of multi-year ice and built a three-dimensional model of sediment. The cave ice is more enriched with mineral ingredient in comparison with aboveground ice and accordingly provides good opportunities for conducting corresponding material investigations. There was performed monitoring of modern mineral formation process (including study of cryogenic minerals) as climate change indicators.

Introduction
Caves and sediments, formed and accumulated therein, reflect many processes on earth's surface. Among the variety of cavities are distinguished caves, whose sediments are responsive to climate change. To these caves belong in the first place, caves with ice deposits. Climate changes are recorded in morphology of underground ice mounds, therefore their study enables tracing of changes over extended periods (in some cases up to several thousands of years).

Information about geometry of multiyear ice in Ural caves is generally limited to calculation of surface area. The only exception is Kungur ice cave [1]. Although there are more examples outside Russia of using georadar for ice thickness determination in Dobsinska cave (Slovakia) [2] and Dachstein cave (Austria) [3].

Objective of this research was to determine the geometric characteristics of perennial ice in Medeo cave and possibility of ice massif homogeneity study using georadar investigations. The future objective will be detection of conditions of cryogenic minerals formation and possibility of their use as climatic markers by means of mineralogical investigations.

General information
Medeo cave (or Badyinskaya Ledyanaya) is located in western part of Pekhach stone on the right bank of Beryozovaya River, at confluence of Badya River therein (Perm region). Entrance (height 3 m and width 7 m) is located 30 m above river level. Cave consists of two grottos 25×16 m and 17×13 m. Overall length of underpasses is 60 m. Grottos floor is covered with layer of multiyear ice with total area 600 m^2.

Research technique
The research technique included georadar survey during cold period (March 2010), mineralogical study of detected mineral bands, as well as general reconnaissance and photographic documentation of ice mound surface performed during cold (March 2011) and warm (August 2011) periods. For monitoring of dynamics of ice massif thickness reference marks were installed.

Operating principle of radar sounding equipment (in universally accepted terminology – georadar) is based on study of ultrabroadband (nanosecond) impulses of VHF band and ultra high frequency band of electromagnetic waves and acquisition of signals, reflected from bedding interface of investigated environment, possessing different electrophysical properties [4].

Study of ice thickness and ice - base rock border is one of the most advantageous variants of georadar survey

in terms of physical suppositions, namely: high electrical resistivity (ER) and low dielectric capacity. Georadar survey were performed using «OKO-M1» equipment, AB-250 shielded antennas with center frequency 250 MHz and AB-1700 with center frequency 1700 MHz, according to survey grid (Fig. 1), spatial location of which were substantially predetermined by cave geometry and accessibility of investigation area. Overall length of profiles was 167.5 m.

For determination of ice chemical composition was collected sample from surface to 1 m depth using hand-held ice drill. Mineral constituent was collected both from ice mound surface after winter evaporation period, and strained out from unfrozen ice, volume of which amounted to 3 dm^3. Study of ice morphology and chemical composition was performed using scanning election microscope VEGA 3 LMH with x-ray energy-dispersive microanalysis system INCA Energy 350/X-max 20 in Mining Institute of Ural branch of RAS (analysts E.P. Chirkova, O.V. Korotchenkova).

Isotopic analysis of carbon and oxygen of enclosing limestone and flour was performed in Mining Institute of Ural branch of RAS using mass-spectrometer MI-1309 (analyst M.A. Kudinova). Values were calculated in pro mille with reference to PDB standards for $\delta^{13}C$ and $\delta^{18}O$.

Research data

Georadar studies

There were received radarograms, an example of one of them is shown in Figure 2a. Received materials are characterized by good quality (in particular by absence of visible noise waves), therefore processing was reduced only to automatic gain control procedure (AGC) and direct wave removal (average subtraction).

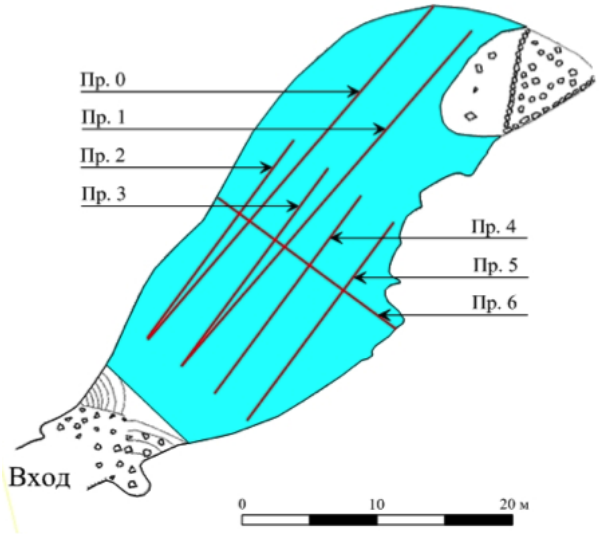


Figure 1. *Profile chart in Medeo cave.*

As a consequence on radarogram were formed two obvious areas with different wave pattern:

1. Area of well-ordered recording with traceable horizontal wave pattern, complicated by diffracted waves from small inclusions in ice or other inhomogeneities. Horizontal wave pattern may be conditioned by cyclicity of ice-flow development; between cycles ice surface is covered by thin layer of fine deposits of limestones alteration products.
2. Area with increased values of signal amplitude, but without long-lasting wave patterns. Such wave pattern showed a complex and inhomogeneous structure of underlying stratum and be identified with layer of highly disintegrated rock. In the course of quantitative interpretation of geological cross section appeared problem of ambiguity of ice - rock boundaries drawing, therefore Hilbert transformation was performed (Fig. 2b) and, as a consequence it was separated by another layer between ice and rock, presumably referred to subglacial clastic deposits.

Therefore in consequence of processing were separated 3 layers (Fig. 3b).

For conversion of time section to depth section following medium parameters were accepted:

1. Ice $\varepsilon^* = 3,5$ (determined by hodographs of diving waves on radarogram).
2. Carbonate rocks $\varepsilon^* = 4\text{-}7$ (accepted value 4,5).
3. Subglacial clastic layer; value of its dielectric permeability is taken as average between top and bottom layers $\varepsilon^* = 4,0$.

According to data of calculated depths were built charts of ice thickness and subglacial moraine deposits (Fig. 3); three-dimensional model of perennial icing (Fig. 4) and calculated approximate volumes of first and second layers within limits of studied area using three methods (trapezoidal approximation method, Simpson method and 3/8 Simpson method) [5].

Average value of multiyear ice volume is equal to 939 m^3. Maximum ice thickness amounted to 4,5 m in cave

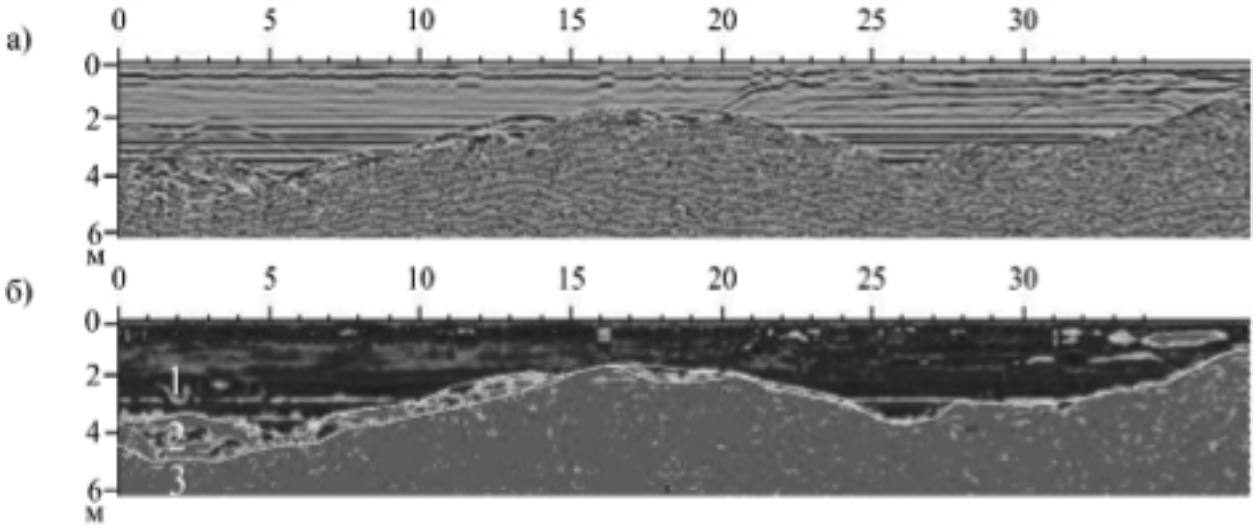


Figure 2. *Example of radarogram processing: a) after direct wave removal; b) after processing with Hilbert transformation: 1 – ice, 2 – subglacial clastic deposits, 3 – bed rock.*

part nearest to entrance. Further inward the cave ice thickness gradually decreases and in remote part is 0,5 m.

Additional usage of reference marks has shown that ice growth from March 29 to August 11 in midsection of cave was 82-101 mm. It was observed that in summer, water falling on surface, flows first in the form of separate streams, incising channels into ice mound, which are gradually changing to plane stream area, characterized by gur presence, oriented transversely to flow, set by fine-grained ice aggregates (slush). In distant part (30 m from entrance) on ice surface polygonal structure has been observed, conditioned by giant - crystalline (5-20 cm) structure.

Along the course of introduced aqueous solutions freezing on ice mound surface, and deposition of carbonate (and, in subordinate quantity of sulphate) material takes place in the form of finely dispersed (less than 150 μ) material – cryogenic cave carbonate (CCC) powder, giving evidence of rapid (shock) crystallization. During spring season band of cryogenic carbonate material, left after winter evaporation of ice is covered again with new portion of water, entering cave at the time of snow melting (Fig. 5).

Use of georadar antenna with center frequency 1700 MHz allowed tracing of this mineral band in ice stratum. By means of ice drill out of ice massif was collected

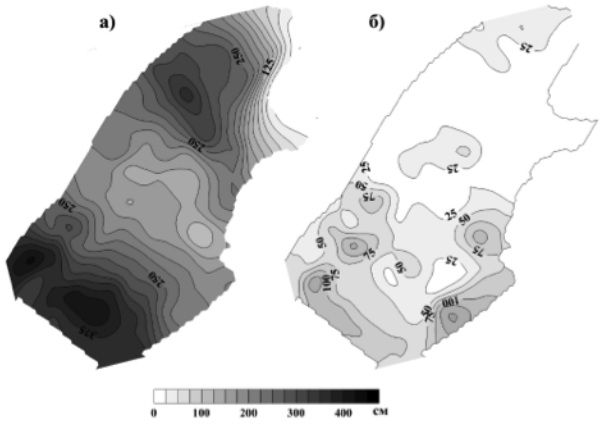


Figure 3. *(a) Diagram of ice thickness and (b) subglacial moraine deposits.*

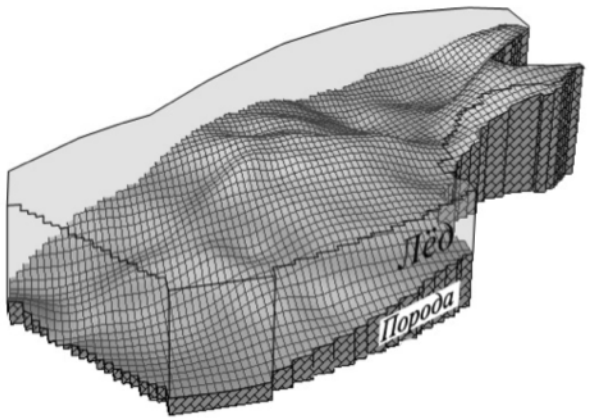


Figure 4. *3-D image of ice stream thickness and its base surface.*

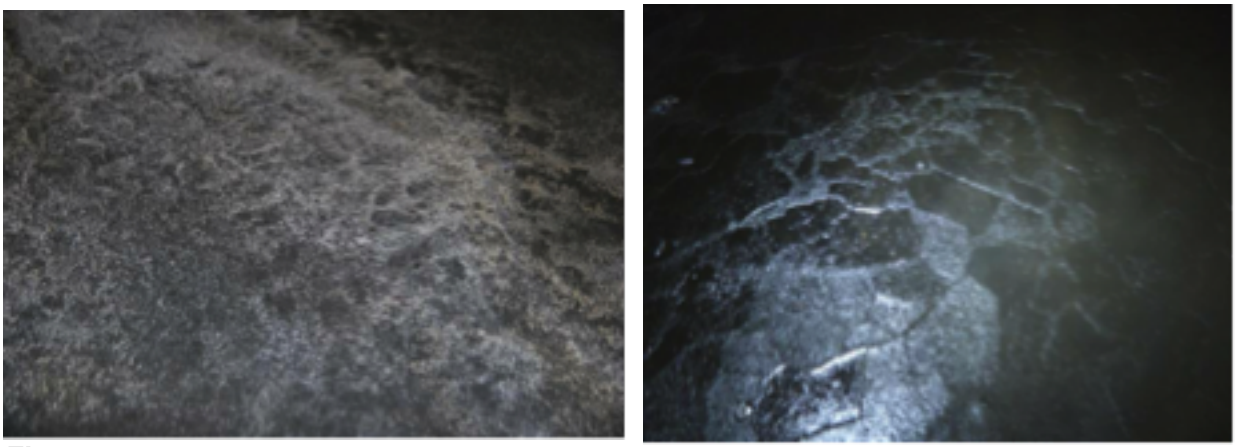


Figure 5. *Cellular distribution of CCC powder, accumulated after winter evaporation of ice (March 2011) and polygonal structure of newly formed layer (August 2011).*

sample and performed comparative analysis of spring surface sample and ice massif sample.

Mineralogical study

Chemical analysis of ice, performed in laboratory of mining regions geoecology of Mining Institute of Ural branch of RAS (analyst Bykova N.V), has shown its low mineralization (57.92 mg/dm^3) and belonging to hydrocarbonate potassic-natrium type of ice (Table 1). Therefore multiyear ice has sweet composition and is formed from melt-water, entering in spring time through entrance of the cave.

Morphological analysis of more than 200 fine particles from ice mound surface and from ice massif has shown that they are represented by own calcite crystals and calcite aggregates along ikaite. Substantial domination of ikaite (Fig. 6) on ice surface and mainly calcite – inside of ice mound (Fig. 7), as well as presence of flat foundations on their aggregates, give ground to suppose that accumulated on ice mound ikaite, released during winter evaporation of ice, when interacting with new portion of entering water is overgrown by calcite. Apparently carbonate material transformation can take place during the progress of ice recrystallization, as well.

Observed relations reflect cryogenic-diagenetic change («ageing») and dehydration of primary crystallohydrate during the progress of ice mass accumulation. Isotopic analysis has shown that: carbonate from ice surface of Medeo cave ($\delta^{13}C = 13.7$; $\delta^{18}O = -4.7$) is different from inclosing limestone ($\delta^{13}C = 4.3$; $\delta^{18}O = -2.4$).

Isotope ratios in ikaite from icing mound surface of Medeo cave are close to CCC powder composition of Canadian caves [9].

Table 1. *Chemical composition of ice in Medeo cave (bore Nr.1).*

Mineralization, mg/dm^3	pH	Content, mg/dm^3, mole/dm^3, % mg-equiv					
		HCO^{3-}	SO_4^{2-}	Cl^-	Ca^{2+}	Mg^{2+}	Na^{2+}
57.92	6.43	34.21 0.56 38.71	1.40 0.04 2.73	5.95 0.12 8.56	6.55 0.33 22.55	0.12 0.01 0.69	9.69 0.39 26.75

Conclusions

Performed researches in Medeo ice cave have shown that by means of georadar is possible to do detailed study of ice deposits in caves and determine zones, where mineral substance were deposited. Cryogenic minerals can serve as age markers of glacierization more stable than ice itself. "Preserved" deposits in caves can serve as sources of information: about paleoclimate conditions of the past.

For the first time was determined thickness of multiyear ice and subglacial clastic deposits in Medeo cave. Maximum ice thickness was 4.5 m, and volume – 939 m^3 meaning that this site preserve in the territory of North Ural.

It was demonstrated that multiyear ice growth takes place on account of surface waters, entering during spring-summer period through the cave entrance. Ice mound surface is characterized by presence of hydrodynamic zones: jet and plane (wave and film) water flow. They determine the ice structure: from fine-grained to giant-crystalline.

In the course of ice accumulationis was formed layer of cryogenic substantially

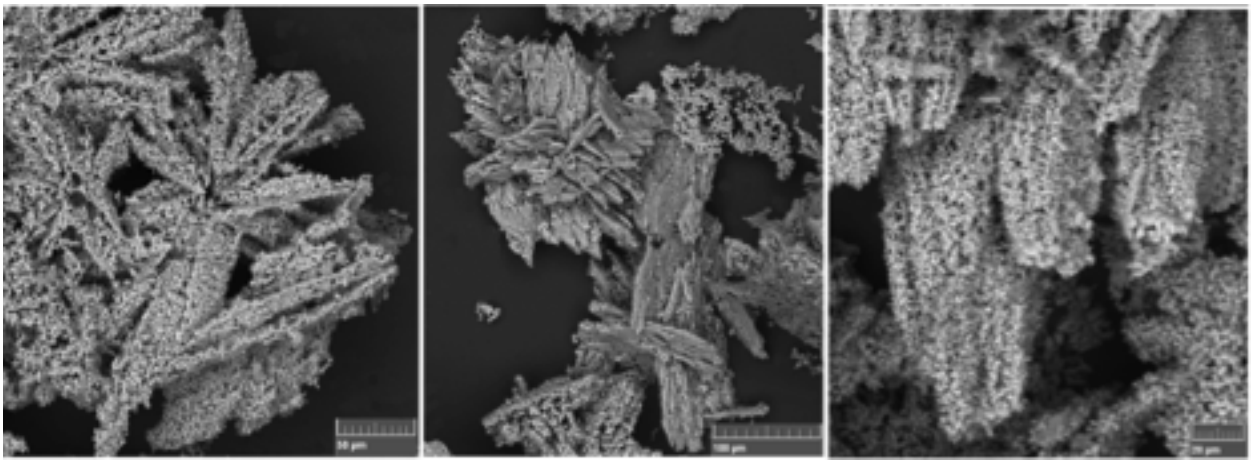


Figure 6. *Skeletal crystal bodies and ikaite aggregates.*

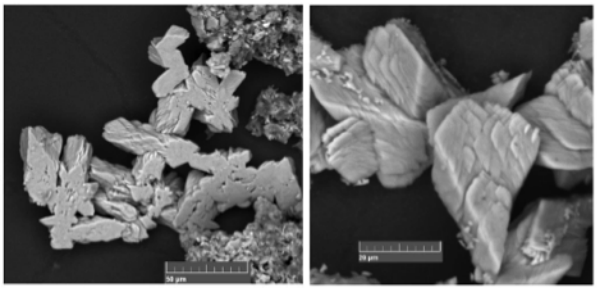


Figure 7. *Calcite crystals from ice stratum with growth marks on smooth ice surface.*

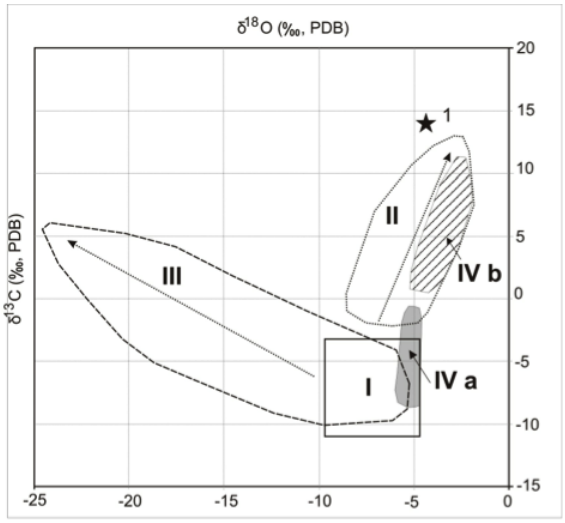


Figure 8. *Ratio of carbon and oxygen isotopes of cryogenic carbonate powder of Medeo cave (indicated by an asterisk). Fields of mineral formations of caves in Europe [7] are shown in Roman numerals: I - sinter; II - cryogenic powder from surface and inside of ice; III - cryogenic carbonate concretions; IV - mineral formations (a - pearls, b - powder) of Skarishoara cave [8].*

carbonatic powder, set by seasonal ikait, exchanging in the course of new solutions inflow (and ice recrystallization?) by calcite. For ikait is characteristic isotopic composition C and O, corresponding to cryogenic powder composition from Canadian caves, which may suggest the similarity of climatic conditions.

Study was performed with the support of grant RFFI № 11-05-96014-р_урал_а «Development of georadar investigations procedure of underground ice in caves».

References

Bakhvalov NS, Zhidkov NP, Kobelkov GM. 2000. Numerical methods. M.: Nauka, 622 p.

Behm M, Hausmann H. 2008. Determination of ice thickness in Alpine caves using georadar / Volume of abstracts IWIC-III international Workshop on ice caves, Kungur Ice Cave, Perm Region, Russia, May 12 –17., p. 53.

Clark ID, Lauriol B. 1992. Kinetic enrichment of stable isotopes in cryogenic calcites. Chemical Geology (Isotope Geoscience Section) 102: 217–228.

Novotny L, Tulis J. 1995. Ice filling in the Dobsina ice cave / Kras a jaskyne (Liptovsky Nikulas), p. 16-17.

Richter DK, Meissner P, Immenhauser A, Schulte U, Dorsten I. 2010. Cryogenic and non-cryogenic pool calcites indicating permafrost and non-permafrost periods: a case study from the Herbstlabyrinth-Advent Cave system (Germany). The Cryosphere 4: 501–509.

Starovoitov AV. 2008. Interpretation of GPR data. Moscow, MSU. p. 192.

Stepanov YI, Kadebskaya OI. 2011. Experience of georadar measurements of permanent ice thickness in Kungur ice cave. Caves. Proc. of Conf., Perm, PSU. Vol. 34., p. 46-50.

Tainitskiy A, Stepanov Y. 2011. Georadar measurements of permanent ice thickness in caves, Volume of abstracts 19th international karstological school, Klassical karst, Postojna, Karst Research Institute, Scientific Research Centre of the Slovenian Academy of Sciences and Arts., p. 44.

Žák K, Onac BP, Perşoiu A. 2008. Cryogenic carbonates in cave environments: a review. Quaternary International 187: 84-96.

NEW RESEARCH IN CAVE LEDENICA IN BUKOVI VRH ON VELEBIT MT IN CROATIAN DINARIC KARST

Prof.dr.sc. Mladen Garašić, PhD.ScD. Geol.
University of Zagreb, Faculty of Civil Enineering
Kaciceva 26
Zagreb, HR-10000, Croatia, mgarasic@grad.hr

Introduction

The first speleological research of Ledenica in Bukovi Vrh on Velebit Mt in Dinaric Karst in Croatia has been made at 22nd of August 1980. Leader of this study and exploration was Mladen Garasic with team members Zarko Supicic, Tomislav Marincic, Jadranka Pezic, and Berndt and Utte Hackler.

Survey and research show that cave Ledenica in Bukovi Vrh on Velebit Mt is situated at 1325 m a.s.l. (position is x= 4914,450 N; y=5542,440 E) and cave were formed in middle Triassic dolomites and limestones. It was much of ice in this 189 m long and 87 m deep cave (Fig.1.)

Some new and recent explorations (2013) show that thickness of ice there is more than 17 meters in the last cave chamber (45 x 25 m) (Fig.2.). Temperature of air in this cave chamber is -1o C.

Material and Methods

The ice body is convex, with a maximum thickness of 15–20 m and a volume more than 7000 m^3. We used Ground penetrating radar (GPR)- Geoscaners Akula 9000 with different antennas for thickness determination. Three bore holes were made with diameter of 32 mm

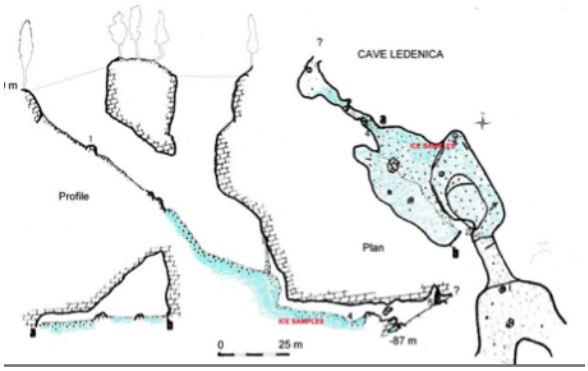


Figure 1. *Survey of Cave Ledenica in Bukovi vrh on Velebit Mt in Croatian Dinaric Karst.*



Figure 2. *Thickness of ice in Ledenica is more than 17 meter.*

and total length of 7,5 meters (3 x 2,50 m). Tritium (^3H) method shows that age of ice is more than 50 years. Samples were also analyzed radio carbon dating ^{14}C and with stable isotope analyses and U-series methods. The oldest part of ice in Ledenica Cave could be age about of 58,000 years.

Results and Discussion

The new data showed that age of this ice part is at bottom about 58,000 years old , and near of top of this ice part is about 560 years old (Fig.3). It means that this is the oldest and the most thick cave ice in Croatian part of Dinaric karst area. Some measurements of cave ice were made on Nothern Velebit Mt. (Horvatincic, 1996; Jelinić et al., 2001; Kern et al., 2008, 2011) but not on Southern Velebit Mt. In this cave (Ledenica on Bukovi vrh) we have left some measuring instruments (for neotectonic movements and characteristics of air and ice). Notice: this part of Velebit Mt was filled with mines in last War (1991-1995). Please be careful and use professional guide to visit this wonderful cave (Fig.4, Fig.5).



Figure 3. *Taking the samples of ice in the cave.*



Figure 4. *In the second chamber.*



Figure 5. *The first chamber in the cave.*

References

Garašić M. 1980. Ledenica u Bukovom vrhu na Velebitu (Cave Ledenica in Bukovi Vrh on Velebit Mt). Naše planine, Zgareb, 11-12, 278-280.

Garašić M. 1981. Neki speleološki objekti s vodom I ledom te praćenje neotektonske aktivnosti u njima (Some cave with water and ice and measuring of neotectoncs activity in this caves [master's thesis]. University of Zagreb. 248 p.

Garašić M. 2013. Report about ages of cave ice in Ledenica. Croatian Academy of Science and Arts, Karst Committee, Zagreb. 17 p.

Horvatinčić N. 1996. Isotopic measurement in ice, Ledenica Cave, Velebit, Croatia. (In Croatian with English summary). In: Kubelka D, Kovač J, editors. Proceedings of the third symposium of the Croatian Radiation Protection Association, Zagreb, p. 297-302.

Jelinić I, Horvatinčić N, Božić V. 2001. Ledena Jama (The Ice Pit) in Lomska Duliba (in Croatian with English summary). Senjski zbornik 28: 5-28.

Kern Z, Bočić N, Horvatinčić N, Fórizs I, Nagy B, László P. 2008. Palaeoenvironmental records from ice caves of Velebit Mountains - Ledena Pit and Vukušić Ice Cave, Croatia. In: Kadebskaya O, Mavlyudov BR, Pyatunin M. editors. 3rd International Workshop on Ice Caves Proceedings, Kungur, p. 108-113.

Kern Z, Széles E, Horvatinčić N, Fórizs I, Bočić N, Nagy B. 2011. Glaciochemical investigations of the ice deposit of Vukušić Ice Cave, Velebit Mountain, Croatia. The Cryosphere 5: 485-494.

CHARACTERIZATION OF TWO PERMANENT ICE CAVE DEPOSITS IN THE SOUTHEASTERN ALPS (ITALY) BY MEANS OF GROUND PENETRATING RADAR (GPR)

Renato R. Colucci
Department of Earth System Sciences and Environmental Technologies, ISMAR-CNR
Viale R. Gessi, 2
Trieste, Italy,34123
r.colucci@ts.ismar.cnr.it

Daniele Fontana
Department of Mathematics and Geosciences, University of Trieste (Italy)
Via Weiss, 1
Trieste, Italy, 34128
fd.beo87@gmail.com

Emanuele Forte
Department of Mathematics and Geosciences, University of Trieste (Italy)
Via Weiss, 1
Trieste, Italy, 34128
eforte@units.it

Abstract
In order to assess the thickness and the inner structure of some permanent ice deposits in two high elevated alpine karstic caves of the Canin massif (Alpi Giulie, Italy), we performed several multi frequency Ground Penetrating Radar (GPR) surveys. The surveys have been conducted within the project MONICA (MOnitoring of Ice within Caves), aimed at the paleoclimatic characterization of the considered cave ice deposits. GPR surveys have proved to be crucial also in finding the most suitable place for carrying out a drilling core. This has been particularly useful in the Vasto's ice cave (VIC) in which the direct/visual estimation of the thickness and the debris content of the ice body was not possible, while the Mt. Leupa's ice cave (LIC) has allowed to test the results of the radar thanks to the total exposure of an ice wall. The possibility to verify the presence of an air cavity, highlighted during the GPR surveys, was a further crucial detail. The thickness of the ice deposits, their internal structure and the peculiar internal layering has been here presented and discussed. Some features highlighted by the GPR traces have been furthermore interpreted as evidence of dynamic within the ice mass in the small glacieret existing at the entrance of the Vasto cave, probably driven by the presence of karstic voids within the rock mass.

Introduction
Alpine ice caves are natural caves formed in bedrock which contain perennial accumulations of water in its solid phase (Perşoiu and Onac, 2012) and for this reason can be therefore classified as a permafrost phenomenon (Hausmann and Behm, 2011). As part of the cryosphere such ice masses are closely linked to the climate but is notably as they exist in several kinds of environments, often at an altitude with an annual outside temperature well above 0°C (Obleitner and Spötl, 2012). The accumulation of cold air into the cave during the winter represents the main factor for the preservation of cold condition leading to accumulation of ice (Ford and Williams, 1989; Luetscher and Jeannin, 2004). The ice is formed mainly from re-crystallization of snow, from refreezing of percolation water or, with much less contribution, from deposition of cave-air vapour (Luetscher and Jeannin, 2004). Depending on the cave morphology, they are generally characterized taking in account the relationship between ice-formation and Cave Air Dynamics (CAD) and are subdivided in: (i) static ice caves (SIC); (ii) dynamic ice caves (DIC); (iii) stato-dynamic ice caves(STIC). SIC show a much simpler air circulation system, where cold air is trapped in a single-entrance cave due to its higher density (Thury, 1861; Luetscher and Jeannin, 2004). DIC are related to the so called chimney effects in which multiple entrances at different elevations produce a more complicated air flow system forcing the air convection and strictly dependent by seasonal effects. (Thury, 1861; Balch, 1900). The term STIC was instead introduced later in order to describe a type of ice caves of an intermediate type (e.g. Bogli, 1980).

Ground Penetrating Radar (GPR) has been used for the measurements of the thickness of ice cave deposits only in few occasions around the world, as in the case of the

Dobsinska ice cave in Slovakia (Geczy and Kucharovic, 1995; Novotny and Tulis, 1995), the Kungur ice cave in Russia (Podshuin and Stepanov, 2008) and in four caves of the Northern Austrian Calcareous Alps (Hausmann and Behm, 2011); the latter represents the first example of GPR application to image the internal structure of the ice and its basal topography.

The study of underground cryosphere is, at present, extremely important and urgent because the ice degradation processes are widely observed all over the world (e.g. Luetscher et al., 2005; Behm et al., 2009). Partial melting phenomena might also caused great limitations in the potential analysis of such deposits. The melting of the uppermost part of the deposits, in fact, might make impossible to calibrate the paleoclimatic signals recorded in the ice during times when instrumental climate and air quality dataset provide opportunities for direct calibration of the preserved cave ice environmental signal (Kern and Perşoiu, 2013).

In order to perform useful ice drilling and collect the longest paleoclimatic record, the best survey location is essential for both avoiding internal debris inclusions and reaching the highest thickness. Previous objectives can be obtained by using GPR dataset. 2D profiles acquired with high frequency antennas are helpful to locate any debris within the ice which can damage the drilling head and limiting long core samples. On the other hand high density 3D GPR dataset must be used to reconstruct the internal ice layering and image its bottom therefore locating the thickest portions.

Study Area

The Mt. Canin massif (Julian Alps) is located in the Eastern Alps (46°21' N, 13°26' E) along the borderline between Italy and Slovenia (Fig. 1). The higher peaks reach altitudes slightly higher than 2500 m (e.g. Canin 2587 m, Ursic 2514 m, Leupa 2402 m). At the foot of the northern rockwalls between 1830 and 2340 m a.s.l. few small glaciers, glacierets and ice patches still persist representing some of the lowest evidence of glacialism in the European Alps. The area of Canin massif hosts a large number of karst cavities and an intense speleological research activity developed since several decades. Although in a certain number of caves

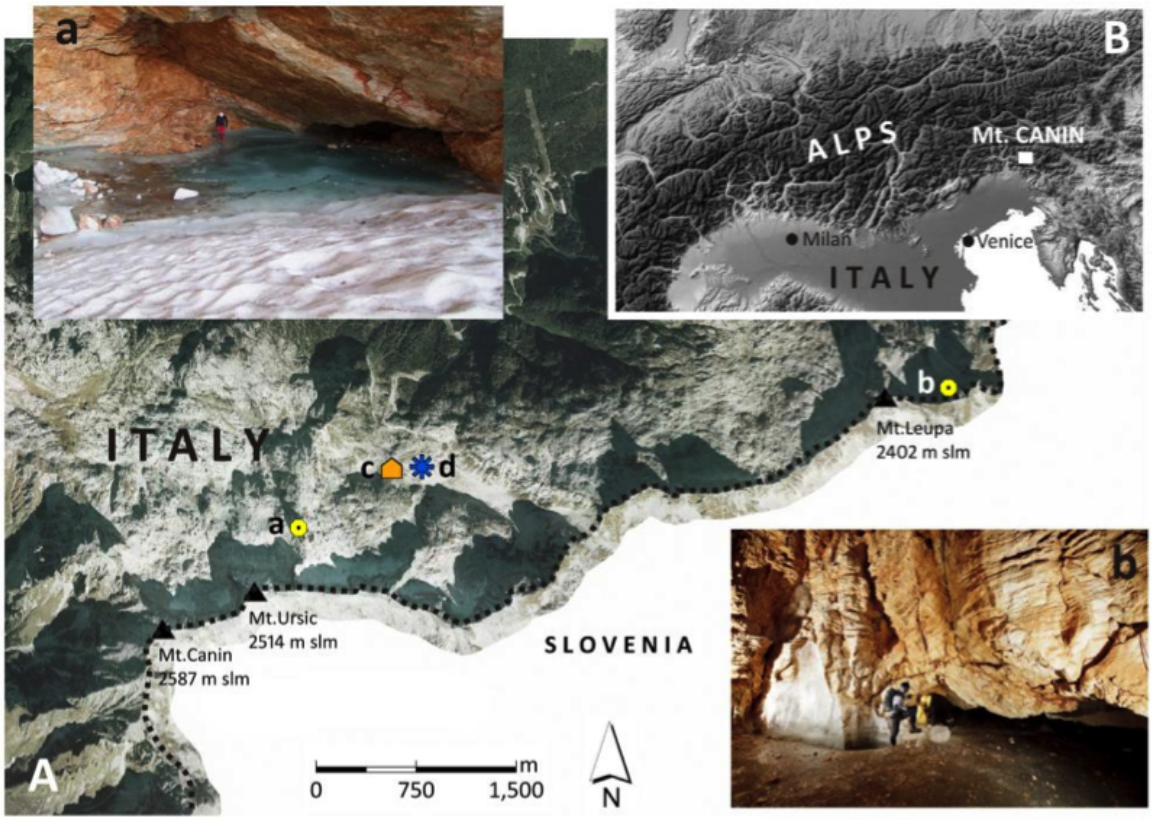


Figure 1. *Study area of Monte Canin (A) in the South-Eastern Alps (B) with the location and pictures of the monitored ice caves: a) VIC; b) LIC; c) Gilberti hut; d) WSA monitoring site.*

the presence of snow and ice were reported, and in some of them permanent and layered ice is well recognizable, the study of the underground cryosphere here has never been undertaken. This is mainly due to the fact that a speleologist sees the ice in a cave as a useless presence that should be avoided, only able to prevent access to continuations of the cave, while a glaciologist often does not have the technical knowledge for a safe progression in the underground environment.

Climatic conditions are rather peculiar in the area, especially with regard to the precipitation. The Mean Annual Precipitation (MAP) reaches values up to 3300 mm on Mt. Canin massif, representing one of the highest mean values for the European Alps. (Gregorcic et al. 2001, Norbiato et al., 2007). MAP influences the mean Winter Snow Accumulation (WSA) of the area that at an altitude of 1830 m a.s.l. was equal to 7.0 m in the period 1972-2012. The Mean Annual Air Temperature (MAAT) at the same altitude was 3.9±0.8 °C for the period 2000-2012. Assuming the normal vertical lapse rate of 0.0065°C m-1 (Barry,1992), in the same period the MAAT at the ice cave entrances (about 2200 m asl) has been estimated in 1.5°C±0.8 °C.

The two monitored caves (LIC and VIC) lie on the north side of the Massif and their entrances open at about 2200 m a.s.l. (Fig. 1).

They both preserve permanent ice deposits inside them, and if the LIC could be classified as a DIC for its air flow system, the air flow system of the VIC is more complicated and much influenced by the presence and amount of winter snow accumulation in a lateral chimney connecting the cavity with the outside (Fig. 2C). When the chimney is filled by snow no air circulation is present, thus the cave act as a single entrance cave, resulting in a SIC behavior. When during summer and fall the snow partially or completely melts, the VIC acts as a DIC.

Methods

Within both caves we acquired GPR data by using a ProEx Malå Geoscience equipment connected with different shielded antennas (250, 500, 800 and 1600

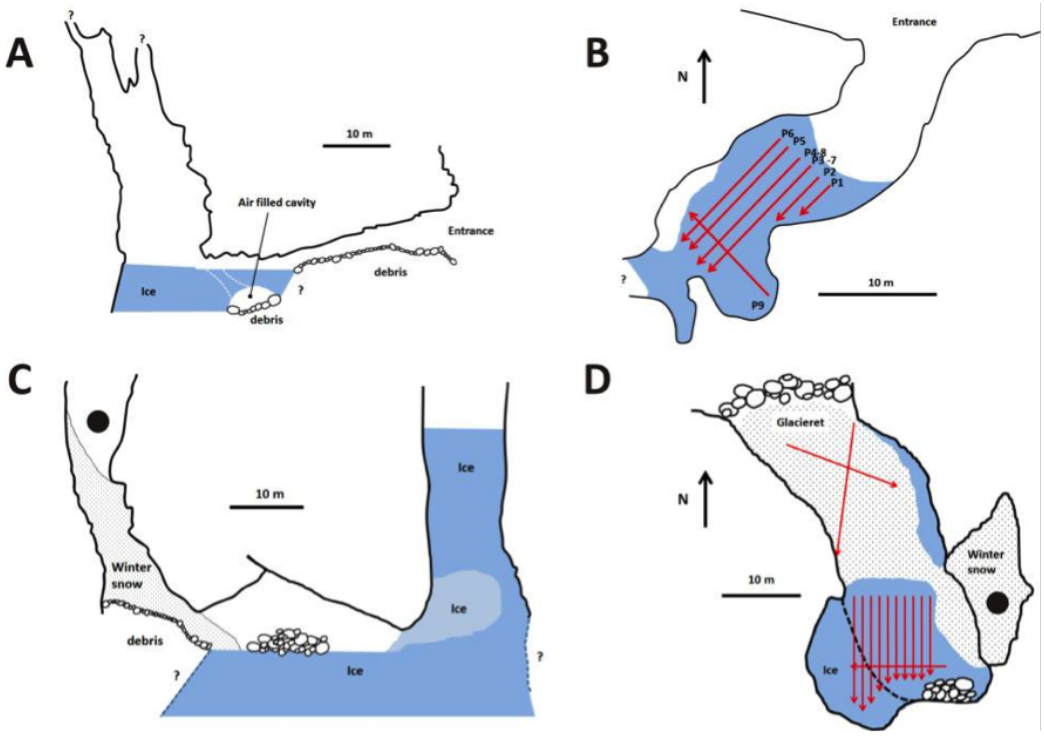


Figure 2. *Plain views and sections of the two ice caves: A) Section of LIC; B) Planimetry of LIC; C) Section of VIC; D) planimetry of VIC and of the Vasto's glacieret located in front of the entrance of the cave. In B and D red arrows show the location of the GPR surveys. In C and D the black dot help the identification of the shaft which is generally completely filled by snow during the winter season. A e B are re-drawn and simplified from the original survey of M. Potleca, 2011 (F.V.G. Regional cave Inventory).*

MHz) as a function of the objectives of the surveys. The GPR triggering was done by an odometer and the mean trace interval was between 0.02 up to 0.15 m. Dedicated total station measures were further acquired at some specific control points to improve the overall accuracy of the topographic survey. For all the surveys the transmitting and receiving antennas were parallel to each other and transverse to the survey direction, which minimizes offline reflections (clutter) because the radiation pattern has its widest energy footprint in the H-plane, i.e. perpendicular to the antenna axis.

The GPR profiles were processed by using a processing flow that included drift removal (zero time correction), geometrical spreading correction, bandpass filtering and 2D depth migration (Kirchhoff). We always applied a constant electromagnetic velocity equal to 17 cm/ns, which is the typical value of pure ice. In addition to the previous algorithms, on the profiles acquired on the glacieret close to the VIC we applied the topographic correction to compensate for the elevation changes along the GPR path.

Results and discussion

Figure 3 shows a full processed and interpreted profile within the LIC. Several structures can be identified: 1) high amplitude diffractions are imaged within about the first 80 cm below the surface (d); 2) a convex continuous and high amplitude horizon showing inverse polarity (in white); 3) an horizon with variable lateral continuity marking the base of a mainly transparent zone (in light blue); 4) an highly diffractive, high amplitude area. We interpret the previously described elements as follow: 1) Single centimetric to decimetric clasts entrapped within the ice, found also on the actual ice surface; 2) An air filled cavity within the ice mass, reached during the summer period and verified by visual inspection; 3) the basal horizon was interpreted as the ice bottom (that is the contact between ice and rocks; 4) a debris filled zone evident from the beginning of the profile (cave entrance) up to about 8 m of lateral distance. Beside this point, there are less diffractions and some dipping reflectors which can be interpreted as a compact layered rock. On Figure 3 we also highlight a low amplitude zone (C) just below the air filled cave which could be interpreted as a downward cave continuation filled with debris or mixed ice and debris.

Figure 4a reports a profile perpendicular to the one shown on Figure 3. Beside the already described elements, a clear cross layering within the ice mass can be imaged; this is confirmed by visual inspection of the free ice face as testified by Figure 4b. In fact the GPR reflections can be correlated to thin clay horizons entrapped into the ice. In detail the sub-horizontal ice layering in the upper part likely represents a younger ice accretion phase while the dipping ice layers has been interpreted as a likely older ice accretion phase. These two sectors of the ice mass are divided by a thicker debris layer likely representing a melting phase, thus interpreted as a stratigraphic gap between the phases A and B (yellow dot line in Fig. 4).

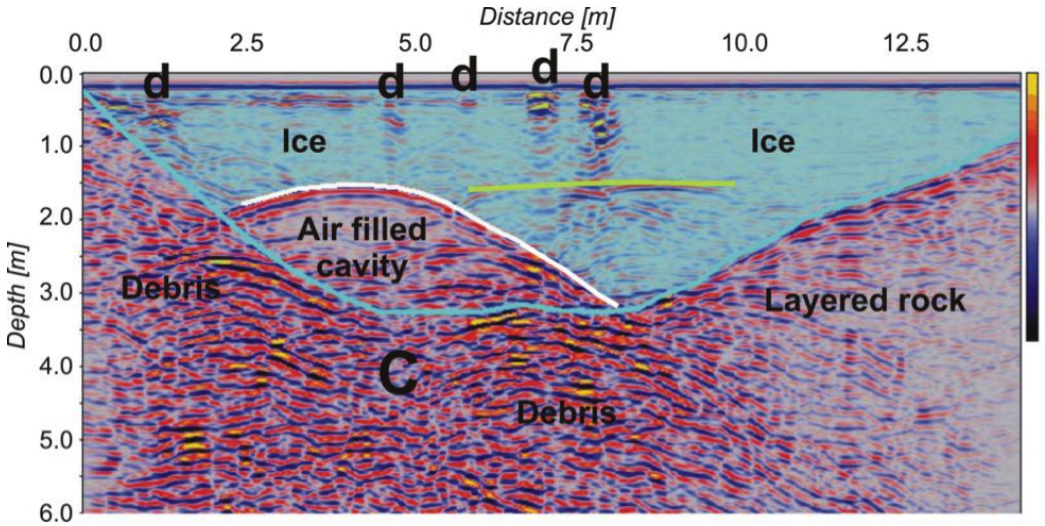


Figure 3. *Example of full-processed and interpreted GPR profile within LIC and perpendicular to the cave entrance. See text for interpretation details: C) downward cave continuation filled by debris; d) centimetric to decametric clasts and debris entrapped in the upper part of the ice deposit.*

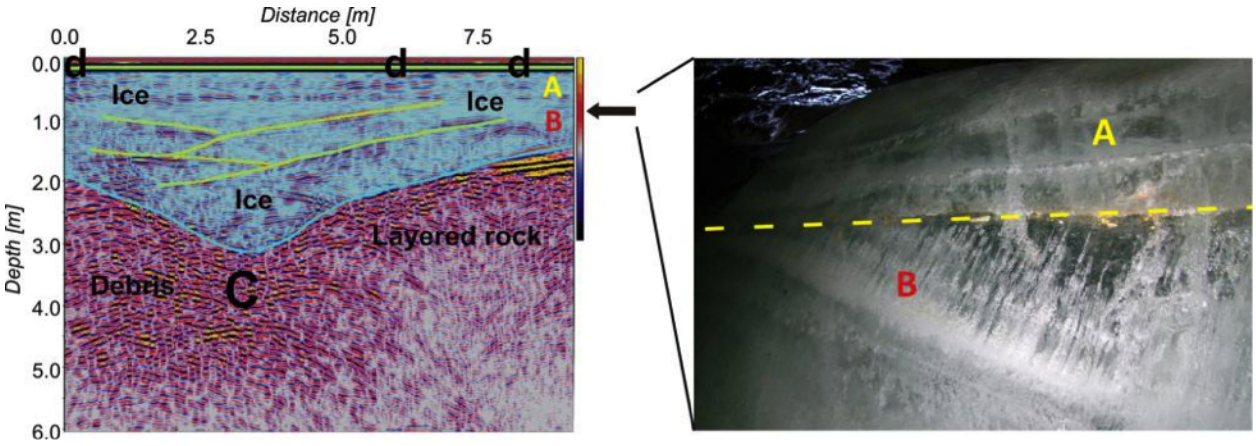


Figure 4. *a) Full-processed and interpreted GPR profile within LIC and parallel to the cave entrance; b) photograph of a free ice face showing cross layering and clay inclusion. In detail: A) sub-horizontal ice layering; B) dipping ice layers; yellow dot line highlight the stratigraphic gap between the phases A and B; C and d) same as Figure 3.*

In order to better define the ice bottom morphology and the ice thickness variations we combined all the available profile (acquired with the same antenna) performing a 3D interpretation. Figure 5 shows an example of the achieved results. The ice bottom has a concave, quite regular shape with higher dip toward the cave entrance. The maximum ice thickness reaches 4.2 m.

In the VIC we repeated twice the same profiles with different objective: first survey (performed in October 2012 with 250 and 800 MHz antennas) aimed to estimate the maximum ice thickness and its bottom morphology, while the second one (performed in October 2013 with 800 e and 1600 MHz antennas) was dedicated to define the optimal place for continuous core drilling. Figure 6 shows a comparison between two profiles acquired with 250 (A) and 800MHz antennas (B) along the same path in 2012 and with the 800 MHz profile acquired in 2013. The maximum ice thickness is about 8.5 m and is clearly images especially on 250 MHz profile. The 800 MHz sections, on the other hand allow to better highlight shallow ice layering and other details like small diffractions related to cm-dm rock blocks. We can furthermore notice that the maximum penetration depth reached in 2013 is sensibly smaller than in the previous year. This is probably related to an higher free water content within the uppermost part of the ice. All profiles highlight an high debris concentration within the first 2-3 m of the ice deposit, while the more transparent zone is related with the presence of massive ice.

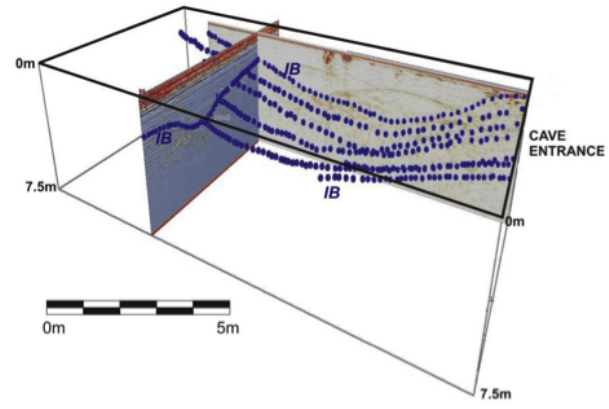


Figure 5. *3D interpretation of the whole GPR dataset acquired within LIC. The blue dots (IB) mark the ice bottom which reaches a maximum depth of about 4.2 m.B.*

Some additional GPR profiles were performed above the small glacieret located close to the entrance of the cave (Fig. 7). The internal stratification, alternating layers of sediments and firn/ice, showed morphologies with upward concavity sloping towards the beginning of the longitudinal profile (Fig. 7). This has been interpreted as evidence of dynamic processes within the ice mass of this tiny glacial body, likely induced by the presence of underground karstic voids below the glacieret.

Conclusions

This work aimed to characterize, through the use of GPR, the permanent ice deposits of LIC and VIC. The data here discussed are the preliminary results of the project MONICA whose main purpose is to extract a

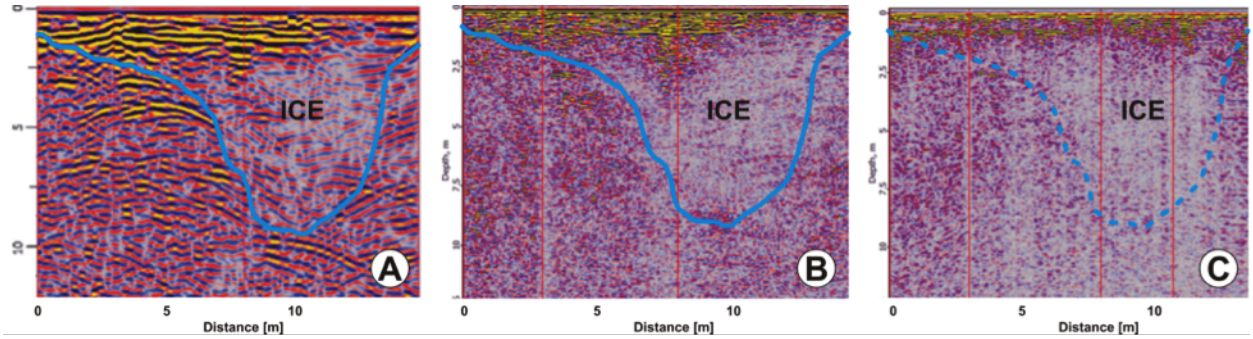


Figure 6. *Comparison between: 250 MHz profile acquired in 2012 (A); the profile acquired along the same path in the same day with 800 MHz antenna (B) and the profile acquired in 2013 with 800 MHz antennas in the same location (C).*

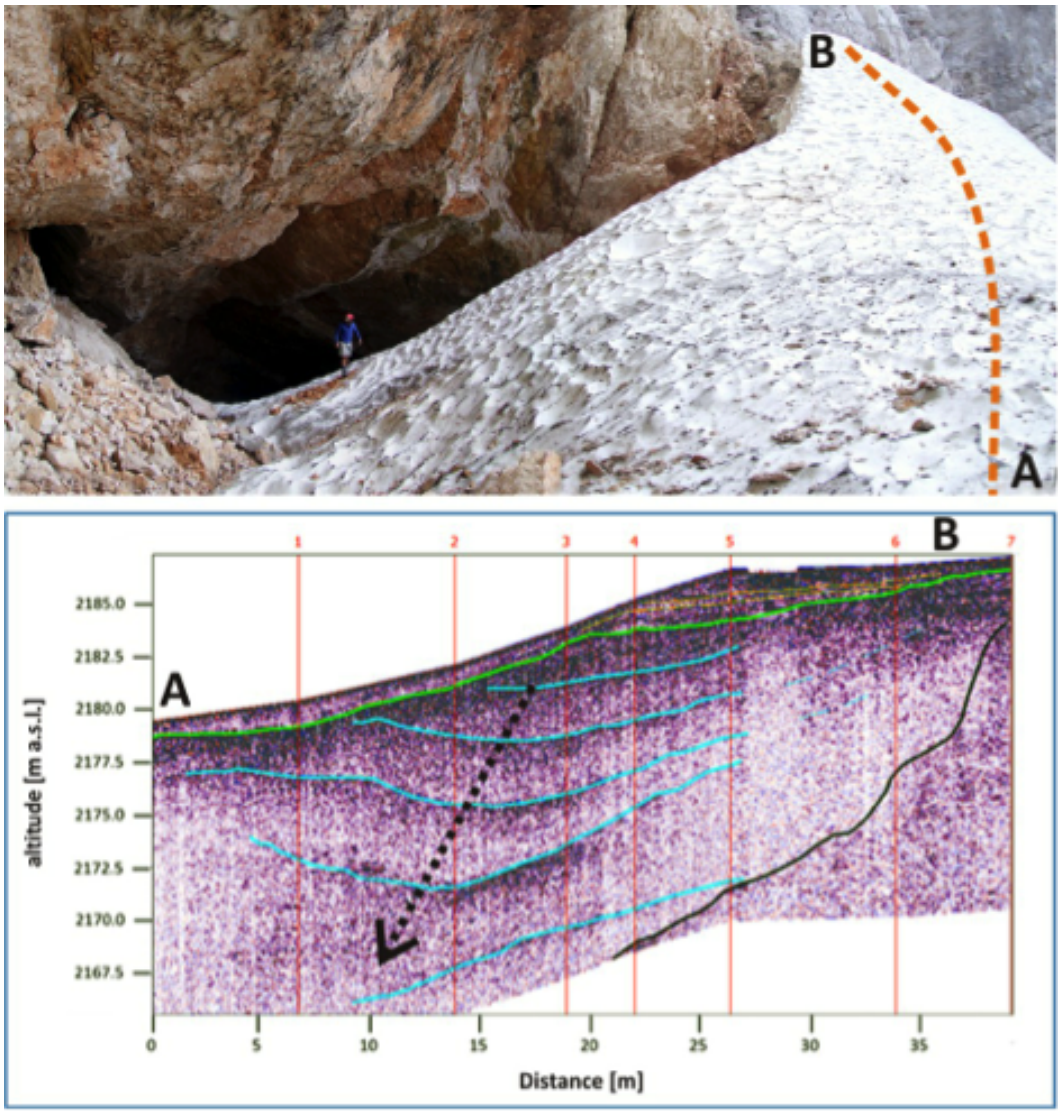


Figure 7. *Longitudinal profile performed on Vasto glacieret, located close to the entrance of the VIC. A and B show the beginning and the end of the longitudinal survey while the black dot arrow highlights the interpreted dynamic within the ice mass. The layer above the green line represents the residual snow of the last accumulation season.*

paleoclimatic record from ice caves in the Southeastern Alps. Different GPR profiles acquired with high frequency antennas have been crucial to define the best location for drilling, both limiting possible damages to the drilling head, caused by internal debris inclusions in the ice, and image the 3D bottom morphology to find the thickest portions of the ice deposit. The surveys performed on a very small glacieret at the entrance of the VIC highlighted an internal stratification pattern interpreted as evidence of movement related to mass beddings linked to possible karstic voids underneath the ice/firn deposits.

Further studies will be addressed to ice core integrated analyses and to a better constrained reconstruction of the ice caves dynamics.

Acknowledgements

This research was supported by the "Finanziamento di Ateneo per progetti di ricerca scientifica - FRA-2012" grant provided by the University of Trieste, and by Unione Meteorolgica del Friuli Venezia Giulia thanks to a financial support given by the "Comunità Montana del gemonsese Canal del Ferro e Val Canale". We are in debt with Marco B. Bondini, Stefano Pierobon and Costanza del Gobbo for helping us during the data acquisition and for sharing the effort in carrying the instrumentation at high altitude.

References

Balch ES. 1900. Glacières or freezing caverns. Philadelphia Allen, Lane & Scott, reprinted 1970 by Johnson Reprint Corp., New York, 38 p.

Behm M, Dittes V, Greilinger R, Hartmann H, Plan L, Sulzbacher, D. 2009. Decline of cave ice e a case study from the Austrian Alps (Europe) based on 416 years of observation in Proc. 15th Intern. Congr. Speleol., Kerrville, Texas, 19-26 July, v. 3, p. 1413-1416.

Geczy J, Kucharovic L. 1995. Determination of the ice filling thickness at the selected sites of the Dobsinska ice cave (in Slovak, English summary). Ochrana ladovych jaskyn Zilina, p. 17–23.

Gregorcic G, Kastelec D, Rakovec J, Vrhovec T. 2001. Evaluation of surface precipitation radar data during some MAP IOPs in western Slovenia, University of Ljubljiana, Slovenia: MAP newsletter, no.15.

Hausmann H, Behm M. 2011. Imaging the structure of cave ice by ground penetrating radar. The Cryosphere 5: 329-340.

Klimchouk AB. 1997. The role of karst in the genesis of sulfur deposits, Pre-Carpathian region, Ukraine. Environmental Geology 31: 1-20.

Luetscher M, Jeannin PY. 2004. A process-based classification of alpine ice caves. Theoretical and Applied Karstology 17: 5-10.

Luetscher M, Jeannin P, Haeberli W. 2005. Ice caves as an indicator of winter climate evolution: a case study from the Jura Mountains. The Holocene 15: 982-993.

Novotny L, Tulis J. 1995. Ice filling in the Dobsina ice cave, Kras a jaskyne (Liptovsky Nikulas), p. 16–17.

Norbiato D, Borga M, Sangati M, Zanon F. 2007. Regional frequency analysis of extreme precipitation in the eastern Italian Alps and the August 29, 2003 flash flood. Journal of Hydrology 345: 149-166.

Obleitner F, Spötl C. 2011. The mass and energy balance of ice within the Eisriesenwelt cave, Austria. The Cryosphere 5: 245-257.

Perşoiu A, Onac BP. 2012. Ice in caves. In: White WB, Culler DC, editors. Encyclopedia of Caves, second ed. Elsevier, pp. 399-404.

Podsuhin N, Stepanov Y. 2008. Measuring of the thickness of perennial ice in Kungur Ice Cave by georadar. In: Kadebskaya O, Mavlyudov BR, Pyatunin M, editors. Proceedings of the 3rd International Workshop on Ice Caves, Kungur, Russia, p. 52-55.

Thury M. 1861. Etude des Glacières naturelles. Archives des sciences de la bibliothèque universelle, Genève, p. 1-5.

ON THE MECHANISM OF THE NATURALLY FORMED ICE SPIKES

Hi-Ryong Byun
Dept. of Environmental Atmospheric Sciences, Pukyong National University
Daeyon, Namku
Busan, Rep. of Korea, hrbyun@pknu.ac.kr

Chang-Kyun Park
Dept. of Environmental Atmospheric Sciences, Pukyong National University
Daeyon, Namku
Busan, Rep. of Korea, qkrxp2@naver.com

Abstract

'Ice spike' denotes the ice bar risen upward from the ice surface in nature. In early 19 century, Buddhist monks in valley of Mt. Mai in Jinan Jeonbuk at Rep. of Korea found a mysterious phenomenon and recorded it first. Every early night they put many manmade bowls that are 15cm diameter and 10 cm height, at the yard of the temple with enough water in it. Next morning they found an icicle rose upward from the ice surface of the bowl. Also they say that the shape of Buddha is seen in the ice bar. These phenomena occur 10 ~ 20 times a year and have been known as a mystery for a long time. This study has carried out 7 days and nights' consecutive meteorological observations, succeeded to make a motion picture that shows upward growing icicle, and afterwards, succeeded to make ice spike artificially in laboratory using refrigerator.

In animated photographs it was caught that not the ice but the water with air parcel rose upward in the bowl through the "breathing-hole" that is unfrozen part of the ice surface. At the round skin edge of the rising water, the ice wall was formed by the evaporative cooling and the conduction from the cold wind nearby. This wall made again the higher path of rising water in it. The water passing inside this wall made the wall higher and higher and finally become the ice bar about 10 ~15 cm height with many bubbles in it that was called the Buddha shape. It is also deducted that the ice spike grows by the synchronized cooling of the bowl not only on upper part but also on lower and side parts together.

Also, it is verified that the ice spike is not a mystery but a naturally grown ice bar caused by the volume expansion concentrated to a point called "breathing-hole" when the status change from water to ice occurs, and by the buoyancy force resulting from the rising air parcel that expelled from water when it freezes. Also, the peculiar meteorological conditions related to the formation of ice spike at the valley of the Mt. Mai are summarized. Firstly, the most favorable condition for the ice spike is the persistent air temperature near 0℃ for a long time. Secondly, the huge tafoni rocks of the Mt. Mai may make this favorable temperature condition frequently. When the tafoni rocks are wet or covered with snow, evaporation and/or sublimation processes make the air colder to near 0℃ and make it sink into the valley. Also the latent heat released by the deposition process of water in the rock may make the air near 0℃. Thirdly, the lower topography of the valley permits only the slow intrusion of cooled air. Fourthly, the water in the valley contains much air parcels obtained during the flow down through the cold tafoni rock.

Keywords

Ice spike, upward icicle, breathing hole, tafoni rock

STABLE ISOTOPE COMPOSITION OF PERENNIAL ICE IN CAVES AS AN AID TO CHARACTERIZING ICE CAVE TYPES

Charles J. Yonge
Yonge Cave & Karst Consulting Inc.,
1009 Larch Place,
Canmore, AB T1W 1S7, Canada chas-karst@telus.net

William D. MacDonald
Yonge Cave & Karst Consulting Inc.,
1009 Larch Place,
Canmore, AB T1W 1S7, Canada

Abstract
Stable isotope studies of perennial ice from western North American ice caves suggest that three main types can be defined: cold trap, permafrost, and cold zone. Some complex cave systems may comprise two or more types. While 14 caves were sampled from the region, in this study, 9 definitive sites were examined in more detail where they exemplified classic perennial ice features: massive ice, hoar frost, ice stalagmites and so on. Stable isotopes of the ice (δ18O and δ2H) assist in the understanding the origin of the freezing moisture, whether from direct snow (cold trap), moist summer air (permafrost) or from humid air within the cave (cold zone). Furthermore, delineating the complex systematics of cave ice formation is vitally important if it is to be used (or rejected) as a proxy climate record.

Introduction
A number of studies of perennial ice in caves have been undertaken (see e.g. Ford, Williams, 2007; Yonge 2004); but there are relatively few studies employing stable isotopes and these are confined to Europe (Kern et al., 2011; Persoiu & Pazdur, 2011; Racovita & Onac, 2000; Lauritzen, 1996) and North America (Lacelle et al., 2009; Yonge & MacDonald, 1999, Yonge & MacDonald, 2006; Marshall & Brown, 1974). With the current interest in climate change, a wealth of studies exists on polar (e.g. Jouzel & Masson-Delmotte, 2010; Johnsen et al., 2001) and cordilleran (e.g. Thompson & Davis, 2005) ices cores.

While ice cores deal with the direct precipitation of snow and the subsequent modification of the resulting layers by various physical processes, the mechanisms of ice formation in caves, being confined, can be quite different and may require an alternative interpretation (e.g. Lacelle et al., 2009; Yonge & MacDonald, 1999). Here we look at three possible ice cave types (and combinations of these where cave systems are complex). We examine caves which are dominated by a cold zone close to the entrance (Cold Zone type), in Permafrost (Permafrost type) and in pit caves where cold air and snow is trapped (Cold Trap type). Formation of ice in the latter is most likely to resemble glacial ice by direct accumulation of snow in open pits and in some cases - where ice flow has been demonstrated - the system is referred to as a Glacier Cave (Holmlund et al., 2005; MacDonald, 1994).

Methodology

Field Sites
While stable isotope data has been acquired from 14 cave sites, we focus on 3 caves from west of the Divide:

Projects Cave (49° 48’ N, 125° 59’ W; elevation 1050m), Q5 (49° 47’ N, 125° 59’ W; elevation 1200m) on Vancouver Island and Trout Lake Cave, Washington (45° 58’ N, 121° 32’ W; elevation 850m).

Six caves were selected from east of the Divide:

Disaster Point Cave (53° 10’ N, 117° 58’ W; elevation 1080m), Rats Nest Cave (51° 04’ N, 115° 16’ W; elevation 1480m), Canyon Creek Ice Cave (50° 54’ N, 114° 47’ W; elevation 1775m) Ice Chest (49° 37’ N, 114° 39’ W; elevation 2250m) in the Canadian Rockies and in the Prior Mountains, Montana: Big Ice Cave (45° 09’ N, 108° 23’ W; elevation 2300m) and Little Ice Cave (45° 07’ N, 108° 20’ W; elevation 2500m).

Sample Collection
Massive ice (floor and stratified) was drilled out using an ice screw. Where the ice was stratified, visually obvious ice layers were sampled sequentially. The contents were then transferred to 100ml Nalgene bottles and the ice screw carefully dried after each extraction. All other ice and seepage water was collected by breakage, or directly, and again transferred to bottles as above.

Analysis

The samples were analyzed at the Calgary University Stable Isotope Laboratory on a Neir-McKinny type Mass Spectrometer. Gases produced from the water samples were hydrogen (by reduction of the water over heated zinc at 450°C) and oxygen (as CO_2 equilibrated at 25°C). $\delta^{18}O$ and $\delta^{2}H$ are expressed in ‰ against the V-SMOW standard as

$$\delta = R_{sample}/R_{standard} - 1)\ 10^3 \qquad (1)$$

R_{sample} and $R_{standard}$ are the ratios of $^{18}O/^{16}O$ and $^{2}H/^{1}H$ in the sample and standard respectively. Precision is +/- 0.1‰ on $\delta^{10}O$ and 0.5‰ on $\delta^{2}H$‰.

Results

Isotopic data for the 14 ice caves in this study is presented in Figure 1. Global precipitation world-wide falls on or close to the Global Meteoric Water Line – GMWL (Craig, 1961; Dansgaard, 1964), given as:

$$\delta^{2}H = 8\delta^{18}O + 10\ (‰) \qquad (2)$$

Some minor modifications of this line have been introduced later (Rozanski et al., 1993) but do not affect the arguments presented here. Positions on the line relate to temperature, where the lowest temperature is associated with the lowest δ-values (Figs. 1 and 7). It can be seen that cave ice also falls close to the GMWL line with a fair degree of precision (R2 = 0.96; Yonge & MacDonald, 2006) where:

$$\delta^{2}H = 8.0\ (+/-\ 0.16)\ \delta^{18}O + 6.6(+/-\ 2.6)\quad (‰) \qquad (3)$$

However, with the data sets presented from caves on each side of the Divide, two Regional Meteoric Water Lines (RMWL) emerge (middle of Table 1).

Despite the universality of the GMWL, it has long been recognized that Local Meteoric Water Lines (LMWL) exist yielding lower slopes that cross the GMWL at various temperatures but whose mean plots close to the GMWL. For the caves in this study the LMWL are presented in Table 1. The LMWL's exhibit slopes around 8 or less. Figure 2 presents the average deuterium excess (d-excess ‰) for each of the 14 caves of Figure1. This is acquired by forcing the LMWLs to a slope of 8 which yields the d-excess at intercept. Again it can clearly be seen that the caves split into two RMWLs east and west of the Great Divide. Included in the diagram and in Table 1 are results from Rats Nest Cave, which examined

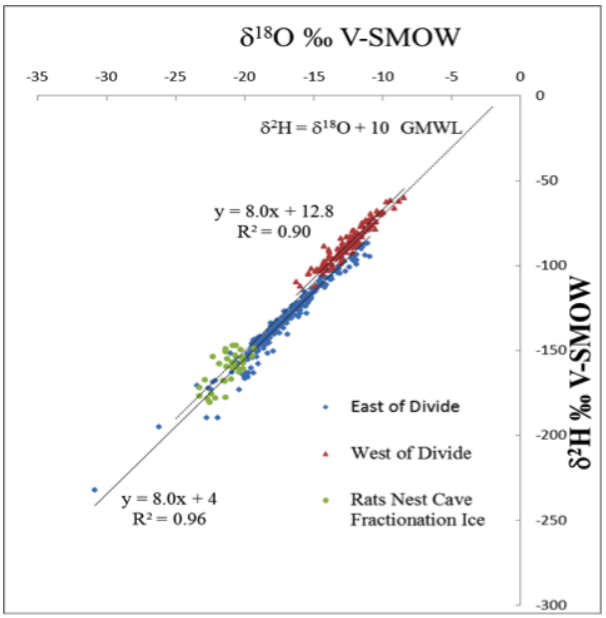


Figure 1. *The $\delta^{18}O$ - $\delta^{2}H$ of ice from 14 North American ice caves from East (<250km from coast) and West (>750km from coast) of the Divide (modified from Yonge & MacDonald, 2006). Rats Nest Cave ice is excluded from the regressions – see Cold Zone Caves.*

Table 1. *Local (LMWL) and Regional (RMWL) Meteoric Water Lines for the ice caves in this study.*

Ice Cave	***LMWL***	***Regression***
Disaster Point	$\delta^{2}H = 8.3\delta^{18}O - 0.8$	$R^2 = 0.96$
Canyon Creek	$\delta^{2}H = 7.0\delta^{18}O$ -14.1	$R^2 = 0.95$
Ice Chest	$\delta^{2}H = 7.7\delta^{18}O$ -1.6	$R^2 = 0.81$
Serendipity	$\delta^{2}H = 7.6\delta^{18}O$ -2.4	$R^2 = 0.96$
Big Ice Cave	$\delta^{2}H = 7.8\delta^{18}O$ +1.9	$R^2 = 0.95$
Little Ice Cave	$\delta^{2}H = 7.4\delta^{18}O$ -5.5	$R^2 = 0.98$
Projects Cave	$\delta^{2}H = 6.1\delta^{18}O - 12.4$	$R^2 = 0.91$
Q5	$\delta^{2}H = 8.2\delta^{18}O$ +14.8	$R^2 = 0.92$
Trout Lake Cave	$\delta^{2}H = 7.5\delta^{18}O$ +8.4	$R^2 = 0.87$
Region	***RMWL (slopes forced to 8)***	
East of Divide	$\delta^{2}H = 8.0\delta^{18}O$ +4.0	$R^2 = 0.95$
West of Divide	$\delta^{2}H = 8.0\delta^{18}O$ +12.8	$R^2 = 0.90$
Ephemeral Ice		
Rats Nest Cave	$\delta^{2}H = 9.1\delta^{18}O$ +30.3	$R^2 = 0.65$

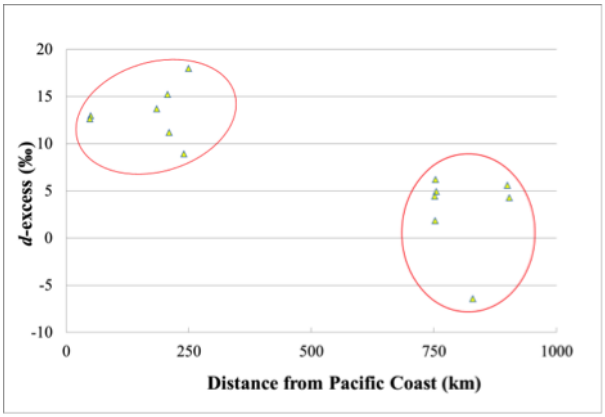


Figure 2. *The deuterium excess versus distance from the Pacific coast for 14 North American ice caves (Circled are fields for caves <250km and >750km).*

exiting cave vapour freezing outside of the cave during a -20°C period, and is used by analogy to understand cold zone Rayleigh fractionation processes.

Discussion

Meteoric Water Lines and Ice Caves

Figures 1 and 2 delineate fields which suggest two RMWLs as defined by the *d*-excess. The ice caves to the east of the Great Divide on average yield a lower *d*-excess (4.0‰), which appears to be a combination of a drier, more evaporative climate there and a greater tendency to precipitate snow and hoar frost in the caves. An evaporative climate tends yield precipitation which falls along a slope of 4 below the GMWL, and additionally the sublimation of cloud vapour to snow and cave hoar also yields values below the GMWL (Fig. 7). Those caves close to the coast are in high humidity regimes where rain is more dominant and the resulting ice (mainly of cold trap origin) tends to plot on the GMWL (intercept of +12.8‰, which while above +10‰ is within significance - +/- 3.0‰). The LMWLs yield slopes around 8 or less, which supports the argument above of a drier, colder climate on the east side of the Divide leading to lower humidity and greater solid precipitation (e.g. data from Projects Cave mostly plots above the Global Meteoric water line and a forced slope of 8 yield an intercept of +13.0‰).

We now examine the ice cave data in more detail.

Cold Trap Caves

Cold traps occur where there is little through movement of air within a pit-like cave. Cold winter air sinks into the cave, generally through a bottleneck, and displaces warmer air within. Snow falling through the entrance aids the cold trap conditions providing an environment for perennial ice. During the summer, buoyant warm air cannot get into the cave other than by eddy currents



Plate 1. *The Booming Ice Chasm – a large, unstudied cold trap cave, Alberta, Canada.*

and the cave maintains a temperature lower than the mean annual temperature. A quantitative study of Trout Lake Ice Cave (Martin & Quinn, 1991) lends support to this mechanism with the cave only 850m AMSL and 185km from the coast. Samples we collected at this site gave a range of seepage δ2H of -82 to -63 (19‰), whereas floor ice was between -77 to -69 (8‰) and average precipitation at -71‰. The mean of seepage -72‰ and floor ice -73‰, where average precipitation -71‰ perhaps shows a slight bias towards the lower δ^2H of snow. The tighter range of floor ice over seepage suggests the integration and thus averaging of seepage along with rain and snow falling into the entrance.

Disaster Point Cave (Fig. 3) at 1080m and 830km from the coast, in a very different environment across the Divide, shows a similar integration of H_2O sources but with snow being a more significant component (i.e., the δ of snow tends to drag the cave ice values down below seepage and average regional water – the latter from an adjacent river).

Despite the environmental differences of these caves, we nevertheless expect stratified ice from each to reflect a muted δ variation of precipitation falling at the cave – much as is interpreted in glaciers (see introduction for references).

Figure 4 plots data from two Vancouver Island caves, both of which contain substantial (40m+) plugs of stratified ice. A moist coastal regime dominates here with substantial inputs of both rain and snow to the caves. Evidence of ice movement (MacDonald, 1994) suggests

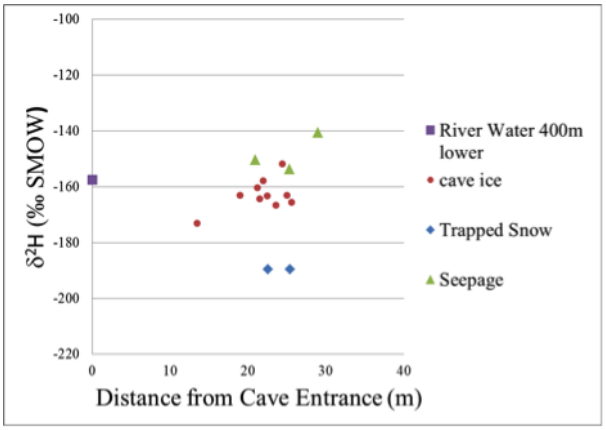


Figure 3. *Distribution of ice versus δ^2H in Disaster Point Ice Cave.*

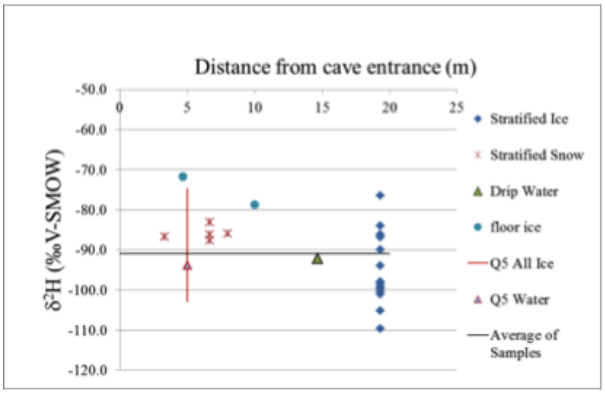


Figure 4. *Distribution of ice in Q5 and Projects Cave versus δ^2H.*

that these caves could be described as *glacier caves* such as Scarisoara Glacier Cave (Racovita and Onac, 2000).

The figure shows that ice samples cluster around mean precipitation (drip water), although Q5 yields a range of δ−values generally higher than those for Projects Cave. However, Q5 has a stream running into the entrance in the summer where the ice samples are found, so is likely more biased towards the heavier summer water. Projects Cave shows lower values, but these cluster around mean precipitation at -92‰. It has no entrance stream and stratified ice occurs almost 20m into the cave – a result of glacial movement perhaps.

Figure 5 shows possible bi-annual (seasonal) variations in the δ-values, which (for Projects Cave) oscillate around the value for mean precipitation. Despite the likely muting of the signal we can associate the higher δ-values with higher temperatures, as with glacier ice and thus with the GMWL.

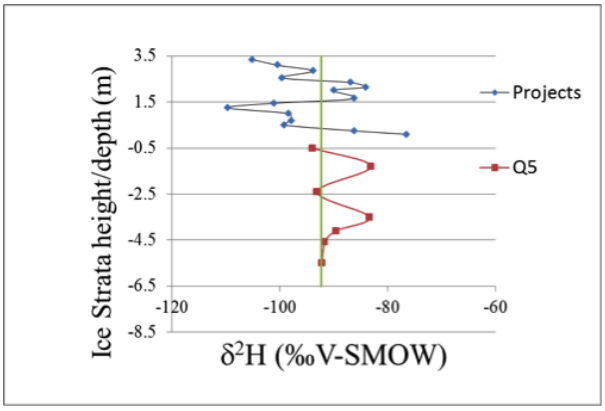


Figure 5. *Variation of δ^2H in the stratified units from Q5 and Projects Cave. The green line is mean precipitation.*

Therefore, despite the isotopic muting (modification) of the precipitation signal within cold trap cave stratified ice, the above suggests that the ice can be useful as climate proxies as has been well demonstrated at Scarisoara Glacier Cave (Holmlund et al., 2005). Similar muting of the signal is after all found in glaciers by stratigraphic distortion and infiltration by pore water (references in the introduction).

Permafrost Caves

Permafrost caves have been discussed by Yonge & MacDonald (1999), where an isotopic model was developed to explain the surprisingly high δ-values and low *d*-deficiencies when compared to snow or average precipitation (see e.g. Fig. 6). This cave, Ice Chest, is far to the east (49° 37' N, 114° 39' W) and high up (elevation 2250m AMSL).

The hoar ice here has similar δ−values to the massive ice in the cave, but the latter declines somewhat as the entrance is approached, perhaps affected by an increase of the lower δ−value seepage water there derived from snowmelt. The model proposed by Yonge & MacDonald (1999) shows that the low δ−values and *d*-deficiencies can arise from summer moist air entering the cave and being forced to sublimate at 0°C.

Figure 7 demonstrates that cloud vapour condensing at say, 0 or 10°C, which would normally fall on the GMWL, in fact falls below it if frozen by sublimation in the cave. The vapour-liquid and vapour-solid fractionation factors used are from Jouzel (1984) and δ/temperature derived from a study of mean monthly Calgary Precipitation where:

$$\delta^{18}O = 0.38T - 19.50‰ \quad (3)$$

$$\delta^{2}H = 3.04T - 146.0‰ \quad (4)$$

When 1,000-year-old stratified ice from another nearby permafrost cave (Serendipity) was studied, Yonge & MacDonald (1999) found variable δ-values that were all above those of mean precipitation at the site (Fig. 11 - next section). Interpretation of swings in the data would suggest variable inputs in the amount and/or temperature of invading moist air, which leads to very different conclusions regarding the paleoclimate compared to those when considering glacier ice (higher δ−values associated with higher temperatures).

Supporting the above argument, Figure 8 illustrates that hoar ice again dominates the higher δ-values of these permafrost caves, suggesting that massive ice is



Plate 2. *Hoar ice in Serendipity Cave, Alberta Canada.*

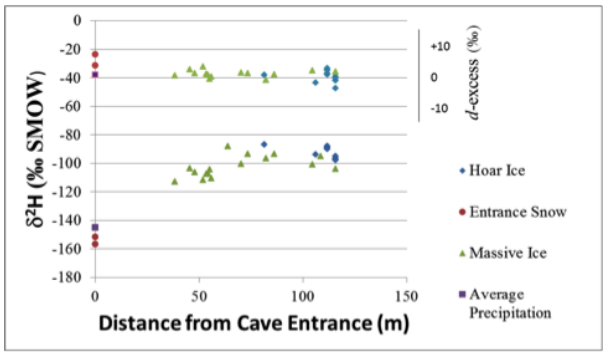


Figure 6. *δ²H versus distance from the entrance of Ice Chest (Permafrost Type).*

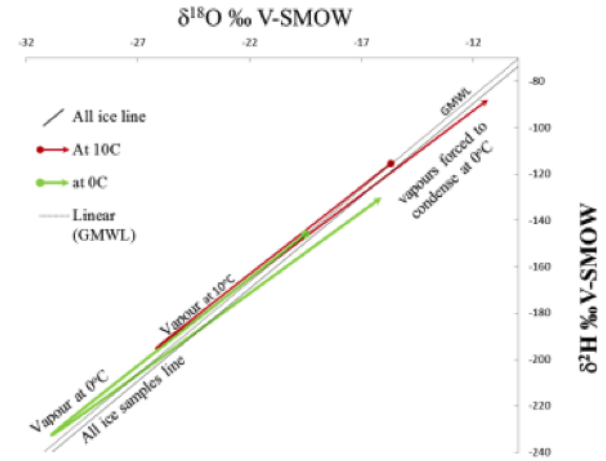


Figure 7. *Model δ18O - δ2H for hoar ice derived from moist air invading the cave.*

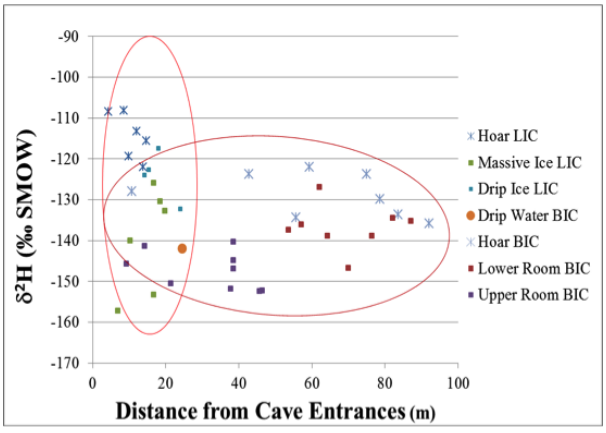


Figure 8. *δ²H versus distance from the entrance of Ice of Little (left) and Big (right) Ice Caves, Montana (both permafrost types).*

a variable combination of hoar and seepage - the latter includes snowmelt. (Note that for Big Ice Cave, the lower room massive ice has higher δ-values than the upper room, suggesting that the upper room, closer to the surface, is more affected by seepage.)

Cold Zone Caves

Cold zones in caves result from evaporative cooling at the cave walls. This condition generally occurs close to the cave entrance where the relative humidity drops from 100‰ deep in the cave to <100% toward the outside. The condition is also seasonal in that summer moisture condensation can transfer energy to the cave surfaces - increasing temperatures –and so it is during the fall and winter when the cold zone is maintained. In some cases the cold zone supports perennial ice, as we discuss here.

Wigley & Brown (1976) have modelled cave temperature and humidity yielding a relaxation length (the cold zone) which is scaled by airflow rate and passage diameter:

$$x_o = 100 D^{1.2} V^{0.2} \quad (5)$$

Where D is the passage diameter, V is the flow rate and the constant has the appropriate dimensions to scale x_o in metres.

In Canada, Castleguard Cave is a classic cold zone cave with ice extending around 400m in winter, but the ice is not perennial. So here, we examine Canyon Creek Ice Cave, a rather low altitude cave which supports a (retreating) cold zone. Figure 9 displays the δ²H of various ice types versus distance from the cave entrance. The cold zone currently extends from around 50m to 180m from the entrance (x_o=130m); which suggests that estimates of D = 1.2m and V = 1.3m/s further into the cave are about right.

The most general feature is that δ-values appear to decline with distance into the cave and that the stratified ice yields some of the lowest values encountered in the study. Low δ-values are usually indicative of low temperatures (as seen for example in snow), being a function of latitude and elevation (Dansgaard, 1964) and of the GMWL. Snow seems an unlikely candidate with the stratified ice being found up-slope and >50m from the cave entrance. Stratified ice varies from -130 to -173‰, so there is a great variation within the ice mass, which was sampled at distinctive layers. Not knowing the age of this ice, and that it is currently retreating, might suggest that it is relict from earlier and cooler times.



Plate 3. *Stratified Ice in Canyon Creek Ice Cave, Alberta, Canada.*

However, another mechanism which could generate low δ-values is Rayleigh fractionation of the outgoing cave vapour. For example, ephemeral ice at Rats Nest Cave (Fig. 10) exhibits the fractionation and mixing of moist air exiting the cave during cold weather (-20°C) and freezing as hoar outside the cave entrance.

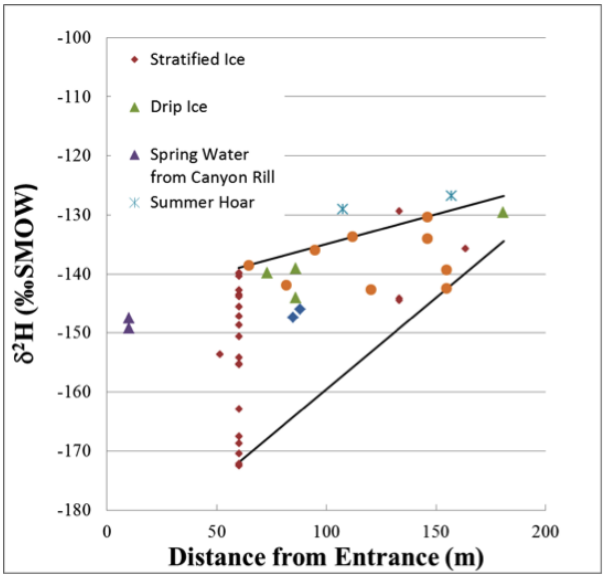


Figure 9. *Deuterium concentration versus distance from the entrance of Canyon Creek Ice Cave (Cold Zone Type). "Mixing" and "Rayleigh" are explained in the text.*

With a temperature range of +5 in the cave to -20°C outside, we see hoar with much depleted δ^2H (down to -181‰). Compared to seepage water - assumed to be in equilibrium with the cave air (-145‰) - and using the sublimation fractionation factor at 0°C (Jouzel, 1986), we calculate that the initial ice should have commenced at -133‰. However the subsequent δ-values for ice are substantially lower (extrapolated to -149‰ at 0m), which suggests a mixing with the outside air. Ice condensate from air at -20°C would yield around - 206‰ (equation 4) allowing us to determine that around 25‰ of the outside air is contributing to the cave vapour and the remaining effect is due to Rayleigh Distillation (RD); at 4m 78‰ of the cave vapour is precipitated out (We have made the assumption of a linear temperature decline over the 0-4m with the concomitant changing of the fractionation factor between 0 to -20°C; Jouzel, 1986.)

For Canyon Creek Ice Cave (Fig. 11) vapour is being precipitated as ice at 0°C in the cold zone (extensive hoar is noted there in winter). If we assume the winter hoar makes up the ice mass, and that this is primarily

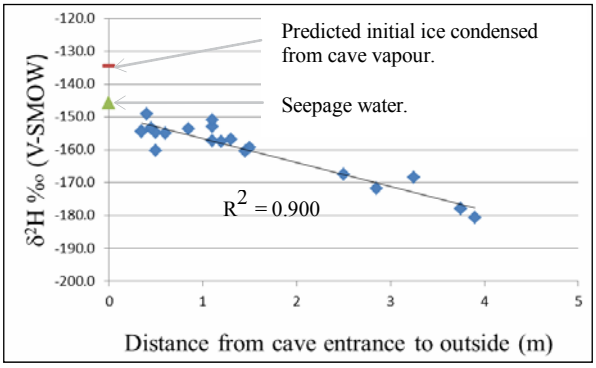


Figure 10. *Variation in δ^2H of hoar with distance from the entrance of Rats Nest Cave (outside temperature was -20°C).*

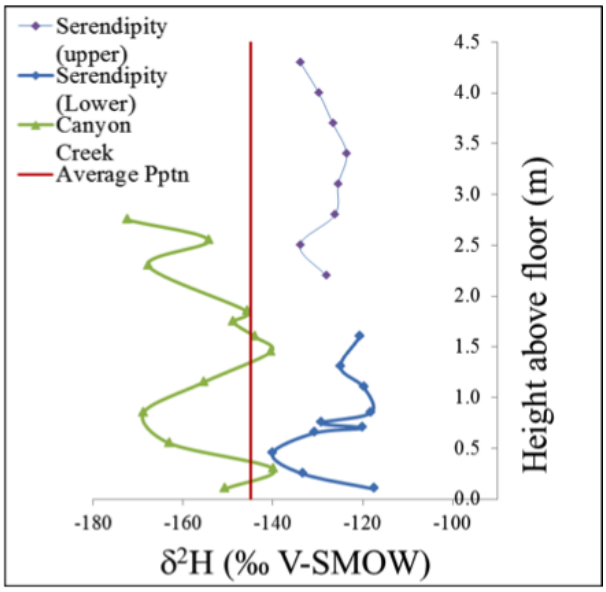


Figure 11. *Variation of δ^2H in the stratified units in Serendipity and Canyon Creek Ice Cave.*
The tan line is mean precipitation.

derived from the cave air, the variation in δ^2H can be accounted for by a 0-29‰ fraction of the cave vapour (in equilibrium) being frozen out by Rayleigh distillation with a varying contribution from seepage and condensed water vapour from outside.

At 29‰ the mechanism is purely Rayleigh ("Rayleigh" in Fig. 9), whereas at 0‰ (no Rayleigh distillation) the δ^2H external contribution plus a buffering composition of cave vapour accounts values along the mixing line "Mixing" in Figure 9. Note that the mixing mechanism cannot produce the very low δ-values observed in the stratified cave ice and represents conditions likely dominant in summer. The greatest mixing is closest to the entrance with a 45% contribution of seepage and moist air from outside.

Furthermore, we have ignored kinetic effects (Lacelle et al., 2009), which can modify both the RD process and seepage, but would tend lead to enriched δ-values overall, while here we are trying to explain the much depleted ice. The stratigraphic record (Fig. 11), very different from Serendipity (in permafrost), then may be made up of varying components of cave seepage and summer hoar accumulating in the cold zone. The balance of Rayleigh/Mixing components to the ice layers can have climatic implications in which the summer component, contributing higher δ-values, can be more or less dominant depending on the summer's intensity. A purely Rayleigh process implies no contribution by external moisture, which is unlikely, but even with some mixing low δ-values can be achieved by freezing a higher fraction of the cave vapour out as it passes through the cold zone.

Conclusions

1. All ice data when plotted as $\delta^{18}O$-δ^2H‰ yield two fields defined by the *d*-excess where geographically they are close to the Pacific coast (<250km; *d*=10+/- 3‰) and east of the Great Divide (>750km; *d*=4+/- 3‰). These data can broadly be explained on the basis of a humid regime in the west compared to a drier, more continental regime in the east.
2. Cold Trap Caves appear to behave much like glaciers, preserving a muted record of precipitation at the site. These sites offer a paleoclimatic record interpretable in the same way that glaciers are. However, a cautionary note is sounded: ice caves are rarely just one type; one type might dominate, but may have components of the other types. Ice stratigraphy from cold trap caves appears to offer the best climate records, but the ice may be modified by Rayleigh and/or permafrost effects.
3. Permafrost Caves yield higher δ-values and lower d- escess than expected. It appears that moist air forced to sublimate at 0°C (as hoar) mixed with a more depleted seepage forms the massive ice within the cave. Paleoclimate might then be inferred from the variation in amount and/or temperature of the invading moist air. Increased hoar and reduced seepage during a cold climate would produce an inverse climate record when compared to glaciers.

4. Data from Cold zone caves appears to show effects of Rayleigh Distillation as cave vapour draining from the cave is cooled at a cold zone by evaporation (i.e., where the relative humidity drops below 100%). A pure form of RD can generate a much depleted signal, which normally be interpreted in terms of low temperature. More likely there are varying degrees of RD modified by seepage. Seepage should be greater during warm periods, which allows climatic information to be gleaned from stratified ice. However, while higher temperatures would yield higher δ-values, their interpretation is quite different from that of glaciers.

Although ice in glacier/cold trap caves might be considered similar to stratified ice in glacial cores, a caution would be that as confined systems other processes as seen in cold zone or permafrost may contribute to the signal. In conclusion, we see that cold zone caves appear to contain the lowest δ-values and that is in part due to a Rayleigh distillation systematics.

References

Craig H. 1961. Isotopic Varations in Meteoric Waters. Science133: 1702-1703.

Dansgaard W. 1964. Stable Isotopes in Precipitation. Tellus 16: 436-468.

Ford DC, Williams P. 2007. Karst hydrogeology and geomorphology: West Sussex, U.K., Wiley: 576 p.

Holmlund P, Onac BP, Hansson M, Holmgren K, Morth M, Nyman M, Persoiu A. 2005. Assessing the paleoclimate potential of cave glaciers: the example of Scarisoara Ice Cave (Romania). Geo. Ann.87A (1): 193-201.

Johnsen SJ, Dahl-Jensen D, Gundestrup N, Steffensen JP, Clausen HB, Miller H, Masson-Delmotte V, Sveinbjornsdottir AE, White J. 2001. Oxygen isotope and palaeotemperature records from six Greenland ice-core stations: Camp Century, Dye-3, GRIP, GISP2, Renland, and NorthGRIP. Journal of Quaternary Science 16: 299-307.

Jouzel J. 1986. Isotopes in cloud physics: multiphase and multistage condensation processes. In: Handbook of Environmental Isotope Geochemistry, Fritz P, Fontes J, editors. The Terrestrial Environment B., Ch. 2: Elsevier, 557p.

Jouzel J, Masson-Delmotte V. 2010. Deep ice cores: the need for going back in time. Quaternary Science Reviews 29: 3683-3689.

Kern Z, Forizs I, Pavuza R, Molnar M, Nagy B. 2011. Isotope hydrological studies of the perennial ice deposit of Saarhalle, Mammuthohle, Dachstein Mts, Austria. The Cryosphere 5: 291–298.

Lacelle D, Lauriol B, Clark ID. 2009. Formation of seasonal ice bodies and associated cryogenic carbonates in Caverne de l'Ours,Quebec, Canada: Kinetic isotope effects and pseudo-biogenic crystal structures. Journal of Cave and Karst Studies 71: 48-62.

Lauritzen S-E. 1996. Karst Landforms and Caves of Nordland, North Norway: Guide for Excursion 2. In: Mylroie JE, Lauritzen S-E, editors, Climate Change the Karst Record, p. 1-160.

MacDonald WD. 1994. Stable isotope composition of cave ice in Western North America [MSc. Thesis]. University of Calgary, Alberta, Canada.

Marhall P, Brown MC. 1974. Ice in Coulthard Cave, Alberta. Canadian Journal of Earth Sciences 11: 510-518.

Martin K, Quinn RR. 1991. Meteorological Observations of Ice Cave, Trout Lake Washington. National Speleological Society Bulletin 52: 45-51.

Persoiu A, Pazdur A. 2011. Ice genesis and its long-term mass balance and dynamics in Scarisoara Ice Cave, Romania. The Cryosphere 5: 45-53.

Racovita G, Onac BP. 2000. Scarisoara Glacier Cave: Monogrphic Study, Editura Carpatica Cluj-Napoca, 139p.

Rozanski K, Araguas-Araguas L, Gonfiantini R. 1993. Isotopic patterns in modern global precipitation. In: Swart PK, Lohwan KL, McKenzie JA, Savin S, editors, Climate Change in continental isotope record. Geophys. Monogr.: Washington DC, Am. Geophys. Union, v. 78, p. 1-37.

Thompson LG, Davis ME. 2005. Stable isotopes through the Holocene as recorded in low-latitude, high-altitude ice cores. In: Aggrwal PK, Gat JR, Froehlich KFO, editors, Isotopes in the Water Cycle: Past, Present and Future of a Developing Science. Dordrecht, the Netherlands Springer: Quaternary Research, p. 321-339

Wigley ML., Brown MC. 1976. The physics of caves. In: Ford TD, Cullingford CHD, editors, The Science of Speleology. Academic Press: 503p.

Yonge CJ, MacDonald WD. 2006. Contrast in isotopic composition of cave ice across the Divide in Western North America. Archives of Climate Change in Karst. Karst Waters Institute Special Publication 10: 26-28.

Yonge CJ. 2004. Ice in caves. In: Gunn J, editor, Encyclopedia of Caves and Karst: New York, Fitzroy Dearborn, p. 437-439.

Yonge CJ, MacDonald WD. 1999. The potential of cave ice in isotope paleoclimatology. Boreas 28: 357-362.

INTERNAL DRAINAGE OF GLACIERS AND ITS ORIGIN

B. R. Mavlyudov
Institute of geography of the Russian Academy of Sciences
Staromonetny, 29,
Moscow, 119017, Russia, bulatrm@bk.ru

Abstract
Ways of occurrence of elements of an internal drainage of glaciers and also origin of internal drainage systems as a whole are considered. It is shown that elements of an internal drainage can be formed either on the base of fissures and crevasses or by incision of water streams into ice from glacier surface. The basic way of glacier drainage is formed on the base of sliding plane which is formed closely to glacier bed and smooth all roughnesses of the bed. Spreading of water on the surface of this plane during spring time forms not effective drainage system however during ablation season drainage channels are formed along this sliding plane and it is an effective drainage system. The offered point of view explains selective erosion on the glacier bed, spring accelerations of ice movement velocity, formation of eskers and outbreaks of glacier-dammed lakes.

Keywords
glacier hydrology, glaciospeleology, internal drainage systems, fractures, crevasses, hydrofractures

Introduction
The internal drainage is inherent for very many glaciers without dependences on glaciers types and their thermal conditions. In spite of the fact that internal drainage was known long ago, its researches were carried out until recently only by indirect methods: modelling, geophysical, hydrological, etc. (Benn & Evans, 2010; Fountain & Walder, 1998). Scientists think about an internal drainage as about «black box» which has signals on input and on exit (Murray et al., 1995).

Speleologists and cavers were the first who started to study elements of an internal drainage of glaciers (Freyfeld, 1963; Gallo, 1968; Halliday & Anderson, 1969; Poluektov et al., 1966). And they do it throughout more than 50 years. For these years the set of articles devoted to studying of glacial caves have been published (Eraso, 1991, 2003; Pulina, 1992; Slupetsky, 1998; Badino, 2002; Mavlyudov, 2005a; Tyc & Stefaniak, 2007; Griselin, 1995), the monographs dedicated to an internal drainage are published (Eraso & Pulina, 2010; Mavlyudov, 2006). However glaciologists persistently did not want to recognize the data received earlier by speleological methods.

We already wrote about internal drainage systems of glaciers (Mavlyudov, 2006, 2007a). These works were based both on our own investigations and on studying of glacial caves by other groups of researchers (Badino, 2002; Reynaud & Moreau, 1995; Grizelin, Marlin, 1993, Pulina, Rehác, 1991, Rehác J., Rehác, 1995, Schroeder, 1998, et al.). Recently there were enough many articles devoted to studying of glacial caves by glaciologists (Gulley, Benn, 2007, 2009a, 2009b et al.). Thus for last years enough extensive material on elements of an internal drainage of the glaciers has collected, it was received in different regions of the world that allows to make some generalisations connected with internal drainage at the new scientific level. This article exactly is dedicated to problems of an origin of glaciers internal drainage.

Methods
The author carried out researches of glacial caves since 1982. Our researches of glacial caves cover regions: Spitsbergen, Caucasus, the Alps, Tien-Shan, Pamir, Suntar-Hayata, the Himalayas and Antarctic. Some researches were at single visit and other was repeated throughout many years to reveal dynamics of elements of an internal drainage. In glacial caves were studied: a structure of cavities (on the base of observations and topographic survey), ice structures, ice temperatures, velocity of incision of water streams into ice, intensity ice creep, etc.

Our data have been complemented by data of other researchers of glacial caves which cover now practically all glacial areas.

Results

Earlier we assumed that systems of an internal drainage at the end of ablation season represent the developed system of the pipelike channels most part of which is located under a glacier (except of vertical parts which are englacial) (Mavlyudov, 2006, 2007a). This structure of channels is considered as effective system of drainage (Benn, Evans, 2010). During a winter season when melting on glaciers surface is stopped drainage channels in glaciers was closed under the influence of plastic deformation of ice (ice creep) and the single system of water transportation inside glacier is divided to pieces forming the isolated fragments. In the spring time when melt water arrive into drainage system and by the excess of water pressure isolated fragments of drainage system are united and water transport system inside glacier is restored. At this time drainage system is not effective (Benn, Evance, 2010). Besides there were some proofs of such way of functioning of an internal drainage of glaciers. It is possible to attribute to them: structure of a through cave on Werenskiold Glacier (Pulina, Rehak, 1991), detection of completely closed by ice creep inactive channels of an internal drainage on Aldegonda Glacier in a year after their first visiting (Mavlyudov, 2006), winter water floods on glaciers of Spitsbergen (Benn, Evans, 2010). It all said that basically we on a correct way however some positions which appeared not clear remained in this case. In particular the origin of drainage system of glaciers concerned such positions not for each concrete glacier but for glaciers as a whole. How this problem was solved? Having noticed cutting of channels into ice Fountain and Walder (1998) have offered the theory of formation of channels by immersing (incision or cutting into ice) from glacier surface (Fountain, Walder, 1998). However it was connected with streams cutting into opened crevasses in ice but they are extended far not on all glaciers and as a rule occupy only rather small part of glacier area. We also wrote about possibility of channels formation by a burial of superficial canyons in ice (Mavlyudov, 2006). But in this case we say directly about the internal drainage channels located superficially in ice. In this case crevasses were not required for formation of such channels. About similar channels (Gulley et al., 2009) have written a little later. They also assumed that such channels can form system of an internal drainage in glaciers without crevasses. But in any way it did not allow to understand how the internal drainage system of a typical glacier was generated. Earlier we offered two ideas which basically could explain formation of internal drainage systems (Mavlyudov, 1995). The first of them consisted that similar to (Fountain, Walder, 1998) we believed that drainage channels can be generated on shear cracks and consequently is situated along glacier edge (marginal caves). For example we observed similar caves on the Southern Inyltchek Glacier in Tien-Shan. It was supposed that at merge of two branches of a glacier two marginal drainage systems connect into one central drainage system. It looks logical but one circumstance afflicted - it was not possible to find such connection of drainage systems in reality. And even if the similar mechanism of formation of internal drainage channels exists it is not universal as far as it cannot explain formation of drainage channels in glaciers without tributaries. The second idea supposes that similar as at (Fountain, Walder, 1998) channels of an internal drainage were initially formed at crevasse zones i.e. in tension zone (Mavlyudov, 1995). In this case we started with the assumption which however was proved by direct observations that crevasses on glaciers can be filled by water but water cannot move deeper. It means that water inflow into at the beginning of crevasse zone and water outflow on the termination of a crevasse zone on a glacier surface. Such phenomenon was observed repeatedly on many glaciers. As ice moves downstream of glacier in crevasse zone lower crevasses were closed but in upper part of crevasse zone new crevasses begin to grow. It was supposed that in lower closed crevasses there was a channel in which water situated under ice surface which below from closed crevasses outflow to ice surface. At glacier movement the buried channel increases its length until the buried channel did not reach glacier tongue. So the central drainage system could be generated. However and this idea has not appeared universal as she cannot explain all cases of occurrence of an internal drainage of glaciers. For example on many glaciers we can see water absorbed by crevasse instead of outflow from other end of a crevasse. Thus it is necessary to state that now there is no satisfactory theory of formation of internal drainage systems of glaciers.

But there are enough possibilities for explanation of formation of separate elements of an internal drainage systems. It is known that moulins are formed on crevasses (Paterson, 1998, Fountain, Walder, 1998, Fountain et al., 2005, Benn, Evans, 2010). However there are glaciers on which moulins are present but crevasses are absent. They are formed on the base of walls of the buried ice

canyons. In this case depth of moulin cannot exceed depth of a parent canyon. Also moulins can origin on ice/rock contact. In case of usual moulins their depth is comparable with depth of a parent crevasse. And as crevasses for example in temperate glaciers cannot exceed depth of 25-30 m (Paterson, 1998) the depth of moulins on temperate glaciers should have comparable size. In many cases this condition is carried out but is far not always. For example on the temperate glacier Mer-de-Glace (Alps) moulins which actually also give name for all moulins had depth more than 80 m (Reynaud, Moreau, 1995). On the same glacier the moulin with depth more than 100 m was known (Forbes, 1845). Musketov (1881) in his book informed that moulins on glaciers can reach depth up to 300 m. Probably it is an error as in a source whence Musketov took these data were feet instead of meters. Moulin investigated on temperate Bashkara Glacier (Caucasus) had depth more than 40 m (Mavlyudov, Solovyanova, 2005). Apparently in ice movement and ice creep there are some moments which existing theories do not explain.

In more rigid cold ice increases of crevasses depth is possible. As it was found out on polythermal glaciers depth of moulins is comparable with thickness of cold ice layer (Mavlyudov, Solovyanova, 2003). On Aldegonda Glacier (Spitsbergen) we studied Moulin up to depth about 80 m and on Tavle Glacier (Spitsbergen) the moulin depth was about 100 m from a surface to glacier bed that say about absence of a layer of temperate ice under this glacier. In cold glaciers moulins depth can be even more. So in Greenland moulins were investigated up to depth about 173 m (Reynaud, Moreau, 1995) and even to 205 m (Gulley et al., 2009b). But the moulins that reach glacial bed as was supposed in (Das et al., 2008) here were not found.

In some cases we see not one large Moulin but series of small pits (the cascade of pits). It is possible to explain cascade form if moulin was generated on the edge of a crevasse (if to look at a glacial crevasse from sideways it in form will correspond to a semicircle) and water flowing down to the crevasse centre forms the cascade. By other way when dead moulin has been deleted by ablation the cascade can be opened subsequently.

There is information about moulin on Brøgger Glacier (Spitsbergen) that during some years has changed from the cascade to one continuous pit (Irvine-Fynn, 2011). Authors have assumed that the new moulin was generated without crevasse participation. However it is impossible because for formation of moulins the primary flat surface is necessary along which water move. It can be a crevasse, a wall of an ice canyon or vertical contact between ice and rocks.

So water gets into a crevasse and forms moulin. Where it moves further? In glacial cavities in the basis of moulins we observe more often cascades of smaller pits. By analogy to an example of an explanation of formation of the cascade described above we can say that cascades in caves are formed on the base of inclined fissure or crevasse. Thus the more abruptly incline the parent fissure the more depth of pits on the cascade and the less step between pits and on the contrary the more flat the parent fissure the less depth of pits and more step between pits. Accordingly horizontal fissure will give rise to horizontal galleries without pits. As moulins meet widely on many glaciers we need believe that in thickness of ice there can exist fissures and cracks of different orientation.

As to horizontal galleries at the bottom of vertical pits (moulins) their genesis is not quite clear. More often they are the canyons of incision generated on the base of vertical crevasses which walls were closed above. I.e. on the channel arch there is a trace in the form of a white strip which represents the channel compressed by ice plastic deformation (ice creep). Often at the compressed channel is present snow like masses brought by streams from glacier surface. We observed the similar phenomena in a moulin № 1 on Aldegonda Glacier (Spitsbergen, Fig. 1).

Actually galleries of caves in glaciers tongues are formed on contact of ice and bed or on the base of horizontal fissure of not clear genesis.

In article (Gulley, Benn, 2007) is affirmed that cave channels can be formed on the base of vertical superficial crevasses after their filling by moraine fragments and compression by plastic deformation. It is an error. Even in the photos in this article is clearly visible that these investigated channels were formed by cutting into ice from glacier surface.

Thus we see that all elements of internal drainage system are formed on the base of crevasses or along elements of old channels and also by cutting into ice. In the latter



Figure 1. *White strip on roof of englacial channel as trace of previous compressed channel, moulin № 1 Aldegonda Glacier, Spitsbergen.*

case cutting depth does not usually exceed 10-15 m and in rare case reaches 30 m as it was observed in upper part of Tavle Glacier (Spitsbergen) (Mavlyudov, 2007b). But it does not give an explanation of formation of an internal drainage as a whole.

Discussion

To understand how all system of an internal drainage of glaciers as a whole is formed we will address at first to caves at glaciers tongues. Carrying out researches of glacial caves on Aldegonda Glacier tongue in 2003 we have found out that at movement inside glacial cave usual englacial channel (R-channel) changed into fissure oriented subhorizontally (Mavlyudov, 2005b). At the lower surface of this fissure were small canals cutting into ice which used for drainage of the largest water streams. The bottom of the fissure channel has been covered rounded and non rounded rock fragments. The width of the fissure channel reached 15 m and maximum height did not exceed 0,7 m. It was possible to see that sideward the channel gradually reduces height and turns into a layer of fragments of rocks clamped in ice.

Carrying out researches of evolution of the drainage channel in the iceblock in cold laboratory of university of Hokkaido (Japan) in 2002 (Isenko et al., 2003), we have found out that at water flow in a horizontal fissure channel is formed englacial channel which very much reminds by its cross-section section the entrance channel in the cave on Aldegonda Glacier investigated in 2003. Analyzing these data and the data received also from research in caves on Western Grønfjord Glaciers, Fridtjoff and Åavatsmark (Spitsbergen) we understand that fissure channels are not similar to englacial and the subglacial channels that were before investigated and described (R-channels, N-channels, H-channels) (Röthlisberger, 1972, Nye, 1976, Hooke, 1984). It means here we deal with new type of glacial channels - fissure channels which are generated on the base of subhorizontal fissures. An important point was that these fissure channels under different conditions could change into other kinds of channels (R-channels, N-channels, H-channels). It means that all these fissure channels were primary and all other channels have occurred from them.

Having carried out researches in variety of glacial caves on other glaciers (Bertil, Spitsbergen; Bashkara, Caucasus; small caves on the edge of the glacial dome Bellingshausen on King George Island, the Southern Shetland Islands, Antarctic) we have found out in them primary horizontal fissures. Thus it was found that glacial caves at tongues of glaciers without dependence from their thermal conditions can origin basically on subhorizontal fissures. Analysis of references has shown that subhorizontal fissures have been found in other glacial caves on Loven Glacier (Spitsbergen) (Irvine-Fynn et al., 2005) and in glacial caves on Tien-Shan (Mikhajlev, 1989). All it said that it may be not universal but a widespread situation.

The researches realized in a glacial cave at tongue of Aldegonda Glacier in 2004-2008 have shown that the subhorizontal fissure is not unique. We have found at least 3 such subparallel fissure. It means that the cave channel arose, later it was closed by plastic deformation, next arose again and was closed again. Besides it was found that initially englacial cave channel further inside cave is changed into the subglacial channel. After that it became clear that the cave channel is formed on the basis of subhorizontal fissure which passes through tops of juts on glacial bed. From this follows that cave channel

is not purely subglacial or englacial and represents alternation of subglacial and englacial sites. Information about water movement under a glacier by such way we can find and in work (Fountain, Walder, 1998) but they assume that such channel cut from glacier surface. Researches of Stor Glacier in Sweden have led to the conclusion that its left internal drainage channel is not subglacial and passes in ice above deepening on a glacier bed (Hooke, 1988).

The further way of reasoning was next. If there is the certain fissure which passing above bed juts smoothes an actual bed relief and creates some not so rough surface on which water in the glacier basis can move we can ask why actually on the same surface cannot move and a glacier? Really, the glacier can move on the basis of this smoothed surface and its movement will occur with a smaller friction than on glacier bed because in this case ice in the glacier basis should not flow round numerous obstacles. And if still to add that water can be found on this surface that will support for glacier the best sliding is becomes clear that movement on this surface will be more preferable to a glacier than along the bed (Fig. 2).

If we accept this statement it means that we will receive some consequences. First in that case ice in the glacier basis slide on crests of juts where exaration take place, contrariwise ice between juts does not move also and is quite possible to consider it as dead ice. One of proofs of possibility of such phenomenon is the finding of the remained vegetation and soil under Longyear Glacier in Spitsbergen (Humlund et al., 2005). Secondly, it is possible to explain spring glacier movement acceleration by not water inflow to glacier bed but water inflow to this sliding surface under a glacier. For example on Unteraar Glacier in the Alps surface uplifting in the spring was noticed that is the indirect certificate of water accumulation in the glacier basis (Iken et al., 1983). Thirdly, as water inflow on a sliding surface is distributed enough widely and non-we will have inefficient drainage system uniformly in this case. During ablation season when the quantity of melt water under a glacier increases water starts to form the dedicated ways of movement along sliding surface of glacier; these canals increase during time. As a result water movement on sliding surface of a glacier as film or pseudo-film begin more and more channelized. In result at the end of summer along this sliding surface will form well worked flat channels which already represent effective system of drainage. However even a short cold snap when melting on a glacier surface is ended and water ceases to arrive on sliding surface is quite enough that the channels generated earlier along it were closed by ice plastic deformation and the drainage system under a glacier became again ineffective. Such situation can proceed up to spring or up the nearest weather warming. Then all will repeat. The annual cycle of functioning of system of an internal drainage works by such way.

Fourthly, it is possible to assume that the mechanism of movement of ice and water on sliding surface is similar both for mountain glaciers and for glacial sheets. In that

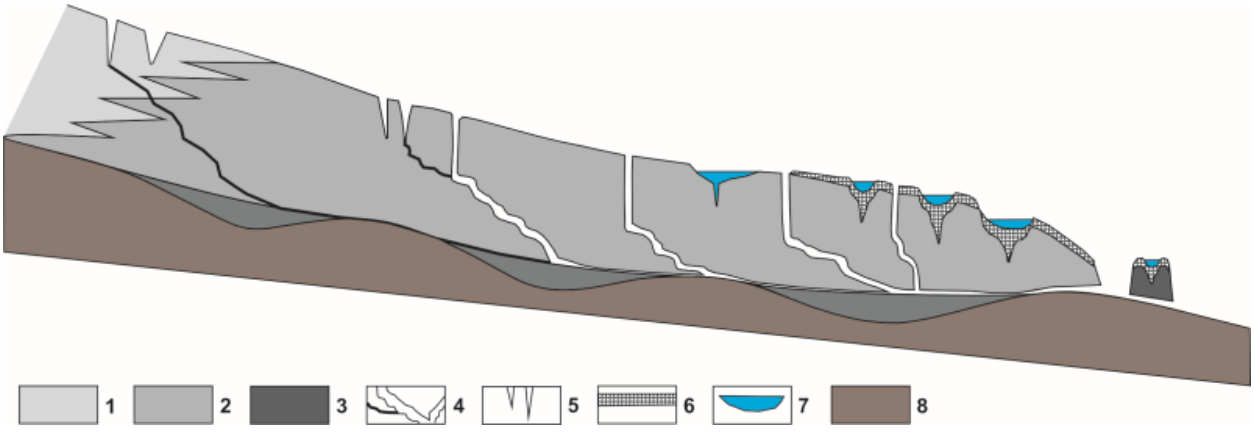


Figure 2. *Longitudinal cross section through glacier with internal drainage system; sliding surface located at the bottom of glacier. 1 – firn, 2 – ice, 3 – dead ice, 4 – channels of internal drainage system, 5 – crevasses, 6 – moraine deposits, 7 – lakes, 8 – glacier bed.*

case and drainage channels on glacial sheets adhered to these sliding surfaces. On the base of these channels possibly were formed eskers which after ice melting were projected on underlying relief. Probably for this reason some eskers are indifferent to underlying relief.

The same sliding surfaces can be used for water outbursts from glacier-dammed lakes.

If we accept the aforesaid above point of view it is necessary for us to find how the sliding surface could be generated. In present time we do not have completely satisfying explanation of this phenomenon. As the assumption it is probable to offer some possible mechanisms: 1) such mechanism probably works here: for a glacier it is more energy-favourable to not crawl through bed deepening but namely move above deepening along contact of dead ice. 2) probably it was impossible without hydrofractures (Benn et al., 2009b) which by high pressure have generated a sliding surface. 3) both offered mechanisms can work.

Now it is necessary to find as water through glacial crevasses and moulins gets to a sliding surface. There is such assumption. Water fills a glacial crevasse and begins propping of fracture At the end of crevasse as a result fractures begin to move to depth (Weertman, 1973). Having met any small transversal fissure water will be switched to this fissure because to open an existing fissure incomparably easier than to create the new one. Along this fissure water will directed aside and on the way will find the gaping crevasse which does not have exit to glacier surface and will start to fill it. If there is a lot of water and the parallel crevasse have more deep low end in comparison with first crevasse, in this case second crevasse will start to move into depth faster because bigger pressure influences on its edge than upon the edge of the first crevasse. Having met on a way the next transversal fissure, water will direct along it. So it will proceed until water will not reach a sliding surface. Probably it is slow or may be fast process. Anyway speed of hydrofracture penetration through kilometer thickness of the Greenland ice sheet by calculations is estimated in 8 m/s (Tsai, Rice, 2010). But most likely that speed strongly depends on concrete conditions.

Thus we have shown possible ways of formation of sliding surface and also possible mechanisms of penetration of water to it. As a result we have received the formation mechanism of all system of an internal drainage. And as a consequence we have received an explanation of the mechanism of spring acceleration of glaciers movement. Here it is necessary to make a reservation. Actually this mechanism does not explain acceleration of ice movement on the Greenland sheet. Otherwise we should agree that water gets to a glacier bed through a hydrofracture (Das et al., 2008). It is difficult to believe in it because such crevasses will blocked by ice if water penetrate in crevasse at ice wall temperature about -29°C. Crevasse cannot blocked by ice if crevasse from the very beginning was gaping and its width should be not less than several tens of centimeters (calculations show that at ice temperature about -8°C the width of a crevasse should be more than 10 cm) and stream velocity should be really monstrous which simply does not exist in the nature (calculations show that even at temperature -5°C that ice on a crevasse wall was in thermal balance with water, stream velocity 60 seconds after the current beginning should exceed 21 m/s) (Mavlyudov, 1998). And as it is supposed that the propping of crevasse by water should begin from zero width, water in crevasse will freeze at once, i.e. penetration of a crevasse into depth of such cold ice simply physically is impossible. From here follows the conclusion that water in this case to a bed does not move and reaches any depth from a surface on which it will transported towards the nearest crevasse zone. Probably on any depth from an ice surface there is a sliding surface and getting water on it lead to acceleration of glacier movement. However for such assumption there should be proofs which for the present are absent. It is possible to assume that if depth of moulins on this place of the Greenland sheet does not exceed 205 m it is possible to expect that somewhere on this depth exist a sliding plane.

Conclusion

We have considered that was known how elements of an internal drainage of glaciers are formed and have offered the new concept of formation of the basic system of glaciers drainage. According to this concept the basic drainage channels of glaciers are formed along sliding surface of glacier which represents the certain surface that smooth all roughnesses of a glacial bed and have touch with rocky juts. Water penetration on this sliding surface provides both an internal drainage of water in a glacier and the accelerated movement of a glacier in the spring. During spring time water spreads along a sliding

surface creating inefficient system of drainage. After channels formation along this sliding surface the system of water drainage becomes effective. This concept is proved because the studied glacial caves were generated on the basis of subhorizontal fissures and represent alternation of englacial and subglacial sections.

References

Badino G, editor. 2002. Proceedings of 5th GLACKIPR Symposium «Glacier Caves and Cryokarst in Polar and High Mountain Regions», 15-16 April 2000, Courmayeur, Italy. Nimbus, Rivista della societa meteorologica italiana 23-24: 81-157.

Badino G. 2002. The glacial karst. Proceedings of V International symposium on glacier caves and cryokarst in Polar and high mountain regions, Courmayeur, 15-16.04.2000. Nimbus 23-24: 141-157.

Benn D, Gulley J, Luckman A, Adamek A, Glowacki PS. 2009. Englacial drainage systems formed by hydrologically driven crevasse propagation. Journal of Glaciology 55 (191): 513-523.

Benn DI, Evans DJA. 2010. Glaciers and glaciation. 2nd ed. London: Hodder Education. 802 p.

Das SB, Joughin I, Behn MD, Howat IM, King MA, Lizarralde D, Bhatia MP. 2008. Fracture propagation to the base of the Greenland ice sheet during supraglacial lake drainage. Science 320 (778): 778-781.

Eraso A, editor. 1991. Proceedings of 1st GLACKIPR Symposium «Glacier Caves and Karst in Polar regions», October 1-5, 1990, Madrid, Spain. Madrid: ITGE, 237 p.

Eraso A, editor. 2003. Proceedings of 6th GLACKIPR Symposium «Glacial Caves and Karst in Polar Regions» (3-8 September 2003, Ny-Alesund; Svalbard, Lat. 79°N). Madrid: SEDECK, 193 p.

Eraso A, Pulina M. 2010. Cuevas en hielo y ríos bajo los glaciares. 3nd ed. Madrid: McGraw-Hill, 300 p.

Forbes JD. 1845, Travels through the Alps of Savoy and other parts of the Pennine Chain with observations on the phenomena of glaciers. 2nd ed. Edinburgh: A.&Ch. Black, 460 p.

Fountain AG, Jacobel RW, Schlichting R, Jansson P. 2005. Fractures as the main pathways of water flow in temperate glaciers. Nature 433 (7026): 618-621.

Fountain AG, Walder JS. 1998. Water flow through temperate glaciers. Reviews of Geophisics 36 (3): 299-328.

Freyfeld VYa. 1963. About some observations into internal tunnels of Kara-Batkak Glacier. Transactions of Uzbekistanskiy geogaphic society 7: 112-124 (in Russian).

Gallo G. 1968. Grotte glaciaire au Spitsberg. Lyon: CNRS, Equipe de Rech. 29.

Griselin M, editor. 1995. Actes du 3 Symposium International "Cavites glaciaires et cryokarst en regions polaires et de haute montagne", Chamonix-France, 1-6.XI.1994. Annales litteraires de l'universite de Besancon 561, serie Geographie 34, Besancon, 138 p.

Grizelin M, Marlin C, Dever L, Moreau L. 1995. Hydrology and geochemistry of the Loven East glacier, Spitsbergen. In: Griselin M. Editor. Actes du 3e syposium international Cavites glaciaires et cryokast en regions polaires et de haute montagne, Chamonix-France, 1-6.09.1994. Annales litteraires de l'universite de Besancon 561, serie Geographie 34: 61-76.

Gulley JD, Benn DI, Muëller D, Luckman A. 2009a. A cut-and-closure origin for englacial conduits in uncrevassed regions of polythermal glaciers. Journal of Glaciology 55 (189): 66-80.

Gulley JD, Benn DI, Screaton E, Martin J. 2009b. Mechanisms of englacial conduit formation and their implications for subglacial recharge. Quaternary Science Reviews 28: 1984–1999.

Gulley JD, Benn DI. 2007. Structural control of englacial drainage systems in Himalayan debris-covered glaciers. Journal of Glaciology 53 (182) 399–412.

Halliday WR, Anderson CH. 1969. The Paradise Ice Caves. National Park Magazine 63 (265) 13-14.

Hook RLeB, Miller SB, Kohler J. 1988. Character of the englacial and subglacial drainage system in the upper part of ablation area of Storglaciaren, Sweden. Journal of Glaciology 34 (117): 228-231.

Hooke RLeB. 1984. On the role of mechanical energy in maintaining subglacial water conduits at atmospheric pressure. Journal of Glaciology 30 (105) 180-187.

Humlund O, Elberling Bo, Hormes A, Fjordheim K, Hansen OH, Heinemeier J. 2005. Late Holocene glacier growth in svalbard documented by subglacial relict vegetation and living soil microbes. The Holocene 15 (3) 396-407.

Iken A, Flotron A, Röthlisberger H, Haeberli W. 1983. The uplift of Unteraargletscher at the beginning of the melt season – a consequence of water storage at the bed? Journal of Glaciology 29 (101) 28-47.

Irvine-Fynn TDL, Hodson AJ, Kohler J, Porter PR, Vatne G. 2005. Dye tracing experiments at Midre Lovénbreen, Svalbard: preliminary results and interpretations. In: Mavlyudov BR, editor. Proceedings of 7th GLACKIPR Symposium «Glacier Caves and Glacial Karst in High Mountains and Polar Regions». Moscow: Institute of geography RAS: 36-43.

Irvine-Fynn TDL, Hodson AJ, Moorman BJ, Vatne G, Hubbard AL. 2011. Polythermal glacier hydrology: a review. Reviews of Geophysics 49. RG4002, doi:10.1029/2010RG000350.

Isenko EV, Mavlyudov BR, Naruse R. 2003. Natural modeling of channels in cold ice. In: Eraso A, editor. Proceedings of 6th GLACKIPR Symposium «Glacial Caves and Karst in Polar Regions» (3-8 September 2003, Ny-Alesund; Svalbard, Lat. 79°N). Madrid: SEDECK: 147-153.

Mavlyudov BR. 1995. Problems of En- and Subglacial Drainage Origin. In: Griselin M, editor. Actes du 3e Symposium International Cavites Glaciaires et Cryokarst en Regions Polaires et de Haute Montagne, Chamonix-France, 1er-6.XI.1994. Annales Litteraires de l'universite de Besancon 561, serie Geographie 34: 77-82.

Mavlyudov BR. 1998. Glacier caves origin. In: Slupetsky H, editor. Proceedings of 4th GLACKIPR Symposium on Glacier Caves and Cryokarst in Polar and High Mountain Regions, September 1st -7th, 1996, Salzburger Geographische Materialien 28: 123-130.

Mavlyudov BR, editor. 2005a. Proceedings of 7th GLACKIPR Symposium «Glacier Caves and Glacial Karst in High Mountains and Polar Regions». Moscow: Institute of geography RAS, 178 p.

Mavlyudov BR. 2005b. About new type of subglacial channels, Spitsbergen. In: Mavlyudov BR, editor. Proceedings of 7th GLACKIPR Symposium «Glacier Caves and Glacial Karst in High Mountains and Polar Regions». Moscow: Institute of geography RAS: 54-60.

Mavlyudov BR. 2006. Internal drainage systems of glaciers. Moscow (RF): Institute of geography RAS, 396 p. (in Russian).

Mavlyudov BR. 2007a. Internal drainage systems of glaciers. In: Tyc A, Stefaniak K, editors. Karst and Cryokarst. Proceedings of 8th GLACKIPR Symposium. Sosnowiec-Wroclaw: Univ. of Silesia Faculty of Earth Sciences, Univ. of Wroclaw Zoological Institute: 49-64.

Mavlyudov BR. 2007b. Investigations of the Tavle Glacier and its internal drainage channels, Nordenskiold Land. Complex study of Spitsbergen nature 7, Apatity: Cola Scientific Center of RAS, p. 187-201 (in Russian).

Mavlyudov BR, Solovyanova IYu. 2003. Comparison of cold and temperate glacier caves. In: Eraso A, editor. Proceedings of 6th GLACKIPR Symposium «Glacial Caves and Karst in Polar Regions» (3-8 September 2003, Ny-Alesund; Svalbard, Lat. 79°N). Madrid: SEDECK: 157-162.

Mavlyudov BR, Solovyanova IYu. 2005. Caves of Bashkara Glacier (Central Caucasus); morphological features. In: Mavlyudov BR, editor. Proceedings of 7th GLACKIPR Symposium «Glacier Caves and Glacial Karst in High Mountains and Polar Regions». Moscow: Institute of geography RAS: 61-67.

Mikhajlev VN. 1990. Glacier caves of Kirgiziya. Peshery (Caves) 22: 57-63 (in Russian).

Murray T, Clarke GKC. 1995. Black-box modeling of the subglacial water system. Journal of Geophysical Research 100 (B6) 10231-10245.

Mushketov IV. 1881. Course of geology, Sankt-Petersburg: Publishing by F. Radlov and N. Koksharov, 776 p. (in Russian).

Nye JF. 1976. Water flow in glaciers: jökulhlaups, tunnels and veins. Journal of Glaciology 17 (76) 181-207.

Paterson WSB. 1994. The Physics of Glaciers. 3rd ed. Oxford: Pergamon.

Poluektov VI. 1966. Cave in glacier. Peshery (Caves) 6(7): 107-110 (in Russian).

Pulina M, editor. 1992. Proceedings of 2nd GLACKIPR Symposium «Glacier Caves and Karst in Polar regions», February 10-16, 1992, Midzygorze, Poland. Sosnowies: Silesia University, 127 p.

Pulina M, Rehak J. 1991. Glacial caves in Spitsbergen. In: Eraso A, editor. Proceedings of 1st GLACKIPR Symposium «Glacier Caves and Karst in Polar Regions», Madrid: ITGE: 93-117.

Rehác J, Rehác J. 1995. New informations on the interior drainage of subpolar glaciers of Southwest Spitsbergen. In: Griselin M, editor. Actes du 3 Symposium International «Cavites glaciaires et cryokarst en regions polaires et de haute montagne», Chamonix-France, 1-6.XI.1994. Annales litteraires de l'universite de Besancon 561, serie Geographie 34: 93-100.

Reynaud L, Moreau L. 1995. Moulins Glaciaires des Temperes et Froids de 1986 a 1994 (Mer de Glace et Groenland). In: Griselin M, editor. Actes du 3e Symposium International Cavites Glaciaires et Cryokarst en Regions Polaires et de Haute Montagne, Chamonix-France, 1er-6.XI.1994. Annales Litteraires de l'universite de Besancon 561, serie Geographie 34 : 109-113.

Röthlisberger H. 1972. Water pressure in intra- and subglacial channels. Journal of Glaciology 11 (62): 177-203.

Schroeder J. 1998. Hans Glacier moulins observed fron 1988 to 1992, Svalbard. Norsk Geografisk Tidsskrift 52: 79-88.

Slupetsky H, editor. 1998. Proceedings of 4th GLACKIPR Symposium «Glacier Caves and Karst in Polar and High Mountain regions». Sept. 1-7, 1996, Rudolfshütte, Salzburg, Austria. Salzburg Geographische Materialen 28, 155 p.

Tsai VC, Rice JR. 2010. A model for turbulent hydraulic fracture and application to crack propagation at glacier beds. Journal of Geophysical Research 115. F03007, doi:10.1029/2009JF001474.

Tyc A, Stefaniak K, editors. 2007. Karst and cryokarst. Proceedings of 8th GLACKIPR Symposium. Sosnowiec-Wroclaw: Univ. of Silesia Faculty of Earth Sciences, Univ. of Wroclaw Zoological Institute.

Weertman J. 1973. Can a water-filled crevasse reach the bottom surface of a glacier? In: Symposium on the Hydrology of Glaciers. IAHS Publ. 95: 139-145.

THE SANDY GLACIER CAVE PROJECT: THE STUDY OF GLACIAL RECESSION FROM WITHIN

Eduardo L. Cartaya
Deschutes National Forest
63095 Deschutes Market Road
Bend, Oregon, 97701,USA, ecartaya@fs.fed.us

Brent McGregor
Deschutes National Forest
63095 Deschutes Market Road
Bend, Oregon 97701 USA, rockiees_58@msn.com

Abstract
The Sandy Glacier Cave Project is a National Speleological Society (NSS) sponsored study on the unique system of glacier caves located on the Sandy Glacier on the western flank of Mt Hood, Oregon. While the study primarily targets the structure, layout and ice volume change of the ever moving cave system by conducting annual grade 5 surveys, numerous tangential observations and trends have been recorded that are of great interest to the study of glacial recession, watershed hydrology, micro-biology and astro-biology, as well as the study of organic specimens and remains being thawed out of the ice mass by the expanding cave. Water analysis of the three cave streams involved show significant differences, despite their close proximity, which could indicate differences in the speed of glacier movement along the span of the glacier. Annual cave surveys are revealing massive volumes of ice melting from within the glacier, a figure not obtainable via traditional surface observations. Biological specimens and remains have been located, perfectly preserved, that were previously encapsulated in the glacier, and thus serve as a time capsule for subsequent study.

Introduction
The project began in July 2011, when 3 NSS members – Brent McGregor, Eddy Cartaya, and Scott Linn– located and surveyed a previously unmapped glacier cave under the Sandy Glacier on the west flank of Mt Hood in the Mt Hood National Forest. For several years, the cave was visited sporadically by summer day hikers who ventured a short way into the massive tube. There were no maps, GPS coordinates, or study records on the unnamed cave, which apparently opened up each year in the July timeframe and was reburied by snow by late November. The 3 researchers became aware of the cave's existence from a You Tube video.

In July 2011, Brent, Eddy, and Scott used the hikers' internet photographs to locate the elusive glacier cave at 1950 meters (6400 feet) elevation. It had just opened in the form of a crevasse. After a short rappel, the three realized they had found the titanic cave and completed a grade 5 survey of the upper section, which bored over 550 meters up the mountain under the hard, blue glacier ice. They named the cave Snow Dragon, after a common analogy to avalanche dangers. Brent and Eddy returned a few weeks later with wet suits to survey the wet lower section of the cave. It travels mostly through firn, a highly compacted, pre-glacial, form of snow that melts off in large sections during late summer. The two discovered a rushing torrent of icy water entering the system from an unexplored side tube. The volume of water indicated that a significant cave was joining there.

A few weeks later, Brent discovered another previously unrecorded glacier cave just 150 meters from the opening to Snow Dragon. The interior was coated with ice, making the rock climbs inside untenable for a solo explorer. Eddy returned with Brent 2 weeks later and the two climbed to the back of the cave. The crown jewel of the new cave was a towering pit entrance traveling over 40 meters straight up through the ice to the surface. This glacial feature is called a moulin, a vertical conduit through which surface melt waters of the glacier used to flow and drill down to the original underlying lava bedrock. The shaft had been abandoned by the water, which had since found a new passage higher up the mountain. They named this cave Pure Imagination (Fig. 1, Fig. 2, and Fig. 3). Brent and Eddy returned again on



Figure 1. *Cerebus Moulin of Pure Imagination Cave as discovered on 11-09-2011.*



Figure 2. *Cerebus Moulin of Pure Imagination Cave as discovered on 11-09-2011, inside view.*



Figure 3. *Cerebus Moulin of Pure Imagination Cave as seen on 11-10-2013, inside view.*

January 4, 2012, braving vicious winter conditions (and frostbite!) to rappel and climb the huge moulin for the first time.

Later that month, Eddy and Brent met with Mt Hood National Forest (MHNF) science staff to propose a study expedition. The scope of these caves was too massive to keep secret, and they were clearly significant caves as defined by the Federal Cave Resource Protection Act (FCRPA). Given the receding glacier issue on Mt Hood, the caves offered a unique and short-lived opportunity to study 40 meter cross- sections of the ice and record glacial melt changes from WITHIN the glacier, as opposed to the traditional surface studies. The proposal was ambitious and obviously required a huge amount of equipment. While Mt Hood NF declined to be the lead agency, they did grant the NSS a research permit to conduct the expedition in July 2012. Geary Schindel, Vice President of the NSS, signed the permit for the expedition and insured the mission.

In July 2012, with the assistance of over 50 sherpas, the expedition moved over 680 kilograms (1500 lbs) of caving, medical, survival, and science gear up the mountain and established a base camp near Snow Dragon, at the toe of the glacier. Over the next 9 days, NSS teams surveyed Pure Imagination, made geology collections for the US Geologic Survey (USGS), conducted water quality and composition tests, took atmospheric readings, and collected ice samples for ash deposition tests. Deschutes National Forest geologist Bart Wills managed the rock collections for the USGS. Gunnar Johnson, a Portland State University Ph.D. Student in Environmental Science, conducted the water and sediment collections. The team succeeded in accessing the 3rd tube joining Snow Dragon via a low airspace flooded passage, and later completed a survey of this 3rd cave in the system, naming it Frozen Minotaur, due to its maze-like layout. Over 2133 meters (7000 feet) of passage was subsequently documented in 3 maps, including a 3-dimensional, wire mesh moving image.

In July 2013, the Sandy Glacier Cave Project conducted another 9-day expedition to resurvey Snow Dragon and most of Pure Imagination. In the Cerebus Moulin alone, a size increase of over 400% was measured, marking a HUGE amount of ice lost. Once again, local Mountain Rescue Association teams came up to assist with the complex rigging to facilitate these surveys, which sometimes involved dangling the surveyor 40 meters in the air over a pit, or belaying an ice climber up a 10 meter ice wall to access a new passage.

Special events of note during the 2013 expedition included a site visit by prominent Portland State University glaciologist, Dr. Andrew Fountain. Fountain inspected the Pure Imagination Moulin and the first third of Snow Dragon, concurring that these caves are extremely unique, large, and rare in the lower 48, and indicative of the dying throes of the glacier. Fountain explained the mechanical structure of the cave's formation and why we are seeing such radical changes. He also suggested more snow melt studies, which were immediately established. Also of note was a film crew from Oregon Public Broadcasting (OPB), who braved arduous logistical challenges to get their crew and equipment to base camp and document the team as it conducted its studies. Their efforts culminated in a 30-minute special that aired on Oregon Field Guide and an interactive website that provided priceless documentation of this year's conditions of the Sandy Glacier Caves. (Check out the link: http://www.opb.org/glaciercaves/.)

The use of cave surveys to record ice volume lost

The initial goal of the project was simply to survey and photo-document the caves. The Paradise Ice Caves of Mt Rainier, formerly the longest glacial cave system in the lower 48 of the United States, are completely melted. As such, the most urgent focus of the project was to memorialize the cave system with a detailed 3 dimensional map and photograph as much detail as possible.

In cave mapping, there are several grades of surveys. A grade 5 survey is one of the most detailed formats, with an inclinometer used to record floor slope, and hence generate not only a floor plan view of the cave, but a profile view (ant farm view) as well. Each survey station records the width of the passage as well as the floor to ceiling height at that point. Distances between survey points are recorded using a Bosch laser ruler with a 500 foot range. Slope between points is measured with a Brunton inclinometer to within ½ degree. Bearing between survey points are recorded with a Brunton survey compass to within ½ degree. Significant cave features, to include isolated domes and waterfalls, are measured with the Bosch laser and plotted on the map. A surface survey of the ice over the caves is also completed in order to compute the thickness of the ice at any given point over the passage. All data are then entered into a cave mapping software called Compass, and the local NSS cartographer, Matt Skeels, then drafts in the details recorded by the surveyors in their sketch book (Snow Dragon Cave map, Fig.4).

Within 4 months of the first survey of Snow Dragon in 2011, significant changes in the cross sectional dimensions were noted. By the 2012 expedition, the cave had increased in volume tremendously, although on the surface, very little appeared to have changed.

Likewise, the dimensions of Pure Imagination were also noted to have increased significantly, again with little surface indication. The only surface indications of glacial recession or melting were gradual crumbling of the entrances up the mountain, maybe 8 meters a year.

During a site visit by Portland State University glaciologist Doctor Andrew Fountain, it was discussed to record and track the changes in ice thickness over the caves, snow melt rate over caves, and specifically the concept of using annual surveys, which effectively capture the air volume of the cave, to calculate an approximate volume of ice lost each year. To do this, the survey data of each year is used to generate an approximate volume of air (cross sectional data averaged over each leg of the survey), and then compare the volume differences with each subsequent survey. The volumetric difference in cubic meters can then be used to calculate an approximate ice volume, or ice mass, lost annually in that section of glacier.

For example, using the dimensions of the Cerebus Moulin in Pure Imagination Cave as recorded in July 2012, the air volume of the vertical passage was 2259.6 m^3. The volume calculated using the 2013 survey of this same passage almost exactly 1 year later was 9613.9 m^3. This results in a volumetric change of 7354.3 m^3, or well over a 400% increase in passage size.

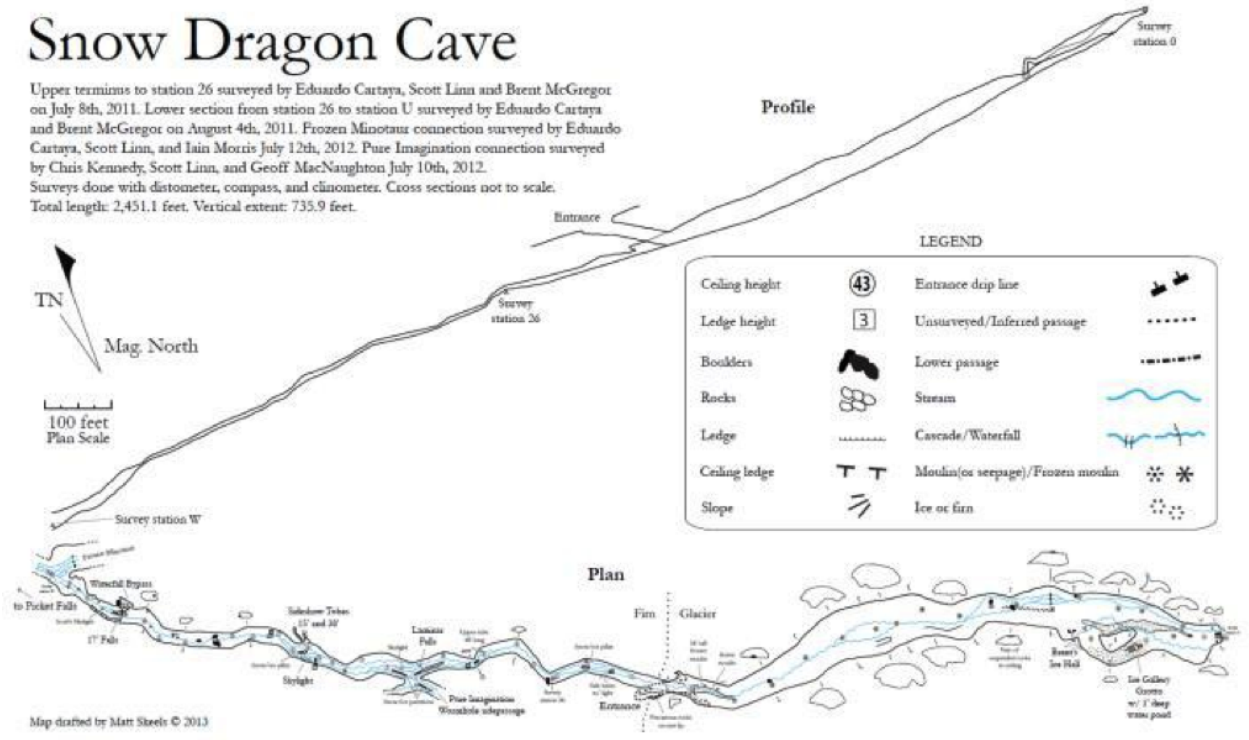


Figure 4. *Snow Dragon Cave Map. Profile view on top, plan view on bottom.*

Glacial ice has a density of about 850 kilograms per cubic meter (kg/m³), somewhat lower than pure ice at 917 kg/m³, due to air bubbles. In the Cerebus Moulin, this equates to about 6,251,155 kilograms of ice lost in about a year. 1 metric tonne of water equals 1 cubic meter of water. So in this context, we can approximate that this one length of passage has liberated about 7300 tonnes of water into the cave and subsequent watershed over a period of one year. (Fig. 5)

Granted, this vertical passage most certainly exhibits a greater rate of melt due to its exposure to the sun and the passage of warm air through the cave and out, what is essentially a warm air chimney. This process of warm air movement, however, is occurring throughout all the caves and contributes greatly to the increasing height and girth of the passages. Water flow, boring its way down through fissures and smaller passages, is also speeding the melting process by flowing laminarly along the walls and ceilings, melting the ice which is barely at freezing level as it is.

Following this summer's survey expedition of 2014, 3 layers of survey will be available for volume comparison. A detailed calculation of volume will be done with a resulting ice lost volume and water mass liberated figure generated for each cave and the system as a whole. Observations to be noted will also include a comparison in rates of melt in the 3 caves.



Figure 5. *Cerebus Moulin of Pure Imagination Cave. As seen on 09-19-2013.*

It is of interest to note that aside from entrance feature differences, there is little indication of rate of change or melting in the glacier as viewed from the surface.

The caves as a time capsule

During the above discussed surveys, numerous organic specimens were located that had been melted out of the ceiling as it constantly melts back and delaminates.

Seeds from trees long past, birds that died on the glacier long ago, and other items that landed on the glacier were buried by snow pack above the firn line (in the accumulation zone) and subsequently became part of the ice pack. As these items flowed downhill with the glacier and got deeper in the ice, they eventually got low enough to be freed from underneath by the cave passages, as their ceilings melted up into the ice. Exactly how long it takes for a seed or feather to travel the thickness of the ice and then rain down onto the cave floor is still unestablished, but preliminary figures based on initial studies of a seedling located in the 2012 expedition indicate it to be approximately 100 years.

Seeds contain enough stored energy to sprout and produce a few leaves to start the food making process of photosynthesis until there is enough green surface area to sustain the tree on its own. It is not uncommon to see sprouted plants deep inside limestone caves, where the seeds have been washed in one entrance and then sprouted in the cave. These sprouts are, of course, short lived, albeit well watered.

In this case, there is no through passage where water flows in one way and out the other. The water flow in the glacier caves starts as small rivulets and seepages along the contact surface of the ice with the underlying bedrock, although it is still possible some seeds could be washed into the cave via tiny, pencil width channels.

Several seedlings from noble firs were located in the caves, and a couple had started to sprout (Fig. 6). Several were collected. Gunnar Johnson with PSU had one such sample analyzed, identifying it as an Abies procerus, or Noble Fir, with a resulting approximate age of about 100 years. Constance A. Harrington, Research Forester and Team Leader for the US Forest Service Pacific Northwest Research Station in Olympia, Washington, advised that seeds frozen in ice for a long period, and then thawed to sprout, frequently exhibit growth pattern anomalies due to their DNA being somewhat "confused" following such a long hibernation. Seeds will frequently sprout abnormally and continue developing with a pattern distinctly different from normal specimens. As such, grant monies and additional permits have been solicited to further these collections and studies to this lab.

Near the very back of Snow Dragon, a fully intact feather was located and collected (Fig. 7). The lab analysis done by Doctor Carla J. Dove of the Smithsonian Institute's Feather Identification Lab revealed this to be a feather of Anas platyrhynchos, or a mallard duck. Again, funds are not yet available to have the feather dated, but the location of its find is not such that it could have entered the cave via any other route than being thawed from the roof ice. The floors of the caves stay almost constantly covered with water flow, thus items such as these will not remain on the floor long before being washed away or buried by collapsing ice, which occurs annually due to ceiling delamination.

This unexpected occurrence of items frozen in the ice being "rained" down onto the cave floor as the caves melt and expand upward provides a unique opportunity



Figure 6. *Noble Fir Seedling in Frozen Minotaur Cave.*



Figure 7. *Mallard Duck Feather located in Snow Dragon Cave.*

to collect and study specimens after a long period of preservation. Future dating of these items may also shed light on the rate of glacial recession and melting.

References

Cartaya E, McGregor B, Mickaelson K. 2013. Sandy Glacier of Mt. Hood: The Snow Dragon Cave System. NSS News 71: 4-21.

Cartaya E. 2013. Sandy Glacier Cave Project Mt Hood, Oregon: Beneath the Forest. Newsletter of the USDA 6: 4-9.

Luccio M. 2014. Under Thin Ice. Professional Surveyor 34: 8-14.

TIME, MONEY, AND MELTING ICE: PROPOSAL FOR A COOPERATIVE STUDY OF THE WORLD'S CAVE ICE IN A RACE AGAINST CLIMATE CHANGE

George Veni and Lewis Land
National Cave and Karst Research Institute
400-1 Cascade Avenue
Carlsbad, New Mexico 88220 USA, gveni@nckri.org, lland@nckri.org

Aurel Perşoiu
Department of Geography
University of Suceava
Universitatii 13
Suceava 720229 Romania aurel.persoiu@gmail.com

Abstract
Climate change is a global phenomenon that is melting and threatening to melt ice deposits in many of the world's ice caves. The National Cave and Karst Research Institute of the USA is concerned that major and important paleoclimate and paleoenvironmental records stored in cave ice will soon be lost, and is proposing an international collaborative effort to overcome funding and logistical challenges to sample and analyze at least a representative collection of ice from several regions before further melting occurs.

The Problem
"Warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades to millennia. The atmosphere and ocean have warmed, the amounts of snow and ice have diminished, sea level has risen, and the concentrations of greenhouse gases have increased" (WGI Technical Support Unit, 2014).

This recent announcement by the Intergovernmental Panel on Climate Change (IPCC) has vast implications for all aspects of humanity. For the cave ice community, the IPCC's observations that "Over the last two decades, the Greenland and Antarctic ice sheets have been losing mass, glaciers have continued to shrink almost worldwide, and Arctic sea ice and Northern Hemisphere spring snow cover have continued to decrease in extent" reflect what is now being observed with cave ice deposits worldwide. Even during the time from when this 6th International Workshop on Ice Caves was proposed for Idaho Falls, decreases in ice have been seen in caves in the area as part of the continued warming trend.

The final report of the 5th assessment by the IPCC won't be available until the end of 2014, but the technical summary predicts a mean annual temperature increase of 1.25-2.00º C by 2100, relative to temperatures from 1850-1900, for the world's high latitude and high elevation regions where most known ice caves occur (Stoker et al., 2013). IPCC predicts warming will continue beyond 2100, that it is "very likely that the Arctic sea ice cover will continue to shrink and thin and that Northern Hemisphere spring snow cover will decrease during the 21st century," "global glacier volume will further decrease," and that "most aspects of climate change will persist for many centuries even if emissions of CO^2 are stopped" (WGI Technical Support Unit, 2014).

No climate simulations have been developed to predict the impacts of climate change on cave ice. Based on losses observed to date and the loss of snow and ice deposits on the surface, it is reasonable to assume that many of the world's cave ice deposits will soon be gone. Many have already been lost.

Perennial deposits of stratified ice form by the successive accumulation of annual layers of ice interlaminated with organic and inorganic sediment and cryogenic carbonates, similar to varves in lakes. They often preserve a large variety of candidate proxies for past climate and environmental changes, including stable isotopes, pollen, ice stratigraphy, and chemical properties of the ice and contained sediment. Ice caves are thus valuable repositories for various forms of paleoclimatic and paleoenvironmental information that has been protected from destructive processes acting on the surface. Moreover, due to the peculiar combination of cave morphology and external climate required for their presence, these types of ice deposits are usually present in areas where surface glaciation is absent. This is especially important because perennial ice deposits, in the form of polar ice and mountain glaciers, offer some of the best sources of paleoclimatic information, thus making ice caves a preferential target for paleoclimate studies.

Previous research has demonstrated that the isotopic composition of cave ice, in-situ formed calcite trapped in the ice, and pollen are reliable proxies for past climatic and environmental changes (e.g. Perşoiu et al., 2011). By combining the age of ice at various depths with high-resolution stable isotope, hydrochemical and palynologic analyses, a detailed record of climate and environmental changes can be derived. These paleoclimatic records are in danger of being permanently lost as cave ice deposits begin to melt due to the effects of climate change.

The Plan

The National Cave and Karst Research Institute (NCKRI) of the USA is proposing to conduct a study to identify and sample cave ice deposits that are at risk of melting from as broad a range of geographic settings as possible. The purpose of the study would be to salvage a wide and representative sampling of cave ice for paleoclimatic and paleoenvironmental analysis. The proposed broad range of climatic regimes for sampling would allow examination of various modes of climate variability, climate forcing, and strength of anthropogenic impacts.

The research would be conducted in three phases. Phase one would involve monitoring and collection of baseline data from selected caves for a period of one year to cover a full climatic cycle. The monitoring program will require monthly visits to measure several climatic parameters and rates of ice accumulation, and to collect water and cryogenic calcite samples for stable isotope analyses. These baseline data are crucial for accurate interpretation of ice cores collected during a subsequent phase of the research.

The second phase of research, which would be concurrent with the ice cave monitoring program, involves construction of a facility for storage of ice cores, or expansion of an existing facility. In addition to providing space for storage of cave ice cores collected for this project, this facility would also be used for long-term archiving of ice cores for future research. The ice core storage unit would include a cold room for archiving, a lab area where ice cores could be slabbed and sampled, and an airlock between the lab and archive space. Back-up diesel power would be established in the event of a failure of the main power source.

The third phase of this investigation would involve collecting cores of cave ice from those caves that have been identified as having the most potential for preservation of an extensive and continuous paleoclimate record. The cores would be analyzed for stable isotopes of oxygen, hydrogen and carbon, carbon-14, tritium, organic and inorganic chemistry of the ice and contained sediment, and fossil pollen. Sites with existing year-long monitoring records that were not monitored by this study could also be incorporated into this third phase of investigation.

The Challenges

While the urgency of climate change is well known in scientific circles, NCKRI has encountered some difficulties in starting this project.

Presently, the sites under consideration are only in the Northern Hemisphere. The intent of this project is for a global sampling of cave ice, but a review of the literature and international calls for information have yet to yield any Southern Hemisphere cave ice localities.

NCKRI's initial plan was to store the cave ice in an existing facility. We have contacted several ice storage centers and discovered, with the exception of one offer for short-term storage, this is not generally possible. Many lack the storage space for additional samples from outside of their projects. Others are incompatible for cave ice, storing ice only from continental glaciers to avoid sample contamination from sediments in cave and mountain glacier ice. Consequently, developing a facility dedicated to cave ice seems necessary.

Funding is critical. Travel is extensive. Many of the sites are remote. Teams are needed during the first phase to sample the caves monthly. Coring of ice could require helicopter transportation. Special shipping is needed for the cores from the caves to the ice storage and lab facility, which needs to be built, equipped, and maintained.

Despite attempts to minimize costs, no funds have been acquired to date for this project. Six years ago, a worldwide economic crisis developed and many countries have not yet fully recovered. Governmental and private funding sources have greatly diminished. Competition for the remaining lesser funds has increased. NCKRI's experience and sources suggest no more than 3-4% of grant proposals in the USA are currently funded. Some traditional major sources of support for scientific research, like the US National Science Foundation,

will not fund the first phase of the project because they incorrectly see it as scientific uncertainty instead of data collection critical to the analysis and interpretation of the third phase results. As a result, this project remains a proposal while the ice continues to melt.

The Hope

When NCKRI began this project, it included primarily the three authors of this paper. Some discussions were held with other scientists, and if the project was funded there would be a broad, international outreach for participation commensurate with the funds available. However, the combined economic and logistical difficulties encountered now require a new approach.

Through this paper, we propose a broad and open discussion to create a partnership among ice cave scientists whereby we can exchange information and mutually support each other to sample and study as much of the world's ice as possible before it disappears. NCKRI would serve as a clearinghouse for information and communication. The goal isn't for NCKRI or any organization to do this research, but to make it as easy possible for any knowledgeable and responsible scientist to do the work in a cooperative fashion that minimizes unnecessary duplication of effort and maximizes efficient use of knowledge and resources. This is an urgent scientific crisis. We seek your cooperation and support, and look forward to working with you.

References

Perşoiu A, Onac BP, Wynn JG, Bojar AV, Holmgren K. 2011. Stable isotope behavior during cave ice formation by water freezing in Scărişoara Ice Cave, Romania. Journal of Geophysical Research: 116.

Stoker TF, Dahe Q, Plattner G-K. 2013. Climate change 2013: the physical science basis. Intergovernmental Panel on Climate Change, Working Group 1 Technical Summary.

WGI Technical Support Unit. 2014. Headline statements from the summary for policymakers. Intergovernmental Panel on Climate Change.

ANALYSIS OF SELECTED CLIMATOLOGICAL OBSERVATIONS OF TALUS & GORGE ICE CAVES IN NEW ENGLAND

David Holmgren
Ruhr-University Bochum
Universitätsstrasse 150 / Building NA 4/171
Bochum, 44780, Germany, david.holmgren@ruhr-uni-bochum.de,

Andreas Pflitsch
Ruhr-University Bochum
Universitätsstrasse 150 / Building NA 4/171
Bochum 44780, Germany, andreas.pflitsch@ruhr-uni-bochum.de

Abstract
Changing temperature regimes inside a field of debris with year-round ice blocks are the base of this study in northern New Hampshire. This unique ecosystem shows strong temperature anomalies in comparison to the surrounding area and ice, especially year-round ice, is not common below 700 m a.s.l. Yearly mean air temperatures can be strongly connected to the yearly ice level variations. Besides the analysis of the complete dataset of five years and a comparison of the impact of different seasons onto the ice considering precipitation, air temperature and special weather phenomena, the question about the use of talus & gorge ice caves as a climate indicator for a region has priority.

Keywords
ice cave, talus, gorge, climate change, climate indicator, subterranean ice, New Hampshire, Maine, New England, United States of America

Introduction
The White Mountains in the northern Appalachian Mountains of the USA are the study area of the Talus & Gorge Ice Cave monitoring network. The Talus & Gorge Ice Caves are also known as talus caves (with ice), because of the forming material, unsorted rocks. The hollow spaces in between the rocks can bury ice, also at altitudes far below the summer snowline, under special conditions. The hollow spaces also known as caves have different sizes depending on the sizes of the rocks.

In October 2008, we started to collect data in different Talus & Gorge Ice Caves of New Hampshire and Maine with the main goal to identify the climate of these unique ecosystems. We observe the air temperature above the talus and within the talus nearby the ice in connection with yearly and scattered semiannual ice level observations. After five years of collecting data, a first review about the past climate and its variations will be given. The temperature and ice level measurements of the study area with a comparison of the collected data of nearby reference stations result in important knowledge about the interaction of the climate between the talus & gorge caves and the external environment.

Since ice caves can be seen as a climate indicator for short- and long-term changes within the climate of their respective region, we will lead to a statement about the recent climate and its possible changes for New England especially northern New Hampshire and western Maine.

A final analysis of regional climate change indicators for New England like “length of ice cover on lakes”, “date of lake ice-out” or “days with snow on the ground” will introduce into a comparison of the results of our yearly ice level observations of the talus & gorge ice caves in that area. We will lead into a new representative idea of climate change observation for New England and discuss its advantages and disadvantages.

Site characteristics
The network of the Talus & Gorge Ice Cave monitoring consists three study sites in New Hampshire and Maine. The focus for this analysis is on the site with the longest datasets, the Ice Gulch in northern New Hampshire. Since 2008 we are measuring the air temperature of the Ice Gulch at different positions in the gulch and the ice level changes in regular intervals.

The Ice Gulch is situated in the White Mountains of New Hampshire, 50 km south of the Canadian border. The Ice Gulch is a small narrow Gorge with ~85 to 100 m high surrounding walls and a width of ~80 m. On the ground of the gulch huge rocks of a diameter up to 3 m form the cave-like hollow spaces, which contain year-round ice at some spots. The special characteristic of that gulch is that one can find ice in the talus right below the surface, at an elevation of approximately 650-690 m a.s.l. (Holmgren & Pflitsch, 2010). The Ice Gulch is far below the summer snowline. Mt. Washington (1,917 m

a.s.l.), the highest mountain in the northeastern USA, in general is ice-free from May to September (Holmgren & Pflitsch, 2011). First obvious signs for an irregular climate are some plants within the Ice Gulch. Alpine plants, like the alpine blueberry, one can find in the Talus & Gorge Ice Caves are not common in this elevation in New England (Ice Gulch: Visiting New Hampshire's Biodiversity, 2009).

Methods

At the study site "Ice Gulch" five data loggers measure the air temperature. One at the vegetation line (compare Fig. 1, red box) and four at different spots within the talus 10 cm above the ice blocks (compare Fig. 1, blue box). The data loggers of the company "GeoPrecision" have sensors from the type PT1000 with a precision of+/-0.1 K at a temperature of 0 °C and a resolution of 0.01 °C (GeoPrecision, 2014). All five data loggers record the temperature in a 15 min interval. The ice level observations are done manually. The observations were observed yearly every potential ice level minimum.

For a data comparison of the Ice Gulch with the surrounding area, reference stations of the nearby Mount Washington Observatory are used. The Observatory at the summit of Mount Washington provides temperature, wind speed and wind direction data. The weather stations along the slopes, especially the 2,300 ft station at similar elevation and similar orientation like the Ice Gulch, provide important temperature data for a comparison.

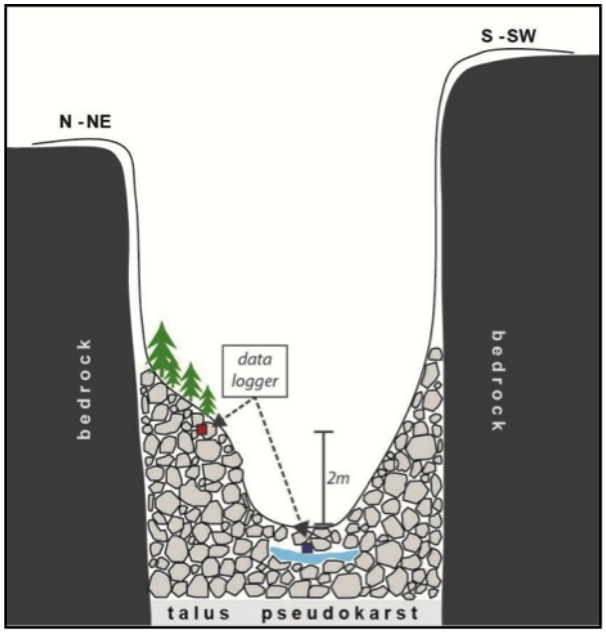


Figure 1. *Schematic cross profile of the Ice Gulch and position of temperature sensors (adapted after Holmgren & Pflitsch, 2011).*

Procedure of data analysis

Temperature regimes of the last five years

A comparison of the last five years (Fig. 2) will give a first overview about the temperature features of the ecosystem Ice Gulch. The graphs in Figure 2 visualize the air temperature of two data loggers. One shows the temperature of the edge of the vegetation line (red) approx. 2 m above the floor of the gulch with one exemplary dataset from inside the talus close to an ice block (blue) (compare position in Fig. 1). The yearly returning cycles and the differences are in focus of that topic. Are there any changes or developments in the progress of the last five years of record? One of the most obvious developments in the past is the increasing period of temperature above freezing inside the talus year by year (Fig. 2 blue graph). The impact of the relatively warm air masses gets stronger and stronger due to the increasing mean summer temperatures of the surrounding area (and the varying mean winter temperatures). The result of this effect is a negative ice mass balance which leads to a less absorption of warm air during summer.

Another topic is the comparison of the yearly cave ice dynamics with the yearly temperature regime from November to October (ice minimum to ice minimum). We identified a strong comparison between the annual mean air temperatures and the yearly ice dynamics in Gorge Ice Caves with talus (like Ice Gulch), but not in Talus Ice Caves. Talus Ice Caves tend to be more sensitive and less

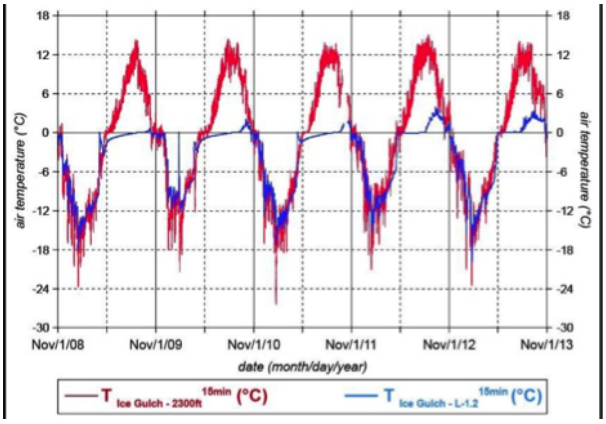


Figure 2. *Temperature regimes of the Ice Gulch - above and within the talus (Nov/1/2008 – Oct/31/2013).*

protected for short-time weather phenomena especially in summer when former Hurricanes or tropical storms hit this area which influence the Talus Ice Caves much stronger. That's an enormous impact factor for a bigger ice loss in Talus Ice Caves (up to 2.2 m) than in Gorge Ice Caves (up to 0.25 m). Gorge Ice Caves, due to their surrounding walls, like you can find in the Ice Gulch, are much better protected against storms pushing air masses into the talus.

The impact of the seasons

For understanding the ice building and melting processes at these unique locations, the different seasons play an important role. The first question for us was, whether the typical known seasons, can find in the Ice Gulch as well? Or do we have a change in the typical cycle of seasons, affected by the specific conditions with a unique climate inside the Ice Gulch? This result will be important for the further view how the ice level measurements can be used as an indicator for a changing climate.

The seasons of the Ice Gulch are defined by a specific temperature behavior. Summer and winter are the seasons when the air temperature at the edge of the vegetation line stays continuously above or below the freezing point. Spring and fall are the seasons in between when the air temperature fluctuates around 0 °C.

First all of the seasons in the talus and gorge caves are different in length in comparison to the outer atmosphere. The mean length of the winter and summer seasons demonstrate the domination of these two seasons since our measurements began in October 2008.

Summer is the longest season with an average of 160 days, followed by the winter season which is a bit shorter than summer with a mean of 157 days. The shorter seasons are fall and spring. Fall has a mean length of 29 days, while spring has only a mean of 16 days.

Interesting are the developments in length of the seasons in the last 5 years. In 2009 fall began with a length of 51 days, a record year. From year to year fall got shorter and ended up with 13 days in 2013. Spring, the shortest climatological season in the Ice Gulch, has a minimum of 8 days and a maximum of 30 days, with a decreasing trend. The biggest development one can see is in winter, the length of winter has an increasing trend over the last five winters. The shortest winter was in 2009 with 129 days and the longest with 175 days below freezing in 2012. Summer with a minimum length of 153 and a maximum of 176 days shows a very light increasing trend of air temperatures above freezing. But an interpretation of the summer trend is very imprecise with this slightly increasing development and an observation period of only five years.

As you can see winter and summer seasons are the dominating seasons inside the talus. Fall and spring are short transition seasons and not very distinct. The climate and the ice blocks of the talus and gorge caves are very sensitive to the extreme temperatures and precipitation in summer and winter and that's one of the reasons why the first two mentioned seasons play besides their length an enormous role.

Ice caves as climate indicators for New England?

Besides the well known and observed climate elements of a weather station, we do have various climate indicators worldwide, like the extent of the arctic sea ice or the bird wintering ranges. For New England and especially the White Mountains in New Hampshire, the regional climate indicators, are for example the lilac bloom date or the Lake Winnipesaukee ice breakup.

An analysis will try to compare the existing long-term observations (partly since 1807 AD) of climate indicators of that region with the ice level variations at the yearly potential ice minimum of the Ice Gulch (since 2008 AD) (USGS, 2010; Lake Winnipesaukee New Hampshire, 2014). Finally, this analysis will result in a statement about the climate changes of that specific region. The validity of this new climate indicator was unknown before for New England. For other regions of the world, like the western European Alps or the ice caves of Lake Baikal in the south of the Russian region of Siberia (Luetscher et al., 2005; Trofimova, 2006), such analyses are already done.

Acknowledgements

The field work was supported by Ken and Jane Rancourt. Thanks for having us year by year and all the support you gave us.

The data for reference were provided from the weather stations of the non-profit institution Mount Washington

Observatory. Thank you for providing the data.

References

GeoPrecision. 2014. Geoprecision.com; [cited 2014 March 25] Available from: http://www.geoprecision.com/de/products- topmenu-45/funk-minilogger topmenu-45/funk-minilogger.html.

Holmgren D, Pflitsch A. 2010. Microclimatological survey of the Ice Gulch in the White Mountains, New Hampshire, USA. In: Spötl C, Luetscher M, Rittig P. editors, Proceedings of the 4th International Workshop on Ice Caves; 2010 June 05-11, Obertauern, Austria.

Holmgren D, Pflitsch A. 2011. The Ice Gulch-Perennial Ice in the White Mountains. WINDswept 52: 20-23.

Ice Gulch: Visiting New Hampshire's Biodiversity. 2009. Concord, NH (USA): New Hampshire Division of Forests and Lands; [cited 2014 March 26]. 2 p. Available from: http://www.nhdfl.org/library/pdf/Natural%20Heritage/icegulch.pdf.

Lake Winnipesaukee New Hampshire. 2014. Ice-Out on Lake Winnipesaukee; [cited 2014 April 28] Available from: http://www.winnipesaukee.com/index.php?pageid=iceout.

Luetscher M, Jeannin P-Y, Haeberli W. 2005. Ice caves as an indicator of winter climate evolution: a case study from the Jura Mountains. The Holocene 15: 982-993.

USGS. 2010. Historical Ice-Out Dates for 29 Lakes in New England 1807-2008; [cited 2014 March 05] 38 p. Available from: http://pubs.usgs.gov/of/2010/1214/pdf/ofr2010-1214.pdf.

Trofimova EV. 2006. Cave Ice of Lake Baikal as an Indicator of Climatic Changes. Doklady Earth Science 410: 113-116.

SOME NEW POTENTIAL SUBTERRANEAN GLACIATION RESEARCH SITES FROM VELEBIT MT. (CROATIA)

Neven Bočić
University of Zagreb
Marulićev trg 19/II
Zagreb, 10000, Croatia, nbocic@geog.pmf.hr

Nenad Buzjak
University of Zagreb
Marulićev trg 19/II
Zagreb, 10000, Croatia, nbuzjak@geog.pmf.hr

Zoltán Kern
Institute for Geological and Geochemical Research,
Budaörsi ut 45.
Budapest, H-1112, Hungary, kern@geochem.hu

Abstract
Despite the frequent reports about their shrinkage, detailed survey of the major subterranean ice deposits is still lacking in Croatia. Here we present cave maps and detailed description of cave ice accumulation from five caves of the Velebit Mt. Morphological constraints allowed ice volume estimation for four of them. Ice volumes were estimated as ~1500 m^3 at the Gavranova Pit in 1999, 100 m^3 at Štirovača ice cave in 1987, 150 m^3 at Japagina 3 in 2000, 1500 m^3 at Kugina ice cave in 2004. These new records provide reference data for future studies to evaluate glaciological changes/processes taking place in the corresponding cave environments. As a common topographical characteristic of these caves and the previous ones, it seems that the present elevational limit of permanent cave ice occurrence in the Velebit Mt is ~1000 m a.s.l. Regarding the climatic parameters it corresponds to the January isotherm of -2° C and 14° C in July, annual sum of precipitation of 1750 mm and 90 days with snow per year.

Introduction
Cryospheric processes in the karst systems remains heavily under-researched, though a pervasive ice loss trend has been documented for the glacierized caves worldwide (Kern and Perşoiu, 2013).

A prominent region of the karstic world is the Dinarides, where numerous cavities host perennial ice and snow accumulation. The exact or approximate number of Croatian caves with permanently glaciated parts is unknown but the data collection is in progress (Buzjak et al., 2011). The first scientific report about Croatian ice caves has been published surprisingly late (Božičević, 1971). Relatively modest research efforts have been focused on them (Jelinić et al., 2001; Horvatinčić, 1996) although recently mass ice loss (Bočić et al., 2008; Kern et al., 2008, 2011) or complete deglaciation (Bočić et al., 2012) have been reported from caves. Therefore the detailed documentation of the major subterranean ice deposits is an urgent task.

Present paper will provide speleoglaciological description of five localities from Croatian part of the Dinaric system, where major perennial cave ice accumulation exists. The provided cave maps and the estimated ice volumes will provide valuable reference data for evaluating glaciological changes/processes taking place in the corresponding cave environments during future times.

Physical geography settings
Mt. Velebit is part of the Dinaric Karst and it is located in Croatia. It stretches between the eastern coast of the Adriatic Sea and continental Lika region in length of 145 km. The highest altitude is 1757 m a.s.l. Because of carbonate rocks Velebit area is highly karstified with numerous and dense surface karst forms, and many vertical caves (Bočić et al., 2012; Bakšić and Paar, 2006). The deepest cave system is Lukina jama -Trojama (-1431 m), and the longest one is Kita Gačešina-Draženova puhaljka system (length 26 km). The studied area includes the northern and central part of the Velebit mountain range (Fig. 1) with the highest altitude 1699 m a.s.l. (Mali Rajinac peak). The zone above 1500 m a.s.l. has a humid boreal climate (Köppen's type *Df*) and the lower parts have a temperate humid climate (*Cfb*) mainly determined by the relief (Zaninović, 2008). Mean annual air temperature in the area up to 1000 m a.s.l. is about 5.5°C and in the highest region drops to 3.5°C. The coldest months are January and February (between -2 and -5°C) and the warmest one is July (12-16°C). Due to proximity of the Adriatic Sea, there are important climate modifications. The most important one is high

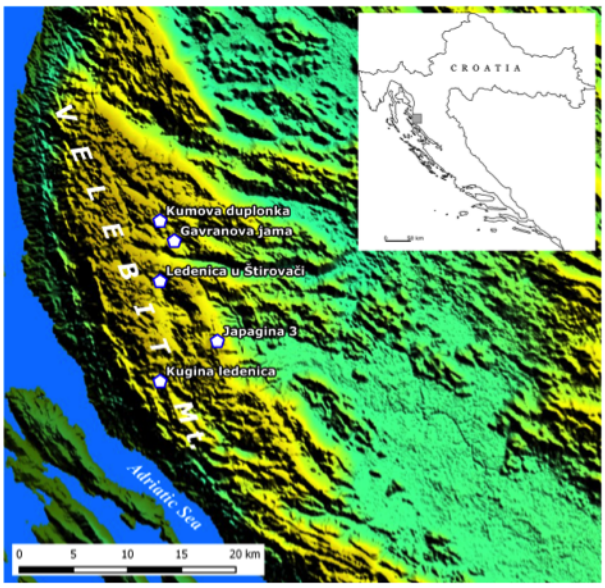


Figure 1. *Location of the presented ice caves.*

amount of precipitation that varies from 2000 to 3900 mm/year. In combination with higher altitude and larger depressions with intense temperature inversion there are good conditions for the accumulation of ice and snow in karst depressions like deep mountain dolines and caves and pits (Buzjak et al., 2010, 2011).

Methods

Maps of visible ice fillings have been sketched using speleological mapping methods (e.g., Kovačić & Čepelak, 2000). Basic speleoglaciological characteristics, such as observed/assumed ventilation regime and type of ice occurrence were provided following the classification schemes of Luetscher and Jeannin (2004) and Citterio et al. (2004). Although ice thickness estimates suffered from major uncertainties, in line with other similar studies (e.g. Luetscher et al., 2005), ice volumes were estimated where morphological criteria supported the estimation.

Results

Gavranova jama (Gavranova pit; Fig. 2a)

Gavranova pit is located in the area Begovača (eastern part of the north Velebit) at 1100 m a.s.l. It has two main entrances (the higher and lower) with 20 m of the vertical, and 95 m of horizontal distance. There is also small third entrance very near the lower one and on the same elevation. The cave has been explored in 1999 (Bočić, 2001). Below larger entrance is vertical channel, which continues to depth of 25 m. On the bottom there

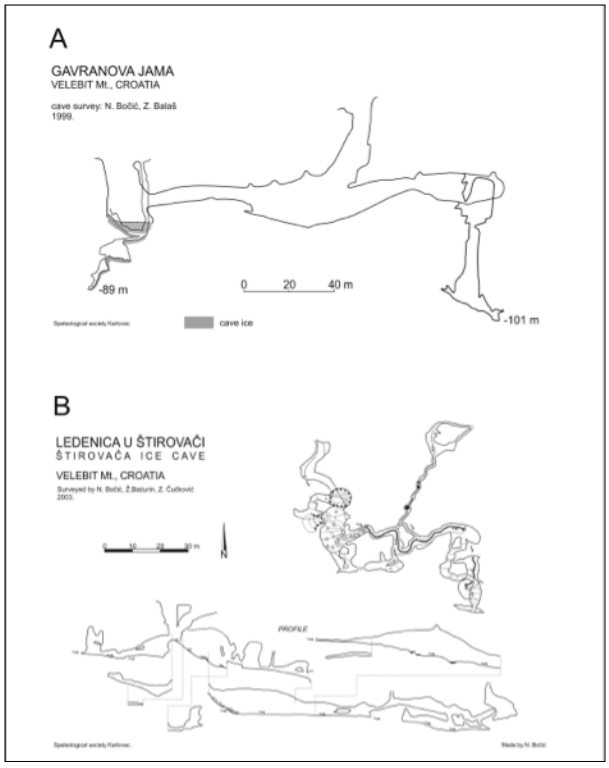


Figure 2. *Cave survey of Gavranova jama (A) and Ledenica u Štirovači (B).*

is a greater accumulation of firn with congelation ice deposits. The diameter of this ice plug is about 15 meters. Between the ice and the bedrock is a narrow passage up to 89 m depth, but due to the re-deposition of ice it is not possible to determine the exact thickness of the ice plug. The estimated volume of the ice was at least about 1500 m^3. During the subsequent visit in 2005, it was found that the level of ice in this period decreased by about 1 m. Specific cave morphology probably influences the complex ventilation of the cave and this has influence on cave ice dynamic. So, it is necessary to undertake a detailed microclimatological measuring to determine airflow regime.

Ledenica u Štirovači (Štirovača ice cave; Fig.2b)

Štirovača Ice Cave is situated in the large Štirovača karst depression, at 1110 m a.s.l. It is a 351 m long cave with two vertical entrances. Its entrances are only 6 m apart one from another, with an altitudinal difference of 5 m. Under the entrances there is a chamber (dimensions 22 x 8 x 14 m). It extends to the south and has inclined bottom (about 30°). It was formed by a collapse of the ceiling in the main channel section. During the first exploration of this cave in August 1987 a substantial mass of snow and congelation ice was noticed in the entrance part,

estimated at a volume of approx. 100 m^3. Therefore the cave was named "ledenica" or "snježnica", which means icy or snowy cave, i.e. "ice cave" or "snow cave". In the next investigation, in the summer of 2003, and afterwards, snow and ice were no longer noticed (Bočić et al, 2012a) actually meaning that Štirovača ice cave has already lost the perennial ice deposit during the last decade of the 20th century.

Japagina 3 (Japagina 3; Fig.3a)

Japagina 3 is located in the area Japaga on the eastern slopes of the central Velebit (Baćurin & Stopić, 2002). There are a significant number of caves in this area of which a part contains more or less amount of ice. Japagina 3 is located at about 1300 m a.s.l., and its depth is -72 m. It was found in June 2000, and was investigated in July 2001. Its ice deposit consists of accumulated snow and firn. Estimated volume of the ice was approx. 150 m^3. The relatively fresh snow surface suggests that the deposition is active. Regarding the morphology of the entrance zone it is likely that the deposit is fed primarily by wind-blown snow.

Kumova duplonka (Godfathers double-barreled gun cave; Fig.3b)

This cave is located at the foot of Begovački kukovi (Northern Velebit) at 1205 m a.s.l. It has one common entrance for two vertical shafts that connect to a depth of -19 m. Morphological characteristics suggest statodynamic ventilation regime. The first Croatian exploration descending to a depth of -35m took place in 1997 (Bočić, 1997), although notes from a latter report suggest a visit by a group of Slovakian cavers in the previous year (1996) to the depth of -31 m (Šmida et al, 1999).

Kugina ledenica (Kugina ice cave; Fig.3c)

The cave has been explored in late July of 2004 (Bočić, 2005). It is a simple cave but with large entrance (43 x 27 m) and one large chamber. At the bottom there is a 15 m wide ice plug. The known depth of the ice profile is about 20 m. Ice plug (profile) extends from the depth of -40 m to -61 m. The estimated volume of the ice was approx. 1500 m^3. Regarding the morphological characteristics it is a typical static cave with firn. A peculiar character of this deposit is the significant number of wood trunks embedded in the ice layers.

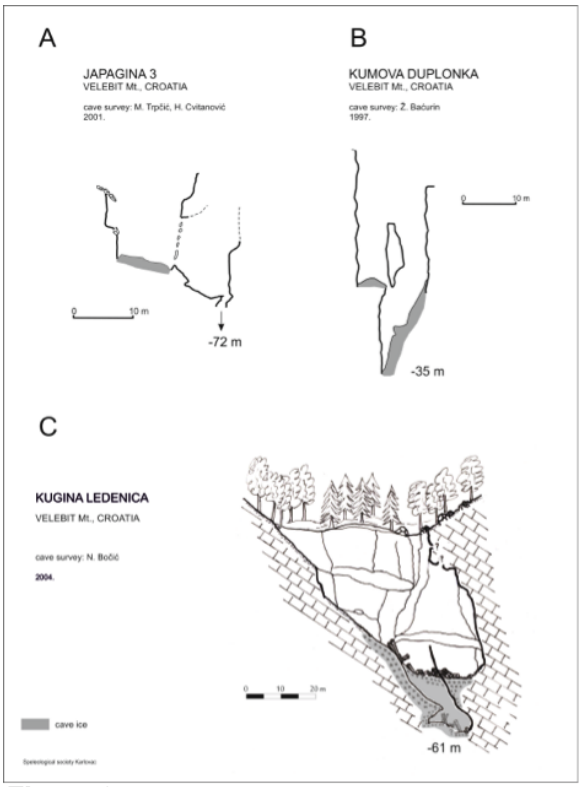


Figure 3. *Cave survey of Japagina 3 (A), Kumova duplonka (B) and Kugina ledenica (C).*

Summary and Outlook

Here are shown some ice caves as potential sites for further detailed speleoglaciological research. Some common characteristics of these caves, as well as previously-explored caves can be classified into climatic, morphological and climatic-morphological criteria. Climatic characteristics are these: they are in the area within the January isotherm of -2° C and 14° C in July, they are in precipitation isoline of 1750 mm and the number of days with snow is over 90 (Zaninović, 2008). Morphological characteristics are mainly related to the characteristics of the entrances. They are generally larger (usually over 10 m) and shaft-like type, which are oriented upward. From the climatic-morphological point of view it is important that all caves are located at an altitude of over 1000 m a.s.l., and most caves are located in larger or smaller karst depressions under the influence of temperature inversions and can function as cold air traps. The above examples, as well as most other observations (Kern et al., 2008; Bočić et al., 2008; Buzjak et al., 2012) during the explorations indicate a negative trend in the ice level of the caves. It is mainly noted lowering levels, i.e. reducing the amount of accumulated ice and open space between the ice and the bedrock. However,

it is important to note that there are caves with different trends. According to previous experiences their number is relatively small, but they have a very interesting ice dynamic. For example, in Lukina jama-Trojama system (the deepest pit of the Dinaric karst), below the main entrance (Lukina jama) the level of accumulated ice has increased and closed the passage, and now for descending into the system entrance Trojama must be used exclusively. In the pit Patkov gušt (the second largest vertical shaft in the Dinarides, 553 m) passage through the ice plug repeatedly closed and opened from the year 1997 when pit was discovered. However, this dynamic is not only or mainly a result of changes in the volume of ice accumulation, but a number of different processes (microclimate variations, the collapse of the accumulation of ice and ice "flowstones", re- freezing of the meltwater, etc.). It should be stressed that there are caves and pits that do not have permanent cave deposits of snow and ice (e.g. Slovačka jama, Meduza, Lubuška jama, Olimp). They are located in the same climatic conditions and same altitude as well as those with the ice but they differ in characteristics of the entrances (Buzjak et al., 2011). Their entrances are usually small (at most a few meters), horizontally oriented (look like a horizontal cave, but not a shaft entrance), and some are partially covered by collapsed blocks.

This brief overview shows that area of the Velebit Mt., especially northern part, has high importance and research potential in speleoglaciology. With the former already known sites, there are many new sites with permanent ice.

Acknowledgements

The research was supported by Ministry of Science, Education and Sport of the Republic of Croatia (Project No. 119-0000000-1299 and Project No. 098-0982709-2741). N. Bočić expresses thanks to the Balassi Institute - Hungarian Scholarship Board Office for the award of research scholarship in Hungary. Z. Kern expresses thanks to the Lendület program of the Hungarian Academy of Sciences (LP2012-27/2012). This is contribution No.11. of 2ka Palæoclimatology Research Group.

References

Baćurin Ž, Stopić D. 2002. Speleološki kamp Japage '2001'. Speleo'zin 15: 3-15.

Bakšić D, Paar D. 2006. Croatia and the Deep Caves of Northern Velebit. In: Oliphant T. editor, Alpine Karst, vol 2. Cavebooks, Dayton, USA p. 105-124.

Bočić N. 1997. Speleološki kamp, Sjeverni Velebit '97'. Speleo'zin 7: 3-6.

Bočić N. 2001. Speleološka ekspedicija, Olimp '2000'. Speleo'zin 14: 3-6.

Bočić N. 2005. Kugina ledenica na srednjem Velebitu. Speleosfera 2: 54-58.

Bočić N, Kern Z, Horvatinčić N, Nagy B, Fórizs I, László P. 2008. Paleoenvironmental record fom ice caves of Velebit mountains - Ice pit in Lomska duliba and Vukušić snow cave, Croatia. Prvi međunarodni geografski znanstveni kolokvij Mostar-Budimpešta-Zagreb, Mostar 2008, Zbornik sažetaka, p. 42-43.

Bočić N, Faivre S, Kovačić M, Horvatinčić N. 2012a. Cave development under the influence of Pleistocene glaciation in the Dinarides – an example from Štirovača Ice Cave (Velebit Mt., Croatia). Zeitschrift für Geomorphologie 56: 409-433.

Bočić N, Buzjak N, Faivre S, Pahernik M, Vidović V, Kovač M. 2012b. Temeljna geomorfološka obilježja i geoekološko vrednovanje reljefa sjevernog Velebita. Znanstveno-stručni skup "Posebne vrijednosti dubokog krša". In: Buzjak N, Paar D. editors. zbornik sažetaka, Krasno, p. 6.

Božičević S. 1971. Ladove jaskyne v Chorvátsku. Slovensky Kras 9: 177-179.

Buzjak N, Paar D, Bakšić D. 2010. Some characteristics of ice and snow caves in Croatia. 4th International Workshop on Ice Caves, Obertraun, Austria, Abstract Volume, p. 7-8.

Buzjak N, Paar D, Bakšić D. 2011. Snow and ice in speleological features of Dinaric Mountains in Croatia. Geophysical Research Abstracts 13: EGU2011-7839-2.

Buzjak N, Paar D, Bakšić D. 2012. Microclimate properties of caves with permanent ice and snow (nothernVelebit Mt), Znanstveno-stručniskup "Posebne vrijednosti dubokog krša". In: Buzjak N, Paar D. editors. Zbornik sažetaka, Krasno, p. 7-8.

Citterio M, Turri S, Bini A, Maggi V, Pelfini M, Pini R, Ravazzi C, Santillini M, Stenni B, Udisti R. 2004. Multidisciplinary approach to the study of the LoLc 1650 "Abisso sul margine dell'AltoBregai" ice cave (Lecco, Italy). Theoretical and Applied Karstology 17: 27-44.

Horvatinčić N. 1996. Isotopic measurement in ice, Ledenica Cave, Velebit, Croatia. (In Croatian with English summary). In: Kubelka D, Kovač J. editors. Proceedings of the third symposium of the Croatian Radiation Protection Association, Zagreb p. 297–302.

Jalžić B, Lacković D, Šmida B. 1995. Lomska Duliba '93. Speleolog 40/41: 5-16.

Jelinić I, Horvatinčić N, Božić V. 2001. Ledena Jama (The Ice Pit) in Lomska Duliba (in Croatian with English summary). Senjski zbornik 28: 5-28.

Kern Z, Perşoiu A. 2013. Cave ice – the imminent loss of untapped mid-latitude cryospheric palaeoenvironmental archives. Quaternary Science Reviews 67: 1-7.

Kern Z, Bočić N, Horvatinčić N, Fórizs I, Nagy B, László P. 2008. Palaeoenvironmental records from ice caves of Velebit Mountains - Ledena Pit and Vukušić Ice Cave, Croatia. In: Kadebskaya O, Mavlyudov BR, Pyatunin M. editors. 3rd International Workshop on Ice Caves Proceedings, Kungur, p. 108-113.

Kern Z, Széles E, Horvatinčić N, Fórizs I, Bočić N, Nagy B. 2011. Glaciochemical investigations of the ice deposit of Vukušić Ice Cave, Velebit Mountain, Croatia. The Cryosphere 5: 485-494.

Kern Z, Széles E, Bočić N. 2012. Lead concentrations and stable lead isotopes from a Croatian cave ice profile. 5th International workshop on ice caves, Barzio, Italy, Book of Abstacts, p. 39.

Kovačić M, Čepelak M. 2000. Topografsko snimanje speleoloških objekata. In: Bakšić D, Lacković D, Bakšić A., editors. Speleologija, PDS Velebit, Zagreb, p. 207-218.

Luetscher M, Jeannin P. 2004. A process-based classification of alpine ice caves. Theoretical and Applied Karstology 17: 5-10.

Luetscher M, Jeannin PY, Haeberli W. 2005. Ice caves as an indicator of winter climate evolution—a case study from the Jura Mountains. The Holocene 15: 982–993.

Šmída B, Ágh Z, Bakšić D, Griflík M, Kapucian E, Kotlarčík D, Kýška K, Sova M, Vykoupil J, Kaknkula J, Audy M. 1999. Velebit - reportáž z objavovania hlbokých priepastí Chorvátska v rokoch 1990 - 1998, Slovenská speleologická spoločnosť, p. 118

Zaninović K. editor. 2008. Klimatski atlas Hrvatske. Meteorological and Hydrological Service of Croatia, Zagreb.

CLIMATE STUDY IN AN ABANDONED AUTO TUNNEL IN ALASKA, USA

Andreas Pflitsch
Ruhr-University Bochum, Geography Climatology,
Uni- versitätsstrasse
150 Bochum 44780, Germany,
andreas.pflitsch@ruhr-uni-bochum.de

David Holmgren
*Ruhr-University Bochum, Geography Climatology, *
Universitätsstrasse
150 Bochum 44780, Germany,
david.holmgren@ruhr-uni-bochum.de

Abstract
An abandoned auto tunnel in south central Alaska at an elevation of 118 m above sea level seemed to be a perfect laboratory for studying the evolution of ice speleothems in a yearly cycle. More than 1,500 ice forms like stalagmites, stalactites, columns in various shapes and arrangements, developed in just 2 months to a height up to 6 meters and lasted for another 5 to 6 months. In October just the remains of the melted ice in rings and rectangular patterns of a white powder could be found. Unfortunately the mostly sealed tunnel was opened in January 2014 by a melt water stream which was redirected by a huge avalanche. The perfect "ice cave conditions" were destroyed abruptly (Hollander & Theriault, 2014; NASA; 2014a).

Keywords
ice caves, tunnel, ice stalactites, ice stalagmites, ice columns, Alaska, Valdez, Keystone Canyon

Introduction
Although, Alaska is the coldest state in the USA and one should expect lots of ice caves in all the mountain areas, just a few caves with permanent ice are well known (Allred, 2008 a & b). They are located in the Wrangell Mountains in the eastern part of the state close to the old mining town of Kennecott. Till now, no meteorological or climatological investigations in these caves are known. There are some reasons for the circumstances that we know more about the ice caves of Hawai'i than Alaska.

First of all, Alaska is remote for most scientists and not cheap to go. The harsh weather conditions limit the time for searching and investigating the caves, which is best in summer. Especially during the summer time the state is full of tourists and everything is much more expensive. Going in the spring season the snow might be still too high, in fall the snow can be too high already. We have had the experience two times, once in the middle of June after a harsh winter and once at the end of September. There was no way to reach the caves, not even by plane. So there might be many more, not yet found, ice caves around.

The other reason is the climate itself. Alaska is pretty cold in the winter but warms up in the summer to average monthly high temperatures of 21.6°C in McCarthy for instance (Snyder, 2013). The temperature itself is not the worst problem. The bigger problem is the very high amount of rain during the summer season. In the southern costal parts of the State, along the panhandle and the Chugach Mountains of south central Alaska, we have lots of rain during the summer season which invades the caves and warms them up. We have this phenomenon even in the Alaska Range in the Wrangell Mountains. Cave entrances in the Wrangell Mountains are plugged with ice and snow in June and were empty or filled with water in September. The average amount of rain for McCarthy is about 1,500 mm just for the three summer months (Snyder, 2013). Where huge ice falls showed nice sculptures in June, in September nice waterfalls replaced the ice. Reachable caves with permanent ice are very limited.

But in the Anchorage Daily News we found an article about lots of ice in a man-made, cave like structure and easy to reach. It was the old Auto tunnel in Keystone Canyon on the road to Valdez (Bickley, 2012a). This 200 m long tunnel is no longer in use and both ends were mostly plugged by walls of rocks and earth. Each winter the inflowing water was freezing to ice and a huge amount of ice speleothems were forming. It was told that the ice was permanent in cold years (Bickley, 2012b). But no real scientific report was found. This tunnel, even not naturally formed, was the lowest in elevation known ice cave, at least in the US and worth starting a measurement program.

Site characteristics

The old Auto Tunnel is located at the north end of Keystone Canyon near the Lowe River and the Alaska Richardson Highway at an elevation of 118 m above sea level. This is 26 km north of Valdez and just 18 km away from the water of the Valdez Arm and 56 km of the open Pacific. So we have a strong maritime influence with a coastal climate, which means for Alaska mild winters (January temperature average: -5.6°C) with a high amount of snow and even rain in winter at the lower elevation. In opposite to that we have cool summers (July temperature average: 12.9°C). The average precipitation is 1712.2 mm (Snyder, 2013).

The tunnel is 193.6 m long, about 8 to 10 m wide and up to 7.3 m high. The very end of the south entrance of about 3.8 m was filled with rocks and soil. The open tunnel construction has four different sections

1. The end at the south entrance of a burned wood structure and bedrock is 7.6 m long.
2. The ongoing southern part and the middle of the tunnel are dominated by natural bedrock (schist) and is 140.5 m long.
3. A structure of wooden and metal beams with wooden cassettes in between is 27.6 m long located in the northern half. The wooden cassettes are partly destroyed showing the hardly cracked rock behind. Here the most water invades the tunnel through the bedrock.
4. The surface of the concrete structure of the very northern end (14.1 m long) shows a strong contrast to the other two sections because no drip water invades the tunnel from the ceiling or walls. All over the other parts water is flowing and dripping inside the tube during all seasons.

Both ends are plugged by some rock and earth walls, which looks artificial made in the north and naturally built by rock fall in the south. Both talli are covered with brush vegetation at the outside.

At the north end, just a small hole in the ceiling of about 1 m in diameter was open in the first year but mostly closed during later visits. The south end had two openings, one at the ceiling of the rock fall of about 8.75 m^2 and two small ones in the middle just big enough to crawl through, but sheltered by some rocks inside the cave to the tunnel as well.

Through the upper south end opening the sun could shine in directly around noon and precipitation could fall in a very small part of the tunnel because the rocks were overhanging.

Since January 2014, both ends are completely open and a pile of rocks of the northern plug covers the ground about a meter high till the middle of the tunnel. A huge avalanche builds up a dam for the Loves River directly at the north end of the tunnel. The high pres- sure of the building lake opened the tunnel and flooded it completely. The plug at the south end is gone as well and the tunnel is open from both ends. Unfortunately our perfect laboratory for the development of massive ice in short cycles is gone (Hollander & Theriault, 2014, NASA, 2014a).

Methods

We have visited the tunnel 5 times; it was in June 2011, in April and October 2013 and in January and April 2014. During our first visit in June 2011 we found most of the tunnel full of ground ice, ice columns, ice stalactites and ice stalagmites, flowing water from the ceiling and walls, dry ice, slush and open water lakes as well as a few ice crystals at the ceiling at the north end (Fig. 1). For a first investigation we put in two data loggers to measure the air temperature. The data loggers with sensors from the type PT1000 with a precision of +/-0.1 K. and a resolution of 0.01°C (Geoprecision, 2014). All three data loggers record the temperature at 5 minute intervals. The first loggers were located 70 m from the north entrance where we found the most ice sculptures at the first wooden beam of the structured part. The second one was located in the middle and dry part of the tunnel where no

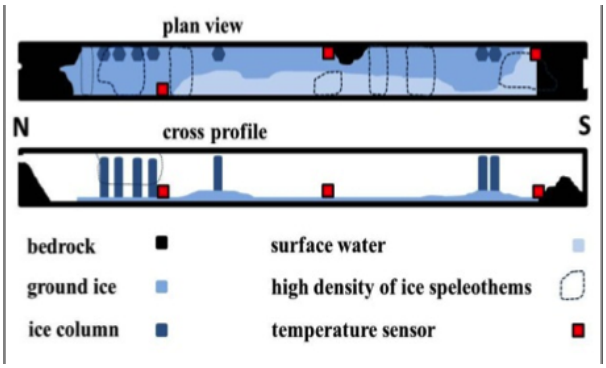


Figure 1. *Schematic plan view and cross profile of the Alaska Auto Tunnel, the distribution of the ice in April 2013 and the location of the data loggers which are described in the text.*

ice was found (Fig. 1). A year later we installed the third logger at the south end, where we expected the strongest influence of the outer atmosphere.

In addition to the recording of the air temperature we took thermal images of the whole tunnel and we mapped the ice speleothems as well (Fig. 1).

The Ice

During our first visit in June 2012, we found still a high amount of ice in the tunnel. About 80% of the floor was shielded with ice, about half of it was covered with a few cm of water. As shown in Figures 2 and 3 we found some columns, stalagmites and stalactites of ice, mostly melting. Three of the columns had a huge base of ice more than 1 meter high; the columns themselves had another 4 to 5 meters (Fig. 2).

The most ice speleothems were concentrated in the structure of wooden and metal beams (Fig. 3), while the concrete structure in the north was dry. During the first visit we did not count the ice forms but at the second one in April 2013 we counted about 550 and in January 2014 we estimated about 1,500.

Because we had heard that the ice was more or less permanent we thought that the different layers seen in some of the ice forms might have been developed in different years (Fig. 4). But after the visit in October 2013 finding no ice in the tunnel and the visit in January 2014 with again layered ice stalagmites it is clear that the layering was caused by different growing circumstances.



Figure 2. *View from the south end of the tunnel to the north, showing the first two ice columns with their huge base in June 2012.*



Figure 3. *View from the middle of the tunnel to the north, showing the section of the very wet wooden and metal construction with ice stalactites, ice stalagmites and ice columns in June 2012.*

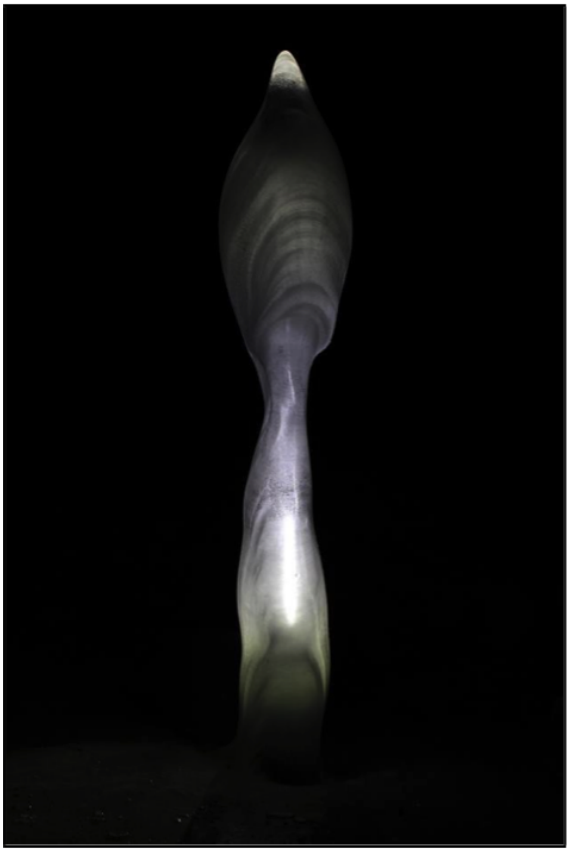


Figure 4. *Layered ice stalagmite of a height of 1.5 m in April 2013.*

For instance we could distinguish clear ice from clear ice with some bubbles and white ice. The clear ice was especially forming at the huge columns with a high amount of drip water, while the white ice was built after

drip water covered some ice crystals, which developed on the clear ice.

Climatic conditions

As seen in Figure 5, a thermal image of the southern part of the tunnel, we found a well-developed vertical temperature profile with an inversion. Take into account that the surface temperature of the rock is shown, but gives us information about the air temperature as well. The edge in June 2012 was at about 2/3 of the tunnel height. The warmer surface temperatures were found around the openings at both ends, while the floor was around freezing. The water on the floor was not just melt water, it was in some parts just water from the water source of the columns not yet frozen. This we found as well in January 2014. In contrast to June 2012 in January there was no clear temperature layering, the whole tunnel had more or less the same temperature.

The graph in Figure 6 shows the course of temperature over the period from June 2012 to January 2014 for the middle section for instance. During our first visit we have been already in the melting season, but found still a high amount of ice in the tunnel. Even with temperatures above freezing not all ice was melting. Some ice was still dry (Fig. 1).

The time below freezing from end of October to the beginning of May is just a bit longer than the frost free time, looking for the yearly period from June 2012 to June 2013. Interestingly the temperature rises rapidly, even with lots of ice in the tunnel in June. This is different from most of the natural ice caves with permanent ice, which haven't such an increase of the summer temperature. The reason for the strong warming in summer was not just the rising outside temperatures. The very high amount of water invading the tunnel throughout the year through the broken schist and especially through some of the drill holes brings additional thermal energy and melts the ice quickly.

While the warm summer periods, once above the freezing point, are clearly stable with no cold air break ins, the winter is kind of sensitive for a warming up, which can be seen best for the second winter. The winter of 2013/14 was relatively mild and in comparison to the Midwest of the mainland unusually warm (NASA, 2014a). During our visit in January the outside temperatures reached already above the freezing point and inside the tunnel they

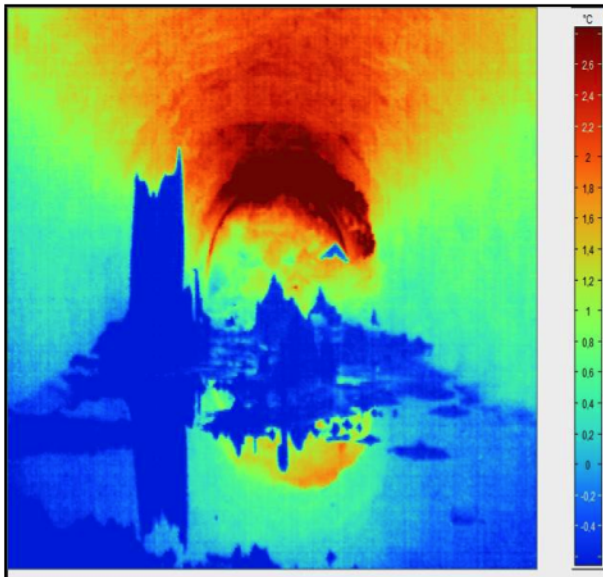


Figure 5. *Thermal image of the old Auto tunnel from the middle to the south end, 12th of June 2012. The Ice column, the stalagmites and the dry ground ice are the coldest parts, while the upper part of the south entrance and the ceiling are the warmest areas. In the lower middle of the picture one can see the reflection of the ice column, some stalagmites and the warm ceiling in the melting water.*

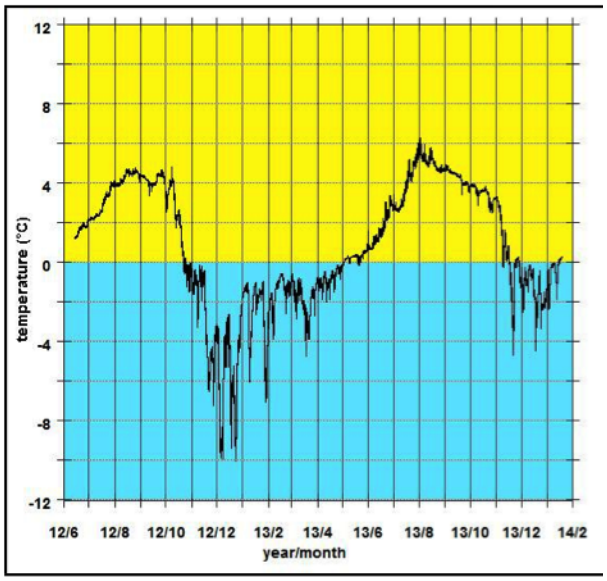


Figure 6. *Course of air temperature in the mid- dle section of the old Auto tunnel from 10th of June 2012 to 17th of January 2014. Sample rate: 5 min. Yellow are temperatures above freezing and blue temperatures below freezing.*

	Min	Max	Mean	Median	Stdw.
year	-10,02	4,80	-0,32	0,00	3,13
all	-10,02	6,28	0,87	0,68	3,10

Table 1. *Statistical overview about the tem- peratures in the middle section of the auto tunnel for a yearly period from June 15th 2012 to June 14th 2013 and for the whole time of measurements from June 13th 2012 to January19th 2014.*

followed this trend (National Weather Service Climate, 2014). These winter cycles of deep cold temperatures and temperatures around the freezing point are the reason for the strong layering of the ice stalagmites. As we could observe, most of the dripping points stop dripping below temperatures around -4 °C; except the water flows from the drill holes forming the huge columns. This means that the layering of the ice gave us a good impression about the meteorological situation during the winter and the temperature condition inside the tunnel.

Table 1 shows the statistic of the temperatures of the temperature sensor in the middle of the tunnel for two different time periods.

Acknowledgments

We thank Paul Burger a lot for giving us a place for hosting our equipment and for accommodating us and some students from time to time in his house in Anchorage.

References

Allred K, Allred C, Huestis J. 2008a. Cave map – Fossy Pothole-Wrangell-Saint Elias National Park Alaska. Surveyed with compass, clinometer and tape September 1, 3 and 4, 2008. (unpublished)

Allred K, Allred C, Huestis J. 2008b. Cave map – Frosty Cave-Wrangell-Saint Elias National Park Alaska. Surveyed with compass, clinometer and tape August 30, 2008. (unpublished)

Bickley D. 2012a Ice formations in old road tunnel [Internet]. adn.com; cited 2014 April 24. Available from: http://www.adn.com/2012/04/24/2438295/ice- formations-in-old-road-tunnel.html

Bickley D. 2012b. Personal comment by email: "A few people have said that the ice in the old road tunnel stays there all year round, (…)." [received: 2012 April 27]

GeoPrecision [Internet]. 2014. Geoprecision.com; cited 2014 March 25. Available from: http://www.geoprecision.com/de/products- topmenu-45/funk-minilogger.html

Hollander Z, Theriault M. [Internet]. 2014. adn.com; cited 2014 January 29. Available from: http://www.adn.com/2014/01/29/3297289/still-no-opening-date-for-avalanche.html

NASA Earth Observatory [Internet]. 2014a. nasa.gov; cited 2014 April 27. Available from: http://earthobservatory.nasa.gov/GlobalMaps/view

NASA Earth Observatory [Internet]. 2014b. nasa.gov; cited 2014 April 27. Available from: http://earthobservatory.nasa.gov/blogs/fromthefield/2014/02/05/alaskapipeline

National Weather Service Climate [Internet]. 2014. nws.noaa.gov; cited 2014 April 27. Available from: http://www.nws.noaa.gov/climate/index.php?wfo= pafc

Snyder DK. 2013. Geography of South-Central Alaska: Explanations and Explorations of its Landscape. Anchorage (AK): Picea Geographics.

SCHELLENBERGER ICE CAVE (GERMANY): A CONCEPTUAL MODEL OF TEMPERATURE AND AIRFLOW

C. Meyer
Università di Milano-Bicocca
Piazza della Scienza 1
Milano, 20126, Italy, christiane.meyer@unimib.it

A. Pflitsch
Ruhr-University Bochum
Universitätsstrasse 150 / Building NA
Bochum, 44780, Germany,
andreas.pflitsch@ruhr-uni-bochum.de

D. Holmgren
Ruhr-University Bochum
Universitätsstrasse 150 / Building NA
Bochum, 44780, Germany,
david.holmgren@ruhr-uni-bochum.de

V. Maggi
Università di Milano-Bicocca
Piazza della Scienza 1
Milano, 20126, Italy, valter.maggi@unimib.it

Abstract
In this paper the primarily results of air temperature measurements from 2007 to 2013 are presented. The focus lies on the climatic description of the thermal conditions of the different ice cave parts and the related conceptual model of the airflow regime. The data will also show seasonal aspects of air temperature caused by the specific winter versus summer conditions. This basic data are the beginning for an interdisciplinary research project, which focuses on the microclimatological and glaciological processes and dynamics of the cave.

Introduction
Ice cave research as scientific discipline is run by scientists and layman since centuries in Europe (Grebe, 2010). In Germany caves were mainly subject to morphological and geological studies, but only little attention have been paid to the processes in ice caves so far. For this reason only very little information is available for processes and dynamics in German ice caves. For the first time ice caves in Germany are mentioned in the Harz Mountains near Questenberg by Behrens (1703). Later in the 19th century, especially the works by Fugger (1888, 1891-1893) and Lohmann (1895) presented ice caves to wider audience. Generally ice caves were and are known - in comparison to other classical ice cave countries like Romania, Slovakia, Slovenia, Austria, Italy, Russia etc. - only in a reduced number of places in the Central German Uplands (Harz & Eifel) and in the German Alps (Untersberg massif, Reiteralm, Hochkalter, Hohen Göll, Hagengebirge). While the ice caves at Untersberg in the Berchtesgadener Limestone Alps have been studied since the 19th century, most of the others were just discovered recently. In the Alpine karst area of Untersberg it is especially Schellenberger Eishoehle" (Fig.1), which was studied with longer breaks of several decades from the end of the 19th century till today.

In this paper we present the first results of our temperature measurements, which were started in autumn 2007. Due to limited access to the cave mainly from early summer to late autumn and the missing availability of electricity so far we mainly focused on the use of air temperature loggers in the different parts of the ice cave. However, the analysis of the data will show the thermal conditions of the cave and a primarily conceptual model also for the airflow regime of the cave. This temperature study is the beginning of a more interdisciplinary study on the dynamics and processes of Schellenberger ice cave. It is planned to use the results of this study with ice caves in different climatic conditions.

Site description
Untersberg (Germany) is an isolated mountain in the most Northern part of the Berchtesgaden Alps (Northern Limestone Alps) at the border between Austria and



Figure 1. *Location of Schellenberger ice cave. (© GoogleMaps).*

Germany (Fig. 1). The Northern part of the plateau is Austrian, the Southern German. Beside Schellenberger ice cave numerous other caves were explored on the plateau, the best known are the Riesending-Schachthöhle, Germany's longest (19.2 km) and deepest cave (-1148m) (Arbeitsgemeinschaft fuer Höhlenforschung Bad Canstatt e.V. 2014), and on the Austrian side the Kolowrathöhle (approx. -1100 m, approx. 38 km), which is possibly connected via a series of shafts to the deep non-ice parts of Schellenberger ice cave (Fig.2). Two passages of Kolowrathöhle are situated below Schellenberger ice cave, while one of them ends in a shaft. It is assumed that this shaft is in connection to those of Schellenberger (private communication Zagler, 2014).

Schellenberger ice cave (Fig.3) (total length: 3621 m, total depth ~260 m), which is run as show cave since 1925, is situated at 1570 m a.s.l. on the foot of the NE-walls of Untersberg (Verein für Höhlenkunde Schellenberg e. V., 2001).

The access to the cave is marked by a 4 m high and 20 wide portal, which leads to the largest room in the cave "Josef-Ritter-von-Angermayer-Halle" with a length of 70 m and a width of 40 m. The floor 17 m below the entrance level of this hall completely consists of an approx. up to 30 m thick and 60,000 m^3 ice block (Verein für Höhlenkunde Schellenberg e. V., 2001), which is surrounded by the show cave trail. Above the entrance hall the "Dohlenfriedhof" is situated - subdivided into two other floors. The two connecting parts Wasserstelle and Mörkdom are leading to the deepest point of the ice cave part, Fuggerhalle, 41 m below entrance level. From here only small fissures between the ice block and the rock give access to the deeper passages. The room below Fuggerhalle is called the "Max-Gadringer-Room", which could be reached last time before the last World War through the "Thomas-Eder-Schacht" (Verein für Höhlenkunde Schellenberg e. V., 2001), but is today filled with ice again. 12 m above the "Lehmgang" is situated, which ends after 30 m in a choke.

Apart from the approximately 500 m ice cave part there is one major non-ice part (Fig. 2), which leads at the Northeastern end through several deep shafts to the deepest point of the cave (-221 m).

Research history

The Schellenberger ice cave is probably known for centuries to the local population because of the big entrance

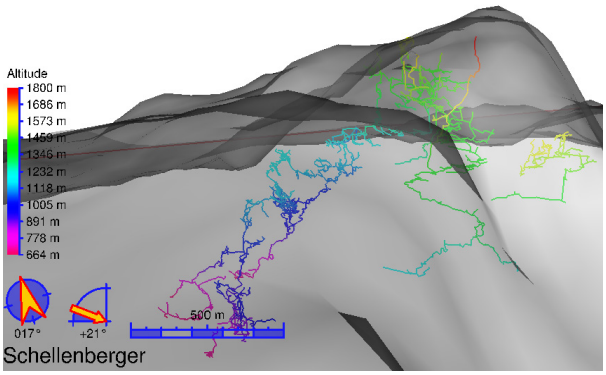


Figure 2. *Centerline plot of Kolowrat cave and Schellenberger ice cave at Untersberg - cave data (© Landesverein für Höhlenkunde Salzburg), graphic (© Arbeitsgemeinschaft für Höhlenforschung Bad Cannstatt e.V.).*

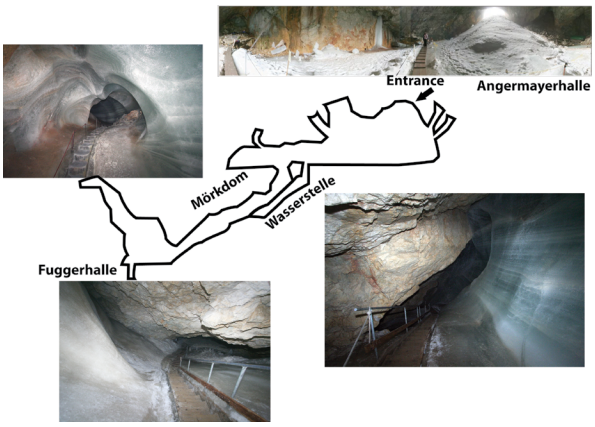


Figure 3. *Sideview of the ice part with pictures (pictures by Lars Bohg).*

portal and was first mentioned in 1826 in the Bavarian ordnance map as "Schellenberger Eisloch" (Vonderthann, 2005). After 1874 the cave was explored by several speleologists of the "Landesverein für Höhlenkunde Salzburg" and later on studied by Eberhard Fugger, who published some of the most important German ice cave publications of the 19th century. He started in 1869 with a study on the ice formations of the Kolowrat cave and worked later also in the Schellenberger ice cave, where he carried out numerous ice mass measurements from 1876-1882 (Vonderthann, 2005). Since 1925 the cave is run as a show cave and to this day carbide lamps only illuminate it, as there is no access to electricity in this part of mountains. The next decades from the 1940s to the 1980s were determined by the speleologist and long-term cave guide Fritz Eigert, who carried out ice-level measurements and a temperature monitoring till the end of his activities in the cave (Ringeis et al., 2008). Starting in October 2007 the authors conducted various long-term

and mobile measurements (Grebe et al., 2008). Long-term measurements include air temperature measurements at various sites in Schellenberger ice cave (see Fig. 4) and ice temperature at one spot in the big entrance hall. Mobile Measurements include among others measurements with thermal camera, mobile temperature measurements and a study on the ice mass changes. In this paper we only discuss the results of the long-term air temperature measurements and the ice temperature in order to describe the general thermal conditions of the ice cave. In summer 2013 we installed 32 new points for ice level measurements as prolongation the study of Fritz Eigert. The results of the other studies conducted in Schellenberger ice cave may be subject to future publications.

Methods

Air temperature was first measured inside the cave (Fig.4) starting from October 17, 2007 to November 7, 2013 in intervals of 10 to 15 min by using GeoPrecision data logger with PT 1000 sensors (precision ± 0,1 K, resolution 0,01°C). The specific points were chosen in order to represent the main parts of the cave and different heights starting from entrance level to the deepest point at Fuggerhalle. In the big entrance hall Angermayerhalle we selected two sites, one in the upper part close to the entrance and one at the lower end of the hall (cp. Fig. 4). The third measuring point is in the connecting passage to the lower parts of the ice cave, called Wasserstelle. The last was installed in the deepest part of the ice cave called Fuggerhalle. From June 2008 to October 2010 one temperature logger recorded also the ice temperature in Angermayerhalle. Unfortunately, somebody took out this logger without our knowledge so that we couldn't continue these measurements. In May 2011 a third logger was also installed temporarily in a separated section of Angermayerhalle for about 14 months, but we will not include these data in this paper. Figure 3 shows the different parts of the ice cave with pictures, where air temperature loggers were installed. Except the logger in Mörkdom, which is completely surrounded by ice and the one in the upper part of Angermayerhalle, which is outside the ice, the other sites of the loggers are situated in room or passages characterized by ice and solid rock.

Results and discussion

In this paper we would like to present primarily results of the air temperature measurements at Schellenberger ice cave to describe the common thermal conditions inside the cave. For the basic analysis we used the air

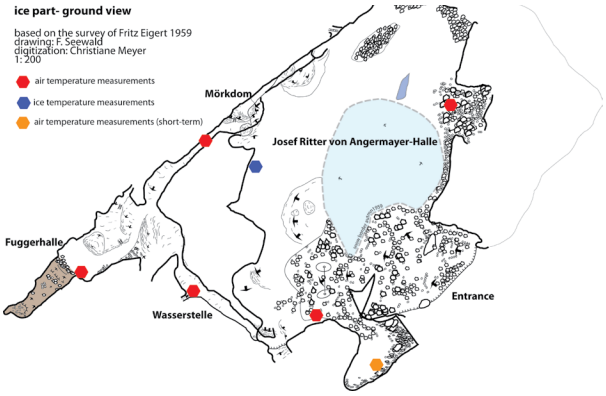


Figure 4. *Measuring points in the ice part of Schellenberger ice cave.*

temperature data recorded between 2007 and 2013. Schellenberger ice cave has only one main entrance (Fig. 3) leading to the deepest part of the cave - Fuggerhalle via a series of descending passages. Thus the cave acts like a cold air trap with thermal conditions throughout the year closely related to external climate variations. In winter conditions the cave follows the external temperatures changes during cold air inflow (Fig. 5), by contrast in the course of the summer conditions the cave air temperatures are mostly independent from external changes. In summer the cave (Fig. 6) temperatures are specifically influenced by the thermal inertia of the ice block, the slowly warming of the overcooled walls of the cave and the direct solar radiation in the entrance hall. Additionally the melting of the snow fan takes some energy away from warming up the cave. Between these two main periods a transition time with rapid changes between winter and summer conditions takes place in April and in November. As the various parts of the cave react divergent in the different seasons, we suggest to subdivide the cave into three different zones: the entrance hall Angermayerhalle upper part (AUP) and lower part (ALP), the connecting tunnels at Wasserstelle (W) and Mörkdom (M) and the deep part at Fuggerhalle (F), which all show unlike characteristics.

The first zone at Angermayerhalle is represented by two data loggers as already described in the previous parts of this paper. The average seasonal temperatures in the upper part vary between -1.8°C and -0.03°C in winter and 1.7°C and 3.8°C in summer. Although in winter the seasonal minimum temperatures can alternate between -6°C and -2°C, AUP is the warmest measuring spot in the cave (Fig.5). Data analysis showed that AUP has also the biggest longest delay during a cold air inflow

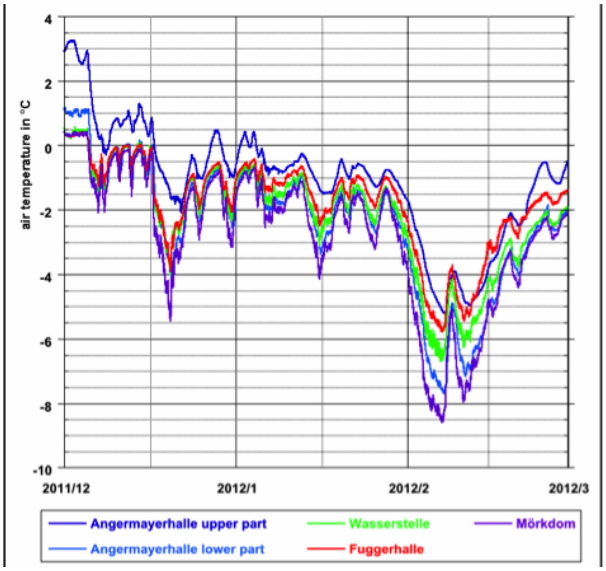


Figure 5. *Exemplary winter conditions at Schellenberger ice cave (here winter 2011/12).*

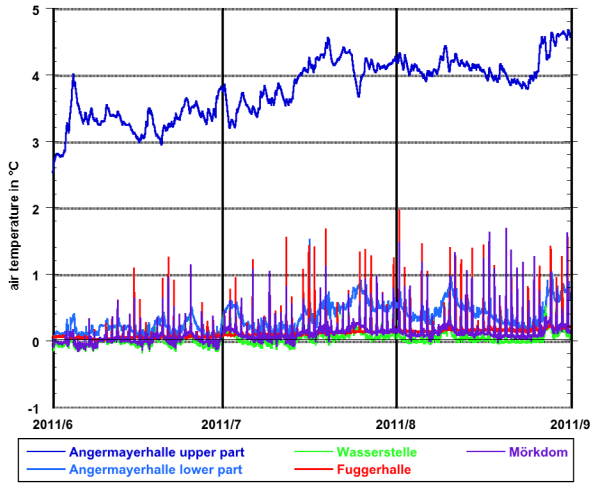


Figure 6. *Exemplary summer conditions at Schellenberger ice cave (here summer 2011).*

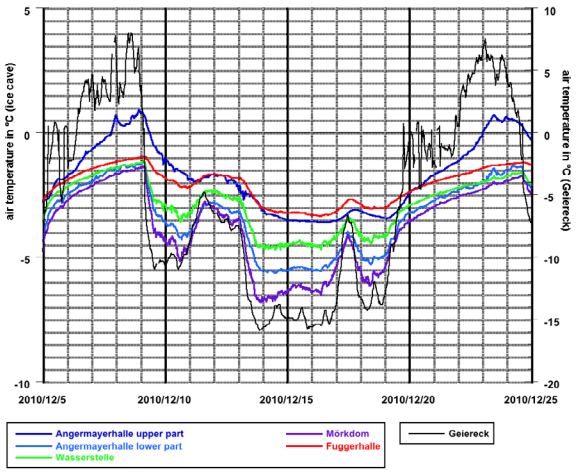


Figure 7. *Cold air inflow event during winter 2010: air temperature in °C inside Schellenberger ice cave and at outside station Geiereck (30 min interval).*

event (Fig. 7) accompanied by a strong damping of temperature signal. This may have two reasons, which need to be proved by further detailed studies. First, the position of the logger plays an important role.

Thinking about the way such a cold airflow takes a while entering the cave through the entrance portal, the logger at AUP is located offside of the cold air inflow. And second, the damping of the temperature signal may reasoned in the fact that we do not measure the inflowing cold external air but the specifically warmer flowing out air from the deeper cave passages, which already underwent a gradual warming during the traverse of the system. As well the sensor is located mostly above the inversion we could measure by mobile measuring campaigns. In summer the whole upper part of the entrance hall especially warms up peaking at maximum temperatures at AUP up to 4.8°C due to the influence due to the effect of the outside warming. Warmer wind is pushed in by turbulences in the entrance area and warmer rain and melting water invades the caves as well. It needs to be mentioned that the logger at AUP is not directly exposed to direct solar radiation.

Angermayerhalle lower part (ALP) in contradiction is the coldest spot of the ice cave during winter with average temperatures alternating between -3.4°C and -1°C and minimum temperatures of -6°C to -10°C. A possible reason for this fact is that the majority of the cold air inflow directly flows widespread over the snow pile into Angermayerhalle and flows more to the left side instead of Mörkdom, which has just a small opening.

During summer ALP the average temperatures show only small variations (taverage= 0.2°C - 0.4°C) as this spot is generally situated below the inversion line.

Wasserstelle and Mörkdom are representing the second zone. Here the dimensions of the passages are more tunnel like, though Wasserstelle is much higher and wider than Mörkdom. Both spots, located at the upper end of the respective cave passage, are slightly warmer than ALP in winter, peaking at minimum temperatures

of -8.3°C (W) resp. -8.6°C (M). Average temperatures underwent already a gradual warming on the rather short way through Angermayerhalle and alternate equally between -2°C to -3°C. In summer both measuring points show strong daily variations depending on the number of tourists visiting the cave (Fig. 6). Occasionally this leads to an interruption of the summer stratification. Thus, this difference in air temperature with the other measuring points triggers air movement between the deepest part (F) and Mörkdom resp. Wasserstelle. It can be assumed that the airflow follows the same way as under typical winter conditions.

The third zone, Fuggerhalle (F) shows the same characteristic with only small amplitudes during summer times. Here summer average temperatures vary between -0.03°C to -0.13°C, while maximum temperatures can peak at ≈ 2°C. Under winter conditions Fuggerhalle, though the deepest ice cave part is always warmer than the upper parts. This fact needs to be studied in further details in the future. Minimum temperature are then between -6.1°C and -2.3°C, maximum temperatures alternate between -0.4°C and 0.4°C. That shows that even under winter conditions with cold air inflow Fuggerhalle does not cool down as much as the upper parts of the cave, regularly reaching temperatures around the melting point. One reason is surely the gradual warming of the cold air inflow while its way through the whole cave. Another aspect, which we would like to study with airflow measurements, is a possible influence of chimney effects from of the deeper parts of the caves, which are connected just by cracks to the non ice-parts of the cave versus the deeper cave passages of the Kolowrat-System, which are assumed to be connected to the ice cave (cp. Fig. 3), too.

Conceptual Model of the airflow regime

The analysis of the air temperature measurements gives us also a first impression of the airflow regime inside the ice part of Schellenberger ice cave, which shall be validated by future airflow measurements. Thus we use for the primarily conceptual model only the air temperature measurement to extrapolate the air movements. Due to the fact that the cave has only one entrance, which is naturally open and not sealed by any door, the ice part mainly acts as a cold air trap depending on the external air temperature. In general the cave shows three main types of air exchange, a winter situation (Fig. 8) and a summer situation (Fig. 9) and the related transition period between the both extremes. The winter situation is limited to external temperatures below 0°C causing intensive inflow of cold air from outside into the cave caused by specific density differences mainly occurring from November to April. The cold external air flows currents through the whole entrance portal and then subdivides in Angermayerhalle into two subsequent streams, which are both directed to the deepest part of the ice cave, "Fuggerhalle". While the one stream current flows down the left side of "Angermayerhalle" through "Wasserstelle", the other stream equally descends to "Mörkdom" (cp. Fig. 8). At the crossing point of both passages, these streams reunite and descend further down until they reach the deepest part. The specific colder air replaces the warm air at the bottom and pushes it out along the ceiling towards the entrance of the cave into Angermayerhalle.

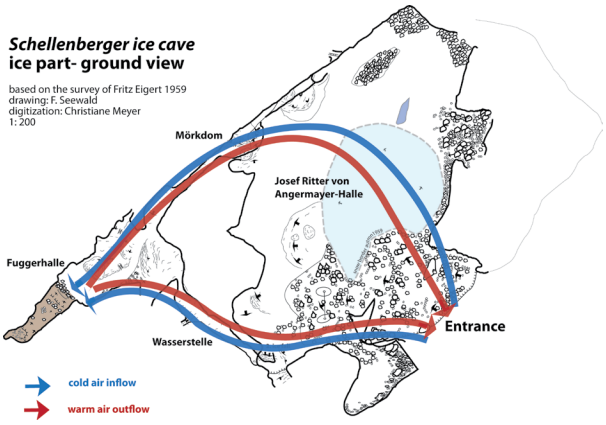


Figure 8. *Conceptual model of the winter airflow regime.*

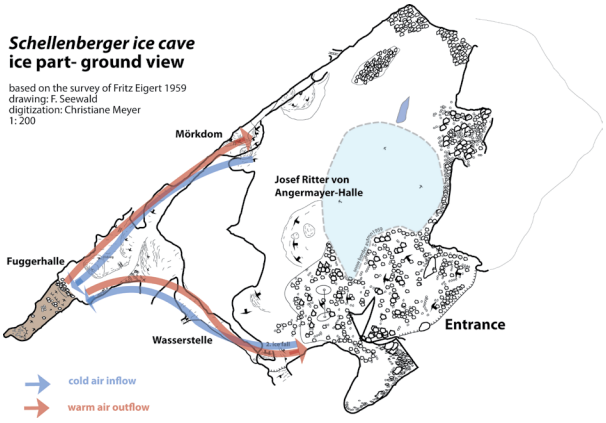


Figure 9. *Conceptual model of the summer conditions (with interruption of the stratification).*

For the warm outflowing air two possibilities exist: either a major outflow of warm air at Wasserstelle due the larger dimensions of this passage or the major outflow takes place at Mörkdom. For the second possibility the wavy structures and scallops at Mörkdom are a hint that this part might react like a chimney because it leads more direct to the higher surface in Angermayerhalle. In the transition period in April, when the external air temperature strongly varies around 0°C, the airflow regime is controlled by the changes between winter and summer conditions. In addition, the change between night and day is another factor that influences the thermal conditions, because nightly cold air inflow interrupts the stratification occasionally (Fig. 9), but also these short events don't stop the slowly warming of the cave (Fig. 8). With a delay of several weeks the cave reaches finally the summer static conditions with air temperatures around 0°C around May. From May to October air exchange between the internal and external air is severely limited and a distinct inversion develops, which vertical location alternates depending on the daytime and the external weather conditions. In the inner parts of the ice cave some small-scale until the first cold air inflow events around air movement can be suspected but need to be proved. October the ice cave remains in the summer condition and slowly transforms again to the transition period, before reaching the winter conditions finally around November.

Outlook

The presented results are the first step of a more interdisciplinary study on the dynamics and processes of Schellenberger ice cave. It is planned to work out the specific microclimatological characteristics in more detail in order to define the locality factors of the processes and dynamics. If possible, we will use the results of this study with ice caves in different climatic conditions. The central focus of this study is the interdisciplinary, for this reason we will also conduct a series of investigations on the processes and dynamics of the ground ice in Schellenberger ice cave.

Acknowledgements

Finally we would like to thank the members of Verein für Höhlenkunde Schellenberg e. V. for the close partnership, support and co-operation for this project in many ways. Furthermore we would like to thank Alexander Kranabetter and the environmental database of the Office of the Provincial Government of Salzburg, Department of Environmental Protection, for providing us free of charge air temperature, humidity and precipitation data of the outside station Geiereck at Untersberg free of charge.

References

Arbeitsgemeinschaft für Höhlenforschung Bad Cannstatt e.V. [Internet]. 2014. [Place of publication unknown]: www.lehmpfuhl.org; [updated 2014 January 10; cited 2014 April 20]. Available from: http://www.lehmpfuhl.org/Html/Forschung/Riesending/Riesending.html

Behrens GH. 1703. Hercynia Curiosa, oder Curiöser Hartz-Wald. Nordhausen (Germany).

Fugger E. 1888. Beobachtungen in den Eishöhlen des Untersberges bei Salzburg. Austria. Mitteilungen der Gesellschaft für Salzburger Landeskunde (MGSLK) 28: 65-164.

Fugger E. 1891. Eishöhlen und Windröhren. Austria. Separat-Abdruck XXIV. Jahresberichte der K.K. Ober-Realschule in Salzburg.

Fugger E. 1892. Eishöhlen und Windröhren. Zweiter Theil. Austria. Separat-Abdruck XXV. Jahresberichte der K.K. Ober-Realschule in Salzburg.

Fugger E. 1893. Eishöhlen und Windröhren. Dritter Theil (Schluss). Austria. Sechsundzwanzigster Jahres-Bericht der K.K. Ober-Realschule in Salzburg: 5-88.

2008:Study of Temperature and Airflow in the Schellenberger Ice Cave (Berchtesgadener, Limestone Alps, Germany) In: Proceedings of 3rd International Workshop on Ice Caves (IWIC-III), Kungur Ice Cave, Perm Region, Russia, 12. – 17.05.2008, S. 26-29.

Grebe C. 2010. Eishöhlenforschung vom 16. Jahrhundert bis in die Moderne -Vom Phänomen zur aktuellen Forschung [master's thesis]. Bochum (Germany): Ruhr-University Bochum.

Lohmann H. 1895. Das Höhleneis unter besonderer Berücksichtigung einiger Eishöhlen des Erzgebirges [dissertation]. University of Leipzig.

2008. Analysis of Ice Level Measurements in the Schellenberger Ice Cave in the German Limestone Alps. In: Proceedings of 3rd International Workshop on Ice Caves (IWIC-III), Kungur Ice Cave, Perm Region, Russia, 12. – 17.05. 2008, S. 48-52.

Verein für Höhlenkunde Schellenberg. 2001. Die Schellenberger Eishöhle im Untersberg. Berchtesgaden (Germany).

Vonderthann H. 2005. Die Schellenberger Eishöhle 1339/26 - Eine touristische Besonderheit des Berchtesgadener Landes. Berchtesgadener Alpen. Karst und Höhle 2004/2005 197-211.

ICE CAVE MONITORING AT LAVA BEDS NATIONAL MONUMENT

Katrina Smith
Lava Beds National Monument
PO Box 1240
Tulelake, CA, 96134, USA, katrina_j_smith@nps.gov

Abstract
Lava Beds National Monument contains lava caves with a variety of significant ice resources. Caves with seasonal melting of some ice resources provide an important source of water for wildlife within the monument and have had many historic uses over the past several decades. In other caves, perennial melting of previously stable ice floors is increasing, with some caves experiencing total ice loss where deposits were greater than 2 meters (6 feet) thick. Simple ice level monitoring has occurred in sixteen of the thirty-five known ice caves since 1990, supplemented with varying amounts photo monitoring. Though this monitoring reveals changes in the level of many ice floors, it does not detect changes in ice volume or differential changes across an ice floor (Thomas, 2010). To increase the quality of ice monitoring, Lava Beds staff are field testing and refining a combination of surface area and ice level measurements to estimate the change in volume of ice floors inside the five most significant ice caves within the monument. This new protocol is being established in accordance with the National Park Service Klamath Inventory and Monitoring Network's Integrated Cave Entrance Community and Cave Ecosystem Long-term Monitoring Protocol (Krejca et al., 2011). The goal of this long-term monitoring protocol is to document changes in cave environments using several different parameters, including ice.

Keywords
Lava cave, ice floor, ice melt, ice monitoring, management, National Park Service

Introduction
Lava Beds National Monument is located in northeastern California, approximately 250 km (155 mi) northeast of Redding, California and 75 km (47 mi) southeast of Klamath Falls, Oregon. Lava Beds lies at the convergence of the Sierra-Klamath, Cascade, and Great Basin geographic provinces and ranges in elevation from 1236 to 1685 m (4055 to 5528 ft). The climate of Lava Beds is considered high elevation semi-arid desert with warm dry summers and cool winters. For the period from 1991 to 2012, average annual high temperatures were 16°C (61°F) and average annual low temperatures were 2°C (36°F). Lava Beds received an average of 37 cm (14.5 in) of precipitation annually during this period, the majority of which was derived from snowmelt. The infiltration of this annual precipitation through the bedrock provides the source of water for ice floors and formations within lava caves in the monument; the water table lays hundreds of meters below the surface while the lowest known levels of ice caves are less than a hundred meters deep.

Lava Beds National Monument contains the largest concentration of lava caves in the contiguous United States; more than 700 caves have been identified (KellerLynn, 2014). Some are multilevel and contain significant seasonal or perennial ice deposits (Knox, 1959); currently, thirty-five caves are known to have varying accumulations of ice. Many of these caves served as a historic water source for Native Americans and early settlers, a rare resource in this high desert terrain. The ice inside these caves was also used for recreational purposes. In the early 1900s, a resort at Merrill Cave beckoned visitors to ice skate on the expansive ice floor inside the cave. Some of the ice caves and associated trenches and sinks were even used to operate liquor stills during Prohibition. Today, ice resources inside caves are protected within the monument, and are enjoyed by visitors all year round. Annual melting of some ice floors provides an important source of water for wildlife within the monument.

Melting of Cave Ice

Lava Beds caves contain both seasonal and perennial ice resources. Both types of ice deposits exhibit varying degrees of seasonal changes, with the highest levels of accumulation occurring in March-May and lowest levels occurring in November (Kern and Persoiu, 2013).

Caves that are highly connected to the surface via multiple entrances or shallow vertical development experience seasonal ice growth and melt (Fryer, 2007). Some, such as Indian Well Cave, contain ice formations that form each winter but melt completely in summer, while others contain various sizes of ice floors and formations that are frozen in winter but melt partially or completely in summer. The ice floor in Big Painted Cave annually experiences nearly full melting, with up to 61 centimeters (24 inches) of water present on top of the little to no ice that remains below. This seasonal melting is also often seen in a backcountry cave that contains a pool of water approximately 45 cm deep (18 in.); this pool freezes in the winter but melts by late spring and serves as a significant water source for birds, skunks, pika, woodrats, foxes, bears, cougars, and other thirsty wildlife (Fig. 1).

Other ice caves are not as well connected to the surface; many have only one entrance and exhibit multi-level development with passages more than 30 m (100 ft) deep. These caves act as cold air traps, stabilizing temperatures in the deep zone and allowing ice formations to develop and subsist year-round (Fryer, 2007). Unfortunately, these perennial ice deposits are experiencing significant melting events and subsequent ice loss. Currently, seven of the sixteen monitored ice caves have completely lost all ice resources, and five others are experiencing varying levels of declining ice deposits. Only four of the sixteen are stable or growing, and nineteen more have no record of monitoring.

Merrill Ice Cave experienced a total ice floor loss in the span of just nine years after a fist-sized hole appeared in the ice floor surface. Beneath this hole was a large void in the ice from which a strong draft blew, suggesting that a warm (relative to ice) air current had been at work beneath the ice for some time (Fuhrman, 2007). Speculation suggests a shift of rocks in a lower, inaccessible passage was the source of this airflow (Fuhrman, 2007). This ice floor abnormality was first noticed during monitoring activities by Lava Beds interpreters and the Cave



Figure 1. *Three young grey foxes (Urocyon cinereoargenteus) drink from the melted ice pool in a backcountry cave, while their mother waits nearby on the right (NPS photo).*

Research Foundation (CRF) in 1997 (Fuhrman, 2007). Frequent photo monitoring ensued and documented the rapid enlargement of the hole and subsequent degradation of the ice floor. By November 2000, only two-thirds of the ice floor remained, and by 2006, the main ice floor had completely disappeared (Fig. 2).

The level of the ice floor in Caldwell Ice Cave has shown a noticeable decline over the past 20 years, but has more recently shown a rapid trend of degradation similar to that of Merrill Ice Cave. During routine monitoring activities led by Lava Beds staff in March 2011, a 0.3 m x 0.6 m (1 ft x 2 ft) hole was discovered in the northwest end of ice floor where it met the cave wall (Fig. 3). This hole extended through the entire thickness of the floor, revealing the bottom of the cave passage 2.5 m (8 ft) below. Though no strong airflow is felt through this void, the hole has tripled in size in just three years, now measuring approximately 1 m x 2 m (3 ft x 6 ft). It seems likely that the ice floor will continue to melt away from the wall, exposing the cave passage below.

A different melting phenomenon has been observed in Crystal Ice Cave, which contains the most extensive ice resources of all ice caves within the monument. Warming temperatures in the upper levels of the cave led to acute melting of large ice floors in the upper levels of the cave, such as the Fantasy Room (Fig. 4), and subsequent refreezing of ice in lower levels of the cave, such as the Red Ice Room.

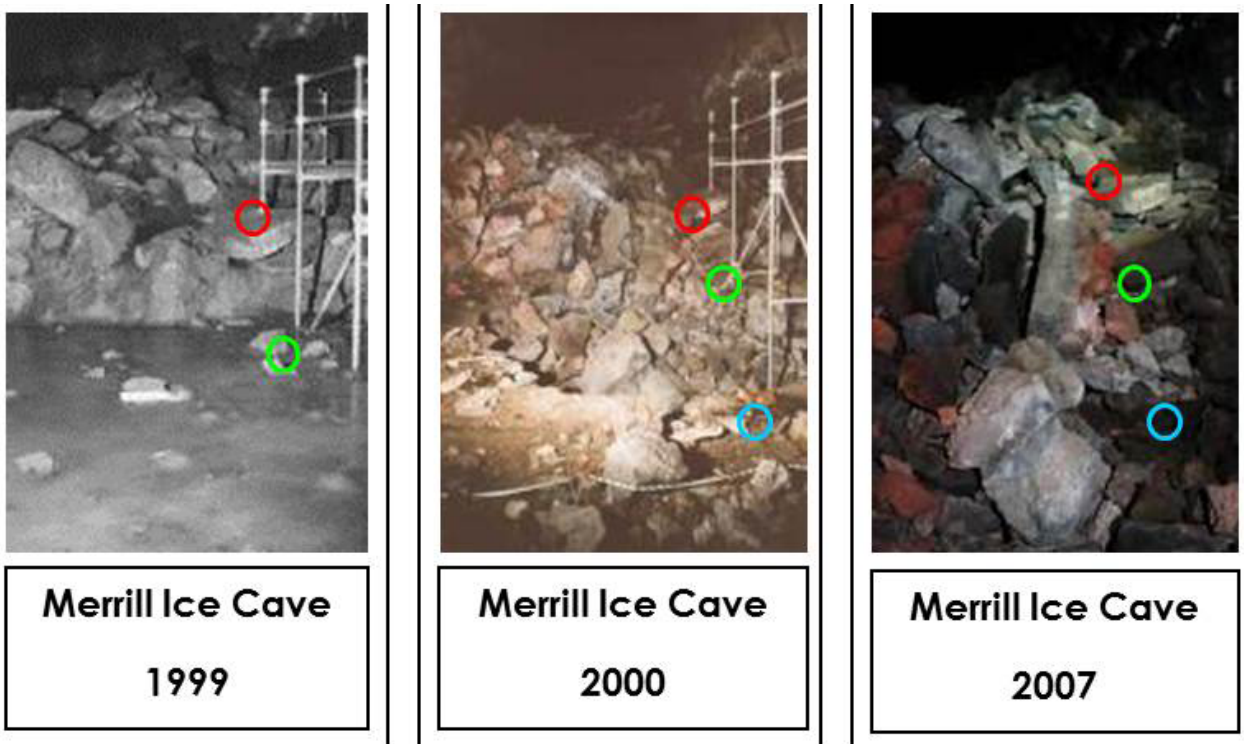


Figure 2. *Photo monitoring shows the precipitous loss of the ice floor in Merrill Cave. The catwalk was removed prior to 2007 due to destabilization (NPS photos).*

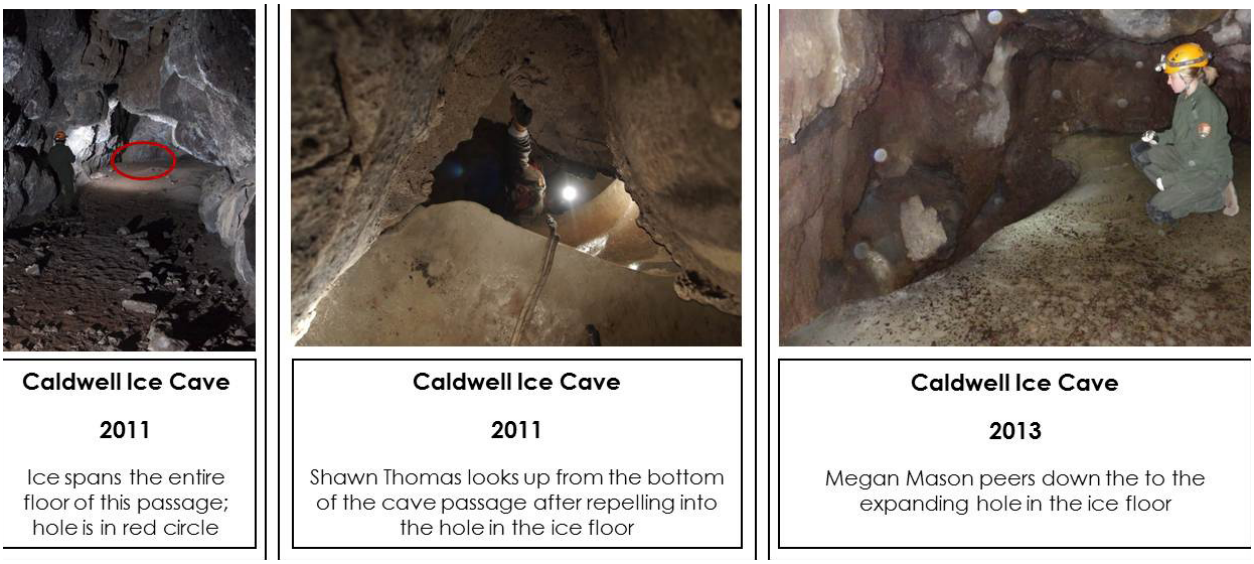


Figure 3. *A new hole appeared at the back of the ice floor in Caldwell Ice Cave in 2011 and has tripled in size in just three years (NPS photos).*

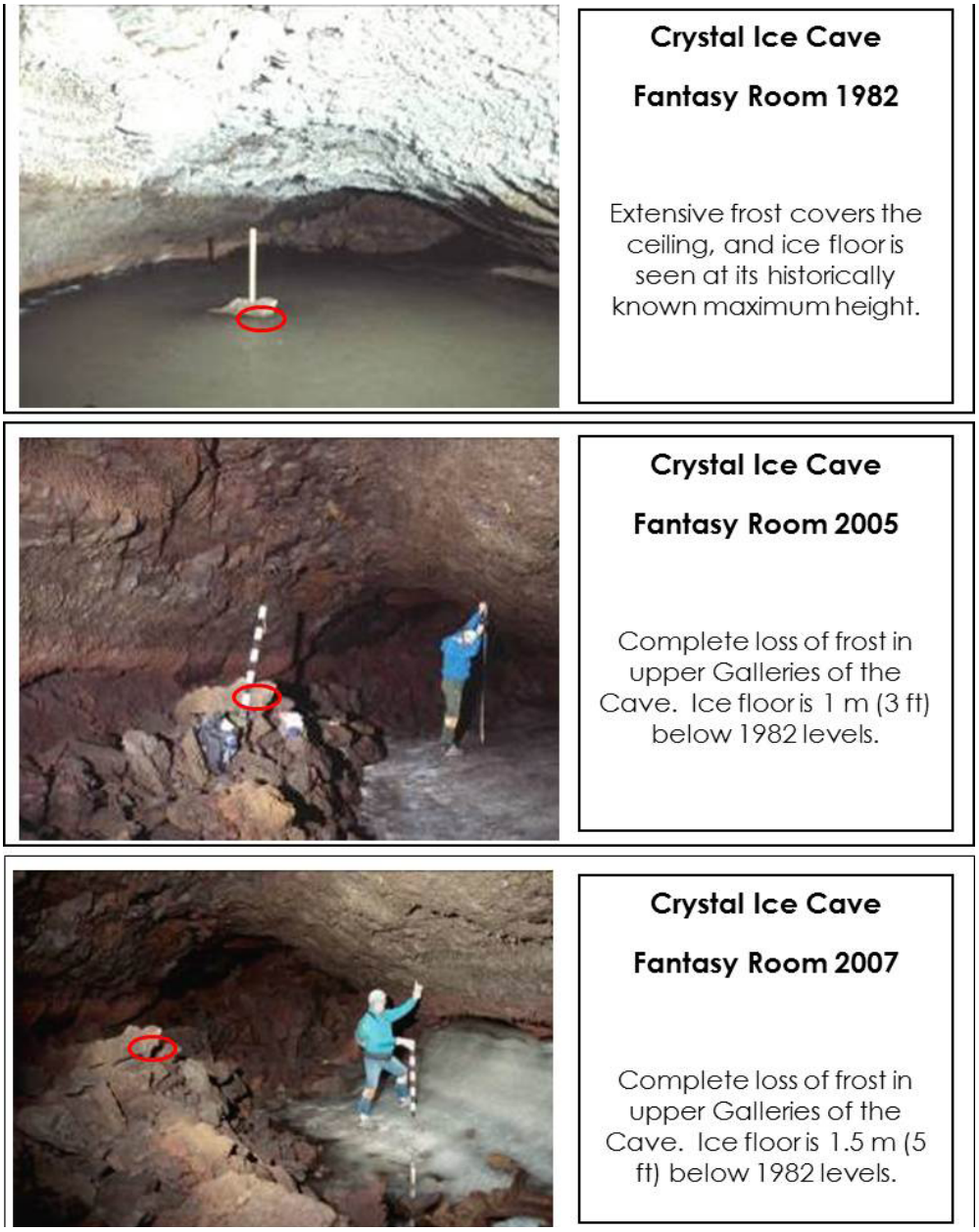


Figure 4. *Photo monitoring shows the loss of the ice floor in the Fantasy Room in the upper level Crystal Ice Cave (NPS photos).*

These trends clearly show the fragility of ice cave resources; because of this and the high resource significance of cave ice, Lava Beds management staff is committed to protecting and monitoring these sites as best as possible for the long-term future.

Historic Monitoring of Cave Ice

The earliest ice monitoring data within the monument goes back to 1982 in Crystal Ice Cave. Ice floor levels in fifteen additional caves have been monitored annually since 1990. The majority of this monitoring has been completed by volunteers of the CRF, predominately Bill Devereaux, Ed Bobrow, and Mike Sims, in association with Lava Beds National Monument. The simple and time-tested method used involves measuring the distance from a fixed point on the cave wall or ceiling above the ice floor, marked by a screw permanently inserted into the rock, to the surface of the ice floor. When water is

present on top of the ice, the depth of the water is also recorded. For simplicity and minimal resource impact to the cave wall or ceiling, each ice floor has only one or two monitoring sites. Cave temperature is recorded at designated sites within each cave during the monitoring visit.

On a smaller scale, some photo monitoring of ice deposits has occurred in a few ice caves. As with the quantitative data, the earliest and most extensive photo monitoring data goes back to 1982 in Crystal Ice Cave, and photo monitoring of the ice floor in Skull Ice Cave started in 1989. More recently, photo monitoring began in Caldwell Ice Cave when a hole appeared at the end of the ice floor in spring 2011. Other photo monitoring sites will be established and implemented as staff and volunteer time allows. As with the quantitative data, volunteers from the CRF completed the majority of the photo monitoring fieldwork, and Lava Beds is incredibly grateful for their assistance in monitoring this important resource.

Methods

Over the past several years, staff from Lava Beds have been assisting with the development of the Klamath Inventory and Monitoring Network's Integrated Cave Entrance Community and Cave Ecosystem Long-term Monitoring Protocol (Krejca et al., 2011). This protocol measures seven parameters: cave meteorology, ice and water levels, human visitation, entrance vegetation, bat populations, scat and organic material deposition, and cave invertebrates. Implementation will occur at both Lava Beds and Oregon Caves National Monuments. Thirty-one caves within Lava Beds were selected for inclusion in this protocol; five of these have significant ice resources.

The application of an extensive long-term monitoring protocol in caves is unprecedented within the National Park Service, and therefore has taken several years to develop and refine. In particular, the ice monitoring protocol is one of the last parameters to be refined, and field testing of methods is ongoing at the time of this publication.

In order to qualitatively assess the changes in ice floor volume within the five caves selected for monitoring, two different measuring strategies are being employed.

The first monitoring method establishes the level of the ice floor and is an extension of the ice level monitoring established in 1990 by the CRF. While their method has been able to show changes in ice levels over time, it leaves us unable to detect changes in ice volume or in differential changes across an ice floor (Thomas, 2010). The new method proposed by the long-term monitoring protocol uses transect methods similar to those commonly used in vegetation sampling. Permanent transects will be established across each ice floor, marked at each end with a screw in the cave wall. For data collection, a measuring tape will be pulled taught from one wall to the other, and the distance from the tape to the surface of the ice floor will be measured using a plumb bob and measuring tape or laser distometer. Depth of water, if any, will also be recorded. Each ice floor will have at least 20 transect points; the final number of points will be established by field technicians to strike a balance between ensuring adequate spatial coverage of the ice floor and minimizing of the number of transects and therefore permanent impact on the cave walls.

The second monitoring method establishes the area of the ice floor. A tripod will be placed in an area of the ice floor where the entire edge of the ice floor is visible, usually the approximate center of the ice floor. A Leica Disto D8 laser distometer will be attached to the tripod and used to measure the distance and inclination to the edge of the ice floor at 6 degree intervals. A total of 60 measurements will be recorded and will begin and end at one of the permanent transect screws in the cave wall. The distance, azimuth, and inclination from the tripod to this screw will be recorded, creating a fixed control point for the survey (Fig. 5). This eliminates the need for the tripod to be placed in the exact same location for each survey, a difficult task on ice floors that fluctuate through time (Thomas, 2010). Data collected will be processed in ArcGIS to obtain the area of the ice floor. Similar data processing has occurred with pilot study data (Fig. 6) using the lineplot program Compass. In this case data were collected for only 10 points, but rough characterization of the ice floor is still possible by connecting the ends of the lineplot.

Together, these two methods will allow us to monitor changes in ice volume across the expanse of each ice floor.



Figure 5. *NPS staff measure distance, azimuth, and inclination from the tripod to the permanent control point on the cave wall to begin an ice floor area survey (NPS photo).*

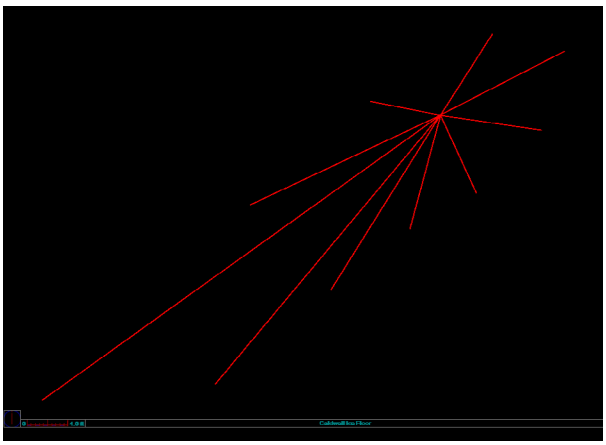


Figure 6. *Lineplot of the ice floor in Caldwell Ice Cave, taken in 2010. Tripod with survey equipment was stationed at the concentric center of the lines. A rough estimation of the ice floor area is given by connecting the ends of the lineplot.*

Conclusions/Outlook

Because field testing and implementation of monitoring methods is ongoing at the time of this publication, results are minimal and methods may change before the protocol is finalized. The goals of the protocol, however, will stay the same. Methods that are simple, repeatable, and yield high quality results about changes in ice volume over the long-term future are desired and will be implemented for many years to come.

References

Fryer S. 2007. The decline of ice resources within the caves of Lava Beds National Monument. Unpublished Report. National Park Service, Tulelake, California.

Fuhrman K. 2007. Monitoring the disappearance of a perennial ice deposit in Merrill Cave. Journal of Cave and Karst Studies 69 (2): 256-265.

Keller Lynn, K. 2014. Lava Beds National Monument: geologic resources inventory report. Natural Resource Report NPS/NRSS/GRD/NRR—2014/804. National Park Service, Fort Collins, Colorado.

Kern Z, Persoiu C. 2013. Cave ice – the imminent loss of untapped mid-latitude cryospheric palaeoenvironmental archives. Quaternary Science Reviews 67 (2013): 1-7.

Knox RG. 1959. The land of the burnt out fires Lava Beds National Monument, California, Bulletin of the National Speleological Society 21: 55-66.

Krejca JK, Myers III GR , Mohren SR, Sarr DA. 2011. Integrated cave entrance community and cave environment long-term monitoring protocol. Natural Resource Report NPS/KLM/NRR—2011/XXX. National Park Service, Fort Collins, Colorado.

Thomas SC. 2010. Monitoring Cave Entrance Communities and Cave Environments in the Klamath Network: 2010 Pilot Study Results. Natural Resource Data Series NPS/KLMN/NRDS—2010/XXX. National Park Service, Fort Collins, Colorado.

THE MONICA (MONITORING OF ICE WITHIN CAVES) PROJECT: A MULTIDISCIPLINARY APPROACH FOR THE GEOPHYSICAL AND PALEOCLIMATIC CHARACTERIZATION OF PERMANENT ICE DEPOSITS IN THE SOUTHEASTERN ALPS

Emanuele Forte
University of Trieste
Via Weiss, 1
Trieste, 34128, Italy, eforte@units.it

Renato R. Colucci
ISMAR-CNR
Viale R. Gessi, 2
Trieste, 34123, Italy, r.colucci@ts.ismar.cnr.it

Valter Maggi
University of Milano Bicocca
Piazza della Scienza 1
Milano, 20126, Italy, valter.maggi@unimib.it

Barbara Stenni
University of Trieste
Via Weiss, 2
Trieste, 34128, Italy, stenni@units.it

Marco Filipazzi
University of Milano Bicocca
Piazza della Scienza 1
Milano, 20126, Italy, marco.filipazzi@unimib.it

Doriana Belligoi
Regional Administration F.V.G.
Via Sabbasini, 31
Udine, 33100, Italy, doriana.belligoi@regione.fvg.it

Marco Basso Bondini
University of Trieste
Via Weiss, 2
Trieste, 34128, Italy, bassobondinimarco@gmail.com

Mauro Colle Fontana
University of Trieste
Via Weiss, 2
Trieste, 34128, Italy, collefontana.mauro@libero.it

Costanza Del Gobbo
University of Trieste
Via Weiss, 2
Trieste, 34128, Italy, costanza.delgobbo@gmail.com

Daniele Fontana
University of Trieste
Via Weiss, 2
Trieste, 34128, Italy, Fd.beo87@gmail.com

Abstract

On days 30 September and 1-2 October 2013, a 7.8 m long ice core has been extracted from a permanent ice cave deposit in the Southeastern Alps (Vasto's cave, Mt.Canin - Julian Alps). Each 20 to 100 cm long section of the ice core has been immediately stored in plastic bags and preserved thanks to dry ice. The ice samples, thanks to the helicopter,have been subsequently brought to the valley and promptly stored in a refrigerated van, made available by BoFrost. Thus the ice cores have been transported intact to the EUROCOLD laboratory in Milan. These operations have been carried out within the project MONICA (MONitoring of Ice within CAves) promoted by University of Trieste, Italy thanks to the "Finanziamento di Ateneo per progetti di ricerca scientifica-FRA 2012". The choice of the place where to extract the ice core has been selected after a dedicated high-resolution GPR survey performed on the surface of the ice deposit. This methodology allowed to visualize and avoid debris and boulders present in the ice deposit that could have damaged the tip of the ice driller. In this way it was possible to extract the longest core ever extracted in the Italian Alps in an ice cave. The ice core has been cut and stored thanks to the EUROCOLD facilities and a detailed full stratigraphic analysis has been realized. All the samples are now ready to be analyzed by using isotope geochemistry techniques (δ18O and δD), crystallographic analysis and C14 radiocarbon dating of organic materials. The preliminary



Figure 1. *One sector of the ice core just extracted from the Vasto ice cave. Photo courtesy Fabrizio Giraldi.*

results allow us to hypothesize the use of additional methods for a complete characterization of this very interesting potential paleoclimatic record.

BRIDGING THE WORK OF FIELD SCIENTISTS AND THE NEEDS OF DATA RE-USERS

Antonia Rosati
National Snow and Ice Data Center (NSIDC)
1540 30th Street
Boulder, CO, 80301, USA, toni.rosati@nsidc.org

Lynn Yarmey
National Snow and Ice Data Center (NSIDC)
1540 30th Street
Boulder, CO, 80301, USA, lynn.yarmey@colorado.edu

Abstract

The National Science Foundation requires Principal Investigators to make the data they collect and create publically available. To assist PIs with this requirement, NSF funded the Advanced Cooperative Arctic Data and Information Service (ACADIS). ACADIS houses data from the Division of Polar Programs (PLR), provides data management assistance to PIs, and advances search and data discovery tools. In short, ACADIS exists for NSF Arctic researchers by providing a safe home for data and encouraging data reuse.

ACADIS is a group of specialist organizations comprised to create a repository of Arctic data that encompasses spatial, temporal, and attribute granularity of data so that "big science" and "small science" may better integrate. The ACADIS project fosters scientific synthesis and discovery by providing services that make data from multiple disciplines freely available for access and analysis. ACADIS provides the arctic research community with data archival and data management services as well as value-added products to make the data more useful to more people. Essentially, the goal is to improve the usability and interdisciplinary re-use of arctic data.

But just putting a data file online is not useful enough. Many researchers and data providers understand their own data so intimately that it may seem that all the necessary information is contained in the file structure itself. This is clearly not the case with re-use. Placing the data and research in the greater scientific context is vital.

ACADIS is a far-reaching program that provides assistance with data submission, data preservation and data sharing services. This poster provides a brief description of these tools to permit a better understanding of the importance and the potentiality of ACADIS. These include pieces from each step of the research process - from proposal writing to meeting NSF requirements to maximizing citations.

ICE CAVES ON EXTRATERRESTRIAL BODIES: WHAT ARE THE PROSPECTS FOR SPELEOGENESIS AND DETECTION?

P. Boston
National Cave & Karst Research Institute
Carlsbad, NM, 88222, USA

New Mexico Institute of Mining & Technology
Socorro, NM, 87801, USA

Abstract
Potential mechanisms for creating cavities in icy extraterrestrial bodies have been tentatively explored by several authors. On one hand we have examples of mechanisms that create caves in water ice here on Earth. In addition, there may be unique mechanisms on other Solar System objects that do not occur on Earth but might produce cavities, e.g. sublimation of comets upon perihelion passage. The methods of detecting such cavities depend upon the nature of the icy body in question, the potential for orbital or landed missions to visit those bodies in the future, and remote or landed methods for detecting the presence of cavities and ways of interrogating them. Robotics, muon imaging, ground penetrating radar, and other techniques may be necessary in addition to high-resolution multispectral imaging. What are the prospects and what may we expect over the course of the next few decades from planetary exploration as it relates to extraterrestrial caves in ice?