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

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

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

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
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

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.

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 Malá Geoscience equipment connected with different shielded antennas (250, 500, 800 and 1600 mm). The equipment was set up in the entrance of the cave, and the GPR surveys were performed in a stepwise manner, with the antennas placed at different depths. The GPR data were then analyzed using a software developed by the authors, which allowed us to obtain a detailed picture of the ice and snow layers present in the cave.

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](image-url)

*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 decimetric clasts and debris entrapped in the upper part of the ice deposit.*
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 MHz 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 800 MHz 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.

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