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Ice genesis and its long-term dynamics in Scărişoara Ice Cave, Romania

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Abstract

The paleoclimatic significance of the perennial ice deposit in Scărişoara Ice Cave has been remarked since the early 20th century, but a clear understanding of the processes involved in the genesis, age and long-term dynamics of ice hampered all attempts to extract valuable data on past climate and vegetation changes. In this paper, we present a model of ice genesis and dynamics, based on stable isotopes, ice level monitoring (modern and archived) and radiocarbon dating of organic matter found in the ice. Ice in Scărişoara Ice Cave mostly consists of layers of lake ice, produced as liquid water freezes from top to bottom in mid-autumn, a mechanism that was also acting in the past, during the Medieval Warm Period and the Little Ice Age. The ice block is not stable in shape and volume, being continuously modified by ablation on top, basal melting and lateral flow. Radiocarbon dating shows that the ice block is older than 1200 years, the rate of ice flow and basal melting suggesting that the ice could be much older.

1 Introduction

Ice caves are a common feature of mid-altitude mountains in Europe, where a combination of cave morphology and local climate makes the perennial accumulation of ice possible. They were a rather underestimated subject for scientific research, with only a few of them (e.g., Dobsinšká Ľadová Jeskiňa, Kungur Ice Cave, Scărişoara Ice Cave) being investigated in more detail. Over the past decade, a series of studies have targeted ice caves as sources of paleoclimatic information (Citterio et al., 2004; Fórizs et al., 2004; Kern et al., 2004, 2009; Holmlund et al., 2005; Luetscher, 2005; Luetscher et al., 2007) and hence resurrected the interest in their study. Although promising, the paleoclimatic potential of the perennial ice in caves is hampered by the problems related to ice genesis, dynamics and age (e.g., Luetscher et al., 2007), as well as the way in which the climatic signal is being transferred from the exterior to the ice (e.g., Perşoiu et al., 2007).

In 2003, an ambitious paleoclimatic research program have been initiated in Scărişoara Ice Cave (Holmlund et al., 2005) which aimed to reconstruct the climatic and vegetation history of the area surrounding the cave, by analyzing various proxies found in the ice (oxygen and hydrogen stable isotopes, pollen, macrofossils etc). As with other ice caves, one of the main problems are the possible complications induced by the style of ice genesis and it's long-term dynamics, which could make impossible to use the present-day processes as analogues for past ones. In this respect, the aim of this paper is to review the processes related to the genesis of ice in Scărişoara Ice Cave, as well as to propose a mechanism for the initiation of ice accumulation and its long term dynamics, as a starting point for further paleoclimatic studies.

2 Site description

Scărişoara Ice Cave (700 m long, 105 m deep) is located in the Apuseni Mountains (Fig. 1), a massive, steep-sided mountain range in East-Central Europe, at 1165 m a.s.l.

The cave is carved in thickly bedded Upper-Jurassic limestones (Bucur and Onac, 2000), its entrance being located on the western wall of a circular shaft 60 m in diameter and 47 m deep, the bottom of which is covered by a perennial layer of snow. Beyond the entrance, the ice block with a volume of ~100 000 m^3 and area extent of 3000 m^2 forms the floor of the Great Hall, its vertical sides delimiting three distinct sectors of the cave: The Church, Little Reservation and Great Reservation (Fig. 1).

Towards the NW, the horizontal floor ends with a steep slope dipping 8 m toward the small "Church" Hall, with ice covered floor and over 100 perennial ice stalagmites. The Little Reservation is on the northern side of the Great Hall and can be entered by descending a 18 m vertical cliff, along which the ice stratification is visible. In the central part of the room, not far from the ice block, a field of ice stalagmites forms. The entrance to the Great Reservation is located on the southern side of the Great Hall. Within this part of the cave, the largest rooms are found (20 to 45 m wide and up to

20 m high). Here the ice forms a steep slope to a depth of 90 m below the surface and 43 m bellow the level of the Great Hall. On the horizontal bedrock floor in the central part of the Great Reservation is another field of ice stalagmites similar to the ones in the Little Reservation. In both Great and Little Reservations, a variety of calcite speleothemes developed, in the inner, non-glaciated parts of the cave.

The climate of the region is continental temperate, showing a strong influence of the westerlies. The mean annual temperature near the cave is ~6.5 °C, with the temperature (T) of the coldest month (January), and warmest (July) being around –9 °C, and 8.5 °C, respectively (Perşoiu et al., 2007).

The prevailingly western circulation of the air in the Apuseni Mountains causes very large precipitation amounts (over 1600 mm per year at Stâna de Vale, some 30 km to the NW) to fall on their western slopes, whereas on the eastern slopes the annual amounts are reduced by half (below 850 mm at Băişoara, ca. 35 km to the NE). In the area surrounding the cave, the mean annual precipitation varies around 1200 mm, with the highest values in spring and early summer months and the lowest values in October.

The mean duration of the interval when the snow layer is likely to exist is estimated to 150–180 days per year. Maximum values can exceed 1 m at the bottom of dolines, and 3–4 m at the bottom of the Scărişora Ice Cave's entrance shaft.

The climate of Scărişoara Ice Cave is the direct consequence of the external climatic variations and underground ventilation caused by the presence of a single entrance and mainly descendent passages (Onac et al., 2007). This peculiar morphology leads to cold air inflow inside the cave during winter months, triggered by the higher density of the cold external air masses compared to the warmer ones inside, while in summer, the same density difference prevents the exchange of air masses between the two environments.

Within the cave, Racoviţă (1984) distinguished four climatic zones: a transitional zone in the entrance shaft, a glacial zone comprising the area occupied by the ice block (Great Hall, The Church), a periglacial zone (Little and Great Reservation), and a warm climate zone in the non-glaciated parts of the cave (Coman Passage and Sânziana's Palace). The spatial repartition of these climatic zones is reflected by the thermal pattern of the cave: while in Great Hall the mean annual temperature is around –0.9 °C, it increases to –0.2 °C in the Great Reservation and 4.3 °C in the Coman Passage.

The air temperature has the greatest variations in the glacial meroclimate. During the periods with cold air inflow in winter (extending from late October to early April), the temperature follows closely the external climate evolution and may decrease below –15 °C. During summer, when aerodynamic exchanges with the surface cease, the underground temperature is independent from external variations, being influenced only by the thermal inertia of the ice block and the overcooled walls of the cave, rarely increasing above +0.5 °C (Racoviţă, 1994a).

Air circulation is one of the most important factors for ice dynamics in the cave. We can distinguish between two seasonal types of circulation: one occurring in summer and the other in winter. Between November and April, airflow triggered by the higher density of external cold air is directed from the surface downward into the cave. The inflowing cold ($T < -15$ °C) and dry (relative humidity <75%) air first reaches the Great Hall, from where it descends along the flanks of the ice block into the Little and Great Reservations, replacing the warmer air, which is pushed out along the ceilings. Between May and October, no air mass exchange occurs between the cave and the outside, as the cold air in the cave is denser than the external air. Meanwhile, the overcooled walls of the cave and ice block account for the persistence of cold air masses in the Great Hall, while the inner parts of the two reservations warm slowly due to the effect of geothermal heat. Thus, this difference in air temperature triggers a slow air movement between the Great Hall and the two reservations, the airflow following almost the same path as in winter. The difference is that the uprising warm air is progressively cooled as it reaches the walls of the Great Hall and sinks to the bottom of it, closing the convective cell. In April and October, rapid changes between summer and winter types of circulation occur as temperature varies around 0 °C.

3 Methods

The study had two aims: (1) to understand the present day mechanisms of cave ice formation, and (2) to develop a model of ice accumulation and long-term dynamics.

Between August 2004 and June 2005 and between August 2008 and January 2009, weekly observations and measurements of ice dynamics were carried out. Two shallow ice cores were drilled in January 2005 and 2009, containing ice formed in the previous months only. The cores were cut in six (core B, 2005) and, respectively five (core A, 2009) equal pieces, allowed to melt at room temperature, and then δ^{18}O and δ^{2}H were measured on the resulting water (see Perşoiu et al., 2010, for details of the analytical techniques). The results are reported in ‰ versus SMOW, the analytical precision (2σ) being better than 0.2‰ and 1.0‰ for oxygen and hydrogen, respectively.

In August 2006, eight samples of organic matter (*Picea abies* branches) were collected from the 18 m tall exposed wall in the Little Reservation, and radiocarbon analyzes were performed in the Gliwice Radiocarbon Laboratory, using the Liquid Scintillation Counting method on a Quantullus 1220 spectrometer (Pazdur et al., 2003). Calibration of the raw data was performed using the OxCal 3.10 software.

For the short-term ice dynamics data, we have used (1) our own measurements performed between October 2000 and July 2010; (2) the monthly (between April 1982 and December 1992) measurements of Racoviţă (1994b), and (3) older ice level data collected since December 1947 and reported by Racoviţă and Onac (2000) and Racoviţă (1994b). All these ice level measurements were performed in the Great Hall (Fig. 1), where the distance between the ice surface and the overhanging rock wall was measured, the data thus reflecting the summed dynamics at both the upper and lower parts of the block. In order to distinguish between the two, a secondary data sets was obtained, by measuring the ice level changes against the 1982 level on a 50 cm-long line, which was inserted in the ice in April 1982. By subtracting the two data sets, it was also possible to calculate a second order parameter, i.e., the rate of melting at the sole of the ice block (Perşoiu, 2005).

4 Results and discussions

The results of ice dynamics measurements, presented in Fig. 2, show a strong ice loss between 1947 and 1980, followed by a period of relative stability with ice build-up in the mid-80s and in 2006 and 2010. Melting at the base of the ice block was determined for the 1982–1992 observational period, being relatively constant, at a rate of about 1.5 cm/year (Perşoiu, 2005).

The results of the radiocarbon dating are shown in Table 1. The upper part of the ice block, as well as the lowermost one (ca. 10 m bellow the lowermost dated horizon) was not dated, due to lack of organic matter in the ice.

The stable isotope values of ice of the short ice cores drilled in the upper face of the ice block are shown Fig. 3. A clear trend of isotopic depletion with depth is displayed for both cores, due to the preferential incorporation of the heavy isotopes in the forming ice (Jouzel and Souchez, 1984; Perşoiu et al., 2010).

4.1 The mechanism of ice formation

Most of the previous work in Scărişoara Ice Cave (Racoviţă, 1927; Şerban et al., 1948; Racoviţă and Onac, 2000), as well as other places (Luetscher, 2004) explained the formation of ice as a polygenetic processes, where both freezing of ice and diagenesis of snow interplay to form each year a new layer of ice. The snow that accumulates at the bottom of the entrance shaft to Scărişoara Ice Cave is only 1–3 m thick, not enough to allow compaction under its own weight to form ice. Moreover, the reduced thickness of the snow pack allows percolating water (from melting snow and summer rains) to reach the bottom of it quickly, without freezing. The freezing of water inside the snow pack is also prevented by the higher than 0 °C temperatures of the air at the bottom of the shaft from ca. mid-April through November (Racoviţă, 1994a). Most of the snow at the bottom of the shaft melts and drains away through impenetrable fissures, with only occasional inflow towards the ice block.

Observations during that past 10 years have shown that the ice block is build-up by ice formed by in-situ freezing of water. This is a multi-stage processes, with two types of ice (Perşoiu et al., 2010) being formed during the accumulation season, lasting between mid-September (earliest) and early-June (latest). In mid-autumn, under the influence of cold air sinking inside the cave, a shallow lake that accumulates during the melting season starts to freeze from to bottom, to form a ca. 10–15 cm thick layer of ice. On top of this layer of so-called "lake ice", thinner layers of ice (termed "floor ice") could form during the winter, when warmer and wetter weather leads to water infiltration inside the cave, and its subsequent freezing in the over-cooled environment. Thus, at the end of the accumulation period, the newly formed layer of ice is composed of two entities: lake ice at the bottom, formed in mid-autumn, and floor ice on top, formed in warmer winter periods. Beginning with mid-April, melting begins, the main driver of it being the infiltration of warm precipitation waters (Perşoiu, 2004) that lead to a rapid ablation of the upper face of the block. By mid-summer, most of the floor ice is melted and the resulting water drained away through a narrow channel carved in the ice. Reduction of precipitation amount in the summer months (Orăşeanu and Varga, 2003) stops the melting and the drainage channel quickly fills up with ice, and thus proper conditions develop for the accumulation of a new lake, which will freeze in the next autumn.

This model of ice genesis is further supported by stable isotope data (Fig. 3). The two ice cores were extracted at the end of the lake ice formation phase, and the δ^{18}O and δ^{2}H data shows an evident decreasing trend from top to bottom. This trend could only be explained by the formation of ice through a downward freezing process, in which the heavy isotopes of O and H are preferentially incorporated in the ice, leaving the remaining water strongly depleted (Jouzel and Souchez, 1982; Souchez and Jouzel, 1984). A similar trend of ^{18}O- and ^{2}H-depletion has been found in ice layers that were dated to 730 ± 70 cal yrs BP and 400±100 cal yrs BP, hence showing that ice formed in a similar way both during the Medieval Warm Period and the subsequent Little Ice Age. Moreover, stable isotope analysis (Žák et al., 2008) of cryogenic cave calcite

(CCC) found at the bottom of the cores revealed extremely high values of δ^{13}C (up to +12‰$_{\text{PDB}}$), typical for calcite formed during fast freezing of water (Žák et al., 2004, 2008). Similar values (up to +9‰$_{\text{PDB}}$) were found in ice layers formed during the MWP and LIA, further supporting the genesis of ice by the freezing of water also under different climatic conditions.

4.2 Ice dynamics

On an annual cycle, the dynamics of the upper face of the ice block shows a cyclic behavior, with a maximum in late spring and a minimum in late summer (Racoviţă et al., 1987; Racoviţă, 1994b). Longer-term trends are superimposed on this annual cycle, under the influence of external temperature and precipitation amount, with the warmer, but drier summers (e.g., 2006 and 2010) and warmer but wetter winters (e.g., 2005–2006 and 2009–2010) leading to less melting and more ice accumulation (Fig. 2). The wet summers of 2005 and 2009 led to a rapid ablation of the ice, while the colder and drier winters between 2001 and 2003 did not allow for much floor ice build-up. This pattern follows that of the past ca. 60 years (Fig. 2), with periods of ice build-up corresponding to drier summers and generally colder years, and periods of ablation during wetter and/or warmer years (Racoviţă, 1994b).

The accumulation of the perennial ice block in Scărişoara Ice Cave must have started after the collapse of the passage that was linking the cave with Pojarul Poliţei Cave, passage that was allowing free circulation of air through the cave and thus preventing its overcooling. Seasonal ice could have been formed before this collapse, but it was possibly melting away in the summer season, under the influence of air circulation, as seen in numerous two (or multiple) entrance, descending caves in the area. Ice could have started to accumulate during the last glacial, as Onac and Lauritzen (1996) have shown that dripping water was available inside the cave some 55 kyrs ago (based on U/Th dating of stalagmites from the cave), but the survival of such old ice is improbable, as basal melting is high enough (see above) and the ice must have melted away.

We consider that the inception and accumulation of ice in the cave must have followed the scheme in Fig. 4, with considerable fluctuations between the main stages, under both external (climatic) and internal (ice flow) controllers.

The first (semi) perennial ice that accumulated inside the cave (Fig. 4a) changed the cave's own climate, its melting over the summer consuming all the heat delivered to the cave by conduction (through the air column in the entrance shaft and the rock walls) and dripping water, as well as by the geothermal heat, thus maintaining the temperatures at 0 °C. A positive feed-back loop was established inside the cave and ice started to grew rapidly, the ever increasing (in steps) ice volume (Fig. 4b) helping to keep the temperature at 0 °C for longer time. Şerban et al. (1948) suggested that ice at one time filled in completely the cave, leaving the innermost sections of it out of the reach of inflowing cold air. Thus, they have proposed that melting started in the isolated parts of the cave, leading to the retreat of the ice from the walls and the subsequent formation of the ice cliffs towards the Little and Great Reservation (Fig. 4c). Thus, the ice block must have reached the shape of a pyramid trunk, with flat surface (formed by the freezing of lake water) and vertical (or inclined) lateral walls (formed by the retreat due to melting). Visitors to the cave in the 19th century (Schmidl, 1863) noticed the horizontal surface and the opening towards the Great Reservation only; that towards the Little Reservation being sealed off by ice coming in contact with the rock wall. Following the warming after the end of the LIA (post 1880) the ice started to recede (both from bellow and from top downwards, Fig. 4c) so that by 1947, the opening towards the Little Reservation was visible (Şerban et al., 1948). An exceptionally fast melting occurred between 1947 and 1963 (Fig. 2), when the upper face of the block lowered by ca. 75 cm, possibly due to the opening of the entrance towards the Little Reservation (Fig. 4d), which led to rapid loss of water that otherwise would have froze to build-up ice.

The accumulation of ice was not continuous, nor was the ice block stable. The layering of the ice block (Fig. 5) is an indicator of the lateral flow of the ice, towards the walls. The fold visible in Fig. 5b must have formed as ice was flowing to fill in the empty space remaining as it was retreating from the walls. Monitoring over the past 10 years have shown that the ice is flowing with a velocity of about 3 cm/year from east to west, towards the direction of the fold. Two conspicuous layers of organic matter are visible at the two ends of the exposed wall, the middle of it being covered by ice formed after the opening of the entrance at the upper face of the ice block (Fig. 4d). Both layers were formed in the middle to late MWP, most probably as enhanced melting led to the merging of a series of annual layers, a possibility already mentioned by Şerban et al. (1948) and Pop and Ciobanu (1950). The accumulation rate during the MWP, calculated based on the SCL1, SCL2 and SCL 3 radiocarbon ages was between 0.9 and 1.6 cm/yr, similar to the modern one (1.3 cm/yr, based on data from 1982 to 2010). Following the end of the MWP and during the LIA, the accumulation rate remained unchanged, the possible lower accumulation during the colder winters (less water available) was being compensated by less melting in the colder summers. This constancy of the accumulation rate during different climatic conditions is due to the complex interplay between the climatic factors that control the dynamics of ice, i.e. wet vs. dry summers and/or winters and cold vs. warm summers and/or winters. As seen above, a cold but dry winter will led to less ice accumulation as a warmer, but wetter one, while a warm but dry summer will lead to less melting than a cold, but wet one. As a consequence, the possibility of extracting a good climatic signal from the various proxies in the ice (stable isotopes, pollen) is very promising, provided that more dating is performed. All radiocarbon ages are in correct stratigraphic order, except for sample SCL 8, which was collected from the disturbed section of the wall (Fig. 5b). Here, the melting at the base of the ice block led to lateral flow of the ice in the middle and lower sections of the block, while the presence of the rock wall prevented flowing in the upper part, hence leading to the development of the fold. Based on radiocarbon dating on this section, ice thickness measurements and geothermal flux values (normal for the area, as suggested by Demetrescu and Andreescu, 1994), Holmlund et al. (2005) give an age of about 2000 years for the onset of the folding. The presence of the fold, as well as present day measurements of ice dynamics (see above), show that basal

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melting does occur at the base of the ice block. However, the inclined layers of ice visible on the side of the ice block, as well as the stratigraphy of an ice core extracted from the middle of it (Holmlund et al., 2005) suggests that this melting is not uniform, and that it's only acting at the sides of the ice block, where geothermal heat is delivered to both the sole and the sides of the it. Moreover, ice temperature measurements at the base of the bore hole drilled in 2003, both at the time of drilling and the years after, show that temperature was constantly bellow −2 °C, hence preventing melting at this point. Consequently, we suggest that basal melting occurs only near the sides of the ice block, thus leading to a slow lateral flow and subsequent thinning of the layers in the middle area of it. It would be than possible that ice at the base of the ice block in its middle part could be much older than on its side, reaching back in time towards the mid to early Holocene.

5 Conclusions

Ices forming processes and long-term dynamics of ice in Scărişoara Ice Cave have been investigated. Ice in the cave forms by the freezing of water in a two-stage process, one in mid-autumn and one lasting from early winter to late spring. Following the melting period in summer, the upper layers of ice are melted away, thus the ice block being build up by ice formed in autumn, hereafter called “lake ice”. The same process was acting under different climates over the past ca. 1100 years, both during the MWP and the subsequent colder LIA. Presently (and at least over the past 30 years), the ice block is in a steady state, melting and/or low accumulation rates in unfavorable years (wet summer, dry winters) being compensated by strong accumulation and/or less melting under favorable conditions (dry summers, wetter winters). Basal and lateral melting have altered the horizontal layering of the ice, but at the same time, allowed for older ice to be preserved in the middle part of the ice block. The age at the base of the ice block could not be directly determined (yet), but based on the rate of ice melting at the base and the already determined ages (this study and Pop and Ciobanu

(1950) who give an age of about 3500 years at 15 m bellow the surface) we estimate that the ice block could be older than 5000 years.

The interplay between melting and accumulation must have destroyed the annual layering of the ice block, but the presence of ice from different types of climate (the warmer MWP and colder LIA, see Johnston et al., 2010) gives us promising perspectives for paleoclimatic reconstructions using the various proxies trapped in ice (stable isotopes, pollen, macrofossils etc.).

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Table 1. Results of the radiocarbon analysis of samples collected from Scărişoara Ice Cave.

Sample name	Age ^{14}C (BP)	Depth bellow surface (cm)	Calibrated age range 68%	Calibrated age range 95%
SCL 8	495±45	901	1405 AD–1450 AD (68.2%)	1310 AD–1360 AD (11.1%) 1380 AD–1480 AD (84.3%)
SCL 7	265±65	1005.5	1490 AD–1680 AD (58.0%) 1770 AD–1800 AD (7.6%) 1940 AD–1960 AD (2.6%)	1450 AD–1850 AD (89.5%) 1900 AD–2000 AD (5.9%)
SCL 6	330±50	1125.5	1490 AD–1640 AD (68.2%)	1450 AD–1650 AD (95.4%)
SCL 3	800±50	1262.4	1185 AD–1200 AD (3.6%) 1205 AD–1275 AD (64.5%)	1050 AD–1080 AD (2.2%) 1150 AD–1290 AD (93.2%)
SCL 1	890±45	1354.4	AD 1048 (22.7%) AD1087 AD 1123 (8.4%) AD1138 AD 1150 (37.1%) AD1212	AD 1027 (95.4%) AD1225
SCL 2	1000±50	1467.4	AD 986 (43.6%) AD1048 AD 1087 (18.8%) AD1123 AD 1138 (5.8%) AD1150	AD 899 (3%) AD919 AD 952 (92.4%) AD1162
SCL 5	820±70	1571	1150 AD–1280 AD (68.2%)	1040 AD–1290 AD (95.4%)
SCL 4	810±130	1682.4	1040 AD–1100 AD (13.8%) 1110 AD–1290 AD (54.4%)	980 AD–1410 AD (95.4%)

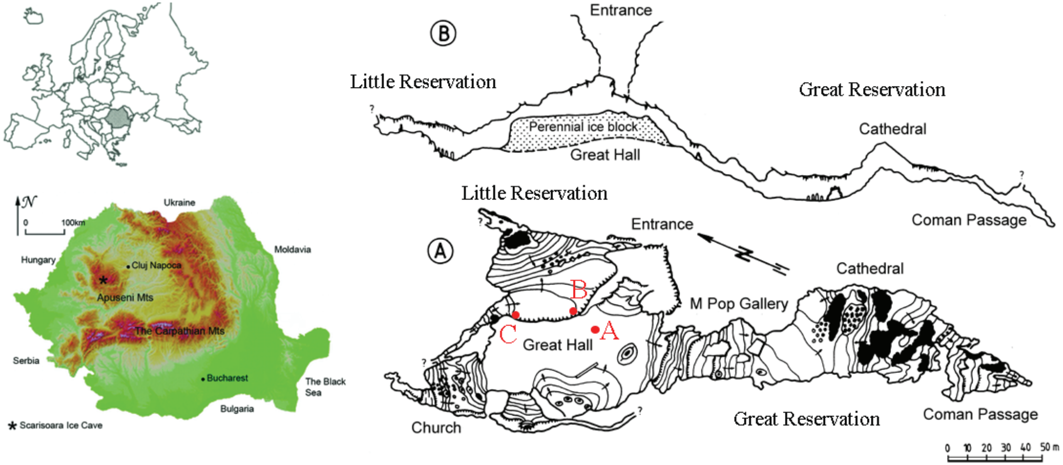

Fig. 1. Location map, plan view **(A)** and cross section **(B)** of Scărişoara Ice Cave. The red points mark: A – position of the cores drilled in 2005 and 2009, B – position of SCL1, SCL2 and SCL 3 samples for radiocarbon dating, C – position of SCL4, SCL5, SCL6, SCL7 and SCL 8 samples for radiocarbon dating.

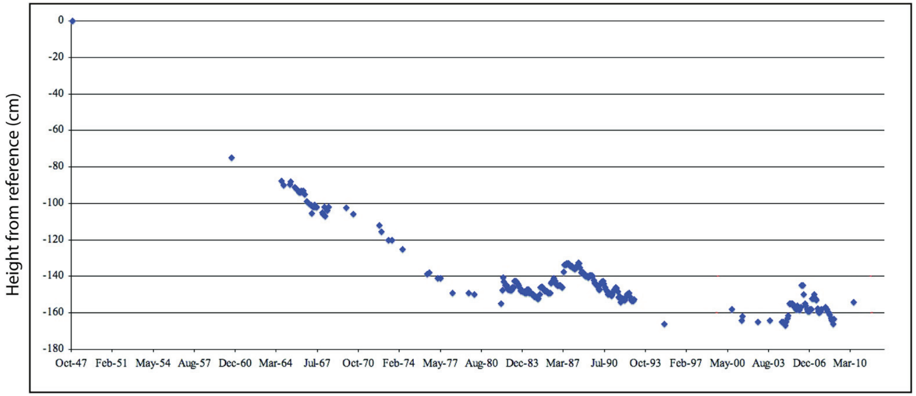

Fig. 2. Short-term dynamics of ice in Scărişoara Ice Cave (modified from Racoviţă, 1994b).

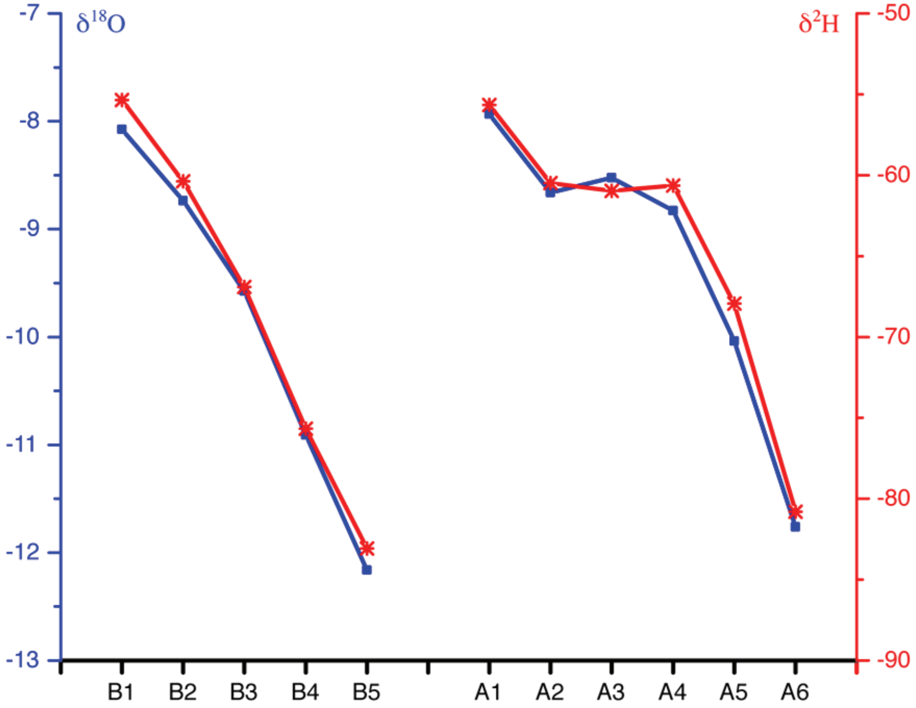

Fig. 3. δ^{18}O (red line and left axis) and δ^{2}H (blue line and right axis) profiles in two short ice cores (A drilled in 2009, and B drilled in 2005) drilled on top of the ice block in Scărişoara Ice Cave.

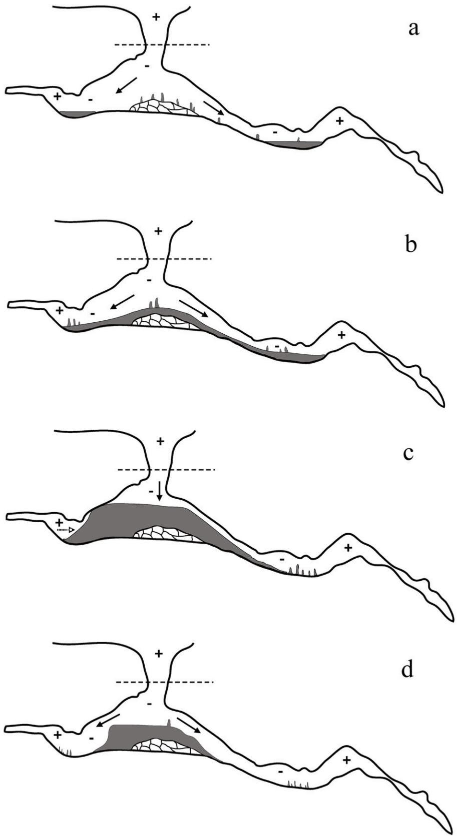

Fig. 4. A conceptual model of the genesis and long-term dynamics of the ice block from Scărişoara Ice Cave (see text for details).

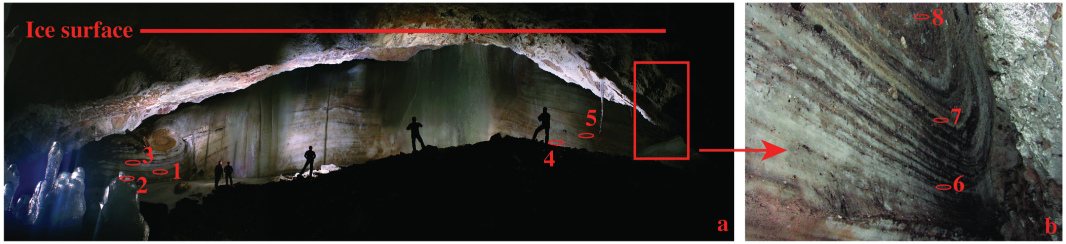

Fig. 5. The exposed wall of the ice block as seen from the Little Reservation, with the position of radiocarbon ages shown.

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