

# Topoclimatic Zones and Ice Dynamics in the Caves of the Northern Yukon, Canada

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**ABSTRACT.** In the upper basin of the Porcupine River, the subhorizontal caves of Bear Cave and Tsi-it-toh-Choh mountains are characterized by a very rich ice zone. The authors propose a model for the build-up of ice based on the formation of hexagonal ice sublimation crystals on the cold walls of underground passages. In this model, water freezes and thaws many times, causing a series of different forms from the ceiling to the floor of the caves. This process will sometimes provoke total obstruction of a passage due to particular topoclimatic conditions or a change of climate, notably an increase in atmospheric humidity. During the summer the passage where the ice is located is preceded by a warm and humid passage and is followed by a cold and extremely dry passage, in which are preserved fragments of wood, animal faeces and remains of small mammals.

**Key words:** Yukon, Porcupine River, Bear Cave and Tsi-it-toh-Choh mountains, caves, climate, cave ice

**RÉSUMÉ.** Dans le bassin supérieur de la rivière Porcupine, les cavernes subhorizontales des massifs de Bear Cave et de Tsi-it-toh-Choh possèdent une zone très riche en glace. Les auteurs proposent un modèle de l'édification des glaces à partir de la formation de cristaux sur les parois froides des galeries. Dans ce modèle, l'eau gèle et dégèle à plusieurs reprises, provoquant une série de formes différentes, du plafond au plancher des galeries. Il arrive que le processus aboutisse à l'obstruction totale de la galerie à la suite de conditions topoclimatiques particulières, ou d'un changement de climat, notamment d'une augmentation du taux d'humidité atmosphérique. La zone des glaces est précédée en été d'une zone chaude et humide, et elle est suivie d'une zone froide et extrêmement sèche dans laquelle sont conservés des morceaux de bois, des déjections animales et des cadavres de petits mammifères.

**Mots clés:** Yukon Rivière Porcupine, massifs de Bear Cave et de Tsi-it-toh-Choh, cavernes, climat, glaces de cavernes

**РЕЗЮМЕ:** В верхнем бассейне реки "Дикобраз", подгоризонтальные пещеры под "Бер Кэйв" и "Тси-ит-то-Чо" характеризуются очень большой зоной льда. Авторы предлагают модель для развития льда, основанную на образовании сублиматических кристаллов на холодных стенах подземных туннелей. В этой модели, вода замораживается и растапливается много раз, вызывая серию разных форм с потолка до пола пещер. Этот процесс иногда провоцирует полное заграждение туннеля из-за особых топоклиматических условий, или изменение климата, а особенно увеличение атмосферной влажности. Летом, этот туннель в котором находится лёд, предшествует тёплой и влажной туннелю. После этого, этой туннели следует холодная и очень сухая туннель, в которой находят обломки дерева, остатки животных и маленьких млекопитающих.

**Важнейшие слова:** Юкон, река Дикобраз, "Бэр Кэйв" и "Тси-ит-то-Чо" горы, пещеры, климат и пещеры льда

## INTRODUCTION

The caves in which ice accumulations are found are situated on the limestone mountains of Bear Cave and Tsi-it-toh-Choh (Fig. 1), in the basin of the upper Porcupine River on the Arctic Circle (Cinq-Mars and Lauriol, 1985). The main caves are Grande Caverne, Caverne Glacée 85, Tsi-tché-han and Bear Cave. The mountains form a north-south alignment measuring 5-6 km wide and correspond to the centre of an anticline. The summits reach 900-1200 m in altitude. The basins situated to the east and to the west are 500-600 m lower.

The area lies north of the continuous permafrost limit. Mean annual temperature in Old Crow is  $-14^{\circ}\text{C}$ , and precipitation is  $215\text{ mm}\cdot\text{y}^{-1}$ , half of which falls as snow. The average annual thermal amplitude is  $50^{\circ}\text{C}$ . The zone below 800 m is occupied by boreal forest, while alpine tundra dominates above that elevation.

During the Pleistocene, glaciers were absent in the region (Hughes, 1972). Deep ravines were carved in the mountains by fluvial processes, exposing caves containing calcite deposits that sometimes reached 3 m in thickness (Roberge *et al.*, 1986). These indicate periods when permafrost was absent or was much less pronounced.

Presently, the existence of permafrost does not allow water to seep through fissures in the rock to reach the underground cavities. Ice formations found in the caves are the result of condensation and freezing of atmospheric water vapour coming from the outside environment.

## ATMOSPHERIC CIRCULATION IN THE CAVES

The atmospheric circulation in the caves was analyzed in July 1985 in Bear and Tsi-tché-han caves by Thibaudeau (1988). The results indicate three climatic zones during the summer (Fig. 2), similar to those observed in the Nahanni by Ford (1972).

**Zone 1:** This zone is situated near the entrance. Both air and ground temperatures are above  $0^{\circ}\text{C}$ , and the relative humidity is around 80%.

**Zone 2:** In this zone, rock temperature is  $0^{\circ}\text{C}$  and the relative humidity is 100%. The transition from zone 1 to 2 does not occur near the ceiling at the same distance from the entrance as it does near the ground. Warm air coming in from the outside intrudes farther into the cave along the ceiling, while cool air, originating from the deeper sections of the cave, moves out farther along the floor. Temperatures in zone 2 may thus be above  $0^{\circ}\text{C}$  at the ceiling and below zero near the floor.

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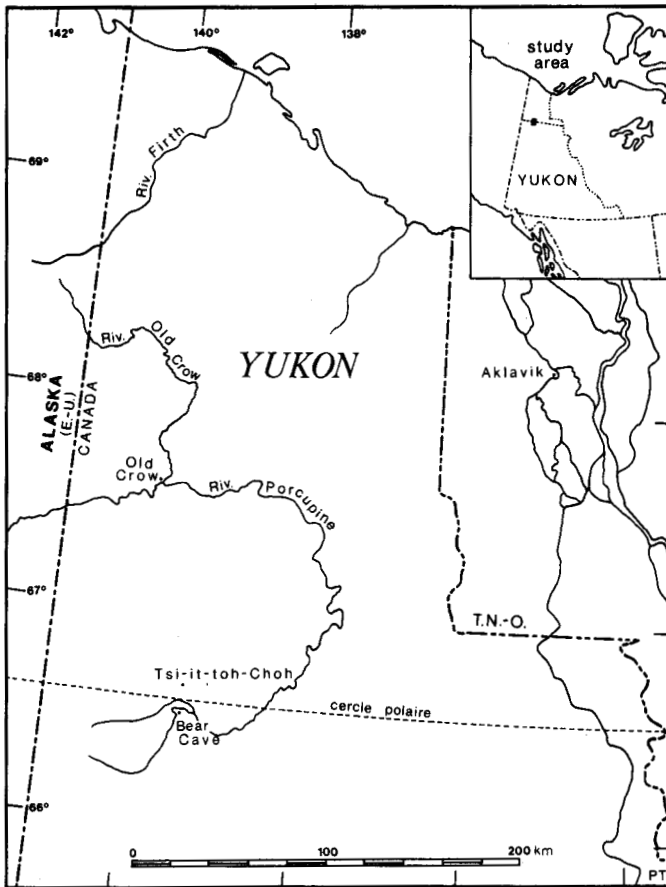


FIG. 1. Location of study area.

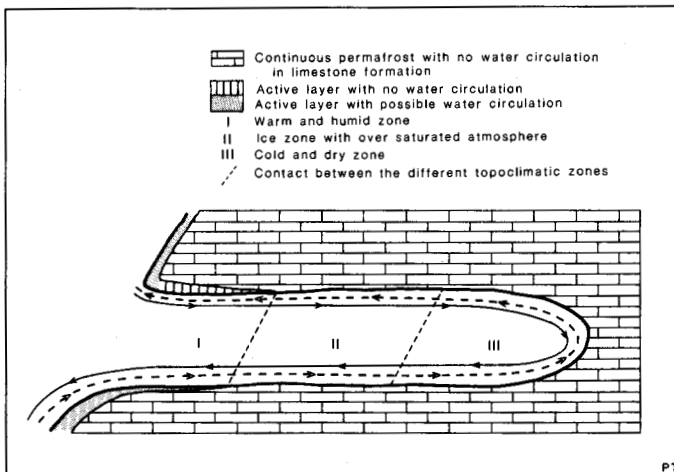


FIG. 2. Climatic zones in the caves. Air and wall temperatures are: I, above 0°C; II, below or equal to 0°C; III, below 0°C. The dashed line indicates winter circulation; the heavy line indicates summer circulation.

**Zone 3:** The measured air temperature in this third zone varies between  $-1^{\circ}\text{C}$  and  $-3.8^{\circ}\text{C}$ , and the relative humidity is 65%. The low water vapour content is explained by the fact that the atmosphere loses an important part of its humidity on cave walls in zone 2, as indicated by the abundance of ice formations.

No measurements were made during the winter period. Nevertheless, according to the air circulation model in horizontal

cavities proposed by Trombe (1965), we may suppose that cold air penetrates into the cave following the floor, while warmed-up air returns towards the exterior near the ceiling.

#### ICE IN THE WARM ZONE

The warm zone is the one characterized by positive temperatures during the summer. The arrival of warm air thaws the walls and the surface of the ground (Fig. 3). A series of measurements undertaken in the silt deposits near the entrance in Tsi-tché-han cave allowed the evaluation of this phenomenon. Thermal profiles were established in July 1985, using a YSI Model 42S thermometer connected to a metal probe driven into the ground. The instrument offered a precision of  $\pm 0.5^{\circ}\text{C}$ . The first measurement, at 10 m from the entrance, indicated a surface temperature of  $4^{\circ}\text{C}$ . The frost table became shallower as the distance into the cave increased. At the end of the first room, 20 m from the entrance, the ground surface had a temperature of  $1.4^{\circ}\text{C}$  and permafrost was apparent at a depth of 10 cm. Five metres farther into the cave the ground surface was frozen (Fig. 4).

Freezing and thawing of the silt in the warm zone of the caves creates a sorting phenomenon. Pebbles and sometimes mammal bone fragments are moved against the walls, forming ripples of about 10 cm in height. Generally, the heterometric pebbles are angular and measure from a few centimetres to 20-25 cm in length.

On the cave walls, frost shattering is limited, despite seasonal thaw. This is due to the fact that the limestone is massive and weakly fissured and that water cannot circulate easily through the fissures. In fact, permafrost makes it impossible for water to reach the cave through infiltration. This characteristic allowed the evaluation of the thickness of the active layer. Following an abundant rainfall in July 1987, water seepage in the cave ceilings was absent, except in the first 4 m from the entrance. This lasted a little over three days. The 4 m distance corresponded with the unfrozen zone, in which water circulation was possible.

#### ICE IN THE 0°C ZONE

During the month of July, ice deposits are found in the zone in which the temperature fluctuates in the neighborhood of  $0^{\circ}\text{C}$  and in which the ground surface is frozen. The different types of ice that occur in this zone are the following:

##### *Hexagonal Ice Sublimation Crystals*

Ice sublimation crystals have an hexagonal shape and contain growth striae. According to Trombe (1965), who calls them bi-dimensional ice crystals, the sides reach several centimetres in width, but those observed in the caves of the northern Yukon measured only 2-3 cm in width. As in the caves of the Nahanni (Schroeder, 1977), they invade the underground passages, beginning at the ceiling, then the walls and finally, but rarely, the ground. The crystals result from the freezing of moisture when the warm, humid air contacts the cold surfaces. In Bear Cave the phenomenon occurs in the second room, which begins 30 m from the entrance. This room, 10 m high and 8 m wide, is almost completely covered with ice crystals reaching a few centimetres in thickness (Fig. 5).

##### *Concretion Ice*

The first ice found during the summer as one enters the cave is on the lower part of the passage walls. It consists of a transparent

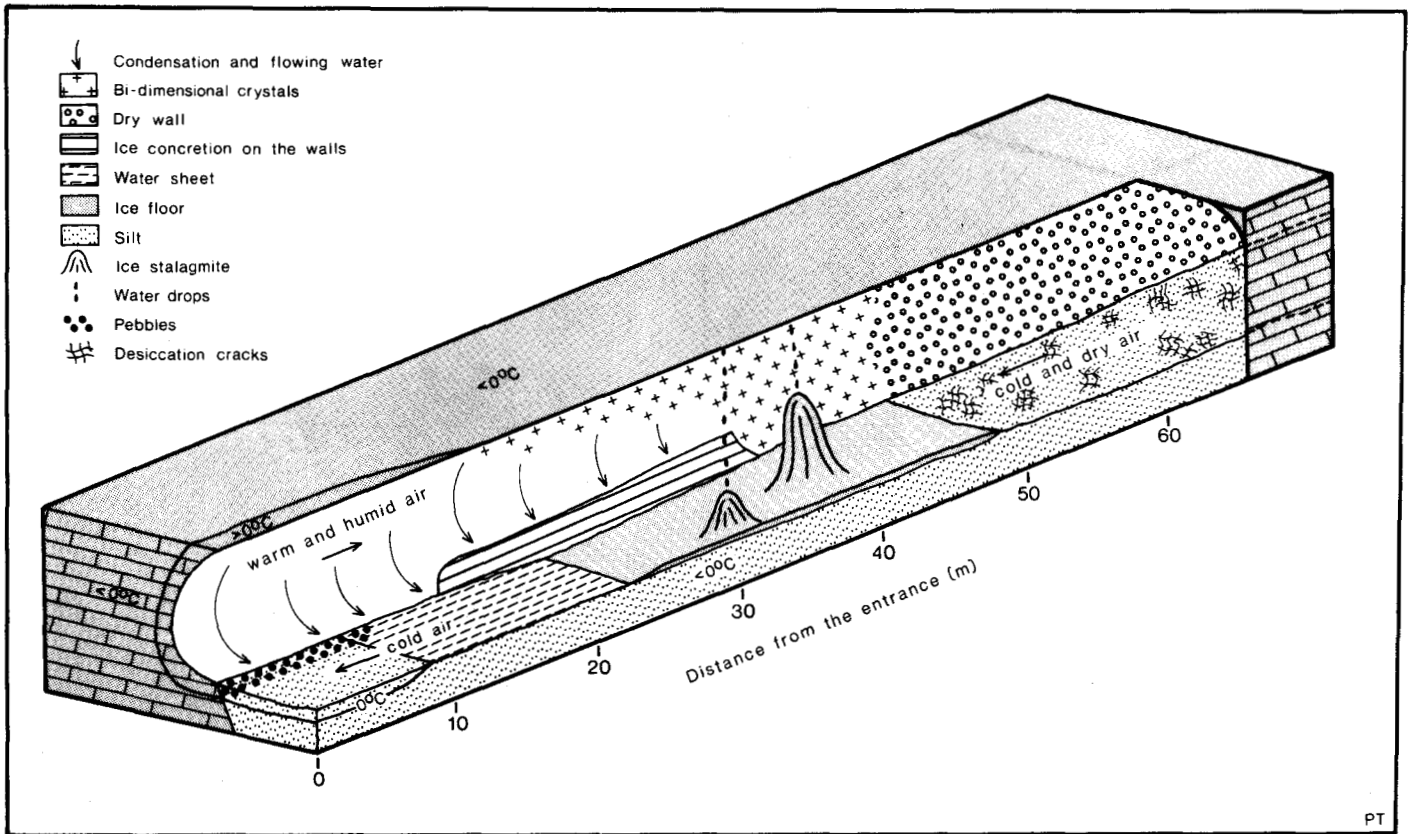


FIG 3. Schematic block diagram of the climatic conditions and the resulting forms in the caves of the northern Yukon during the summer season.

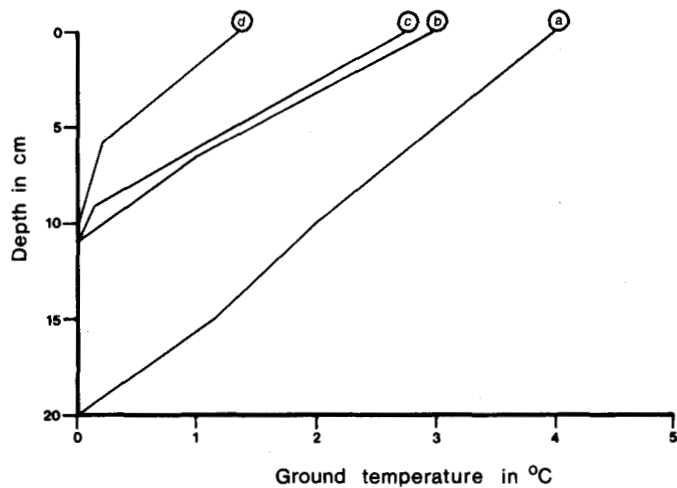


FIG. 4. Thermal profile in the ground of Tsi-tché-han cave on 5 July 1985. Distance from the entrance: a, 1 m; b, 10 m; c, 15 m; d, 20 m.



FIG. 5. Ice crystals covering carbonate concretions in the second room of Bear Cave. The freezing of moisture when warm and humid air contacts the cold surfaces produces the ice. The white dots are drops of water issued from the ceiling. (Photo taken in July 1987.)

ice layer, with few air bubbles. In small-dimension passageways, less than 1 m in diameter, the ice layer covers only the bottom 20-30 cm of the walls, while its thickness is 2-3 cm. In the larger passages, 4-5 m high and 2-3 m wide, the ice covers the walls up to 1.5 m high and its thickness at the base of the walls may reach 40 cm (Fig. 6).

The transparent ice covering the walls is likely derived from the freezing of water coming from the warm, upper part of the

wall. Another possibility is the melting of ice crystals resulting from warm air penetrating the cave and flowing along the ceiling. This phenomenon brings about the melting of ice crystals located on the ceiling of the cave. Water from the melting of these crystals streams down the walls, freezing as it reaches the lower part of the passageway, which tends to be colder than the ceiling. This phenomenon was observed in Tsi-tché-han cave, where the temperature was 2°C at 5 cm at the ceiling, while near

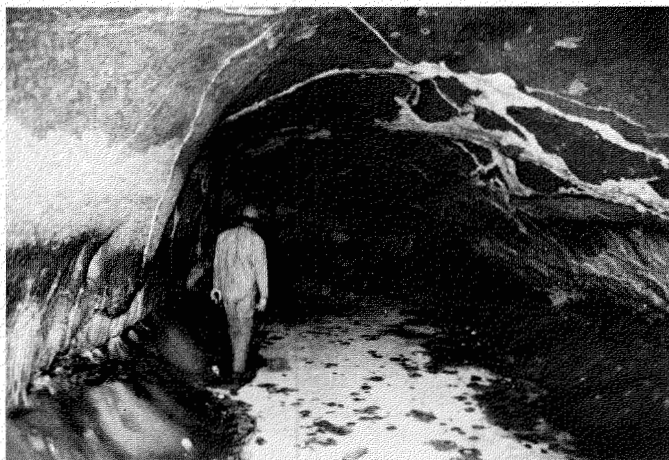


FIG. 6. Grande Caverne — The base of the walls is covered with concretion ice; the floor is covered with a white powder 10 cm thick. This is probably a result of carbonates dissolved by water, then exuded during ice formation or left behind following the melting of an ice floor.

the ground it was  $-0.6^{\circ}\text{C}$ . The  $0^{\circ}\text{C}$  isotherm was found 50 cm above the floor (Thibaudeau, 1988).

Water drops falling from the ceiling freeze on the ground to form ice stalagmites (Fig. 7) that are perfectly transparent and lack air bubbles.

In the long run, the growth of ice concretions in the caves would end up obstructing the passages. However, phenomena such as incoming warm air in summer or cold and dry air in winter intervene and reduce the volume of the ice by sublimation and melting.

The sublimation phenomenon seems to have been evident in Bear Cave. During a first visit in 1985, Polaroid film envelopes left behind by Geist (1953) were found to be covered with 10 cm of ice at the base of an ice stalagmite measuring 3 m in height. In July 1987, at approximately the same date, those same envelopes appeared at the surface. The persistence of soluble chemical powder in the torn Polaroid film suggests that no water flow occurred. It is probable that the volume of the ice stalagmite had



FIG. 7. Ice concretions in the second room of Bear Cave. (Photo taken in July 1985.) These stalagmites are formed by the freezing rain process (see Fig. 5).

decreased through sublimation, particularly during the winter, when the air temperature was below  $0^{\circ}\text{C}$  and very dry.

#### Ice Floor

Ice floors consist of ice sheets occupying the bottom of passageways (Fig. 8). Their presence is explained by the refreezing of melted water. In fact, during a few days in summer, the atmospheric temperature rises above  $0^{\circ}\text{C}$  in the first metres inside passages covered with ice concretions and crystals. Their total or partial melting causes the ground, which is already covered with ice, to flood.

In the caves visited, the ground water never reached more than 8 cm in depth. Lying over a previously formed ice layer, the water showed a few pebbles and sometimes a thin, yellowish silt layer. In winter, when the water freezes, this material becomes trapped between the new ice layer and the previous one.

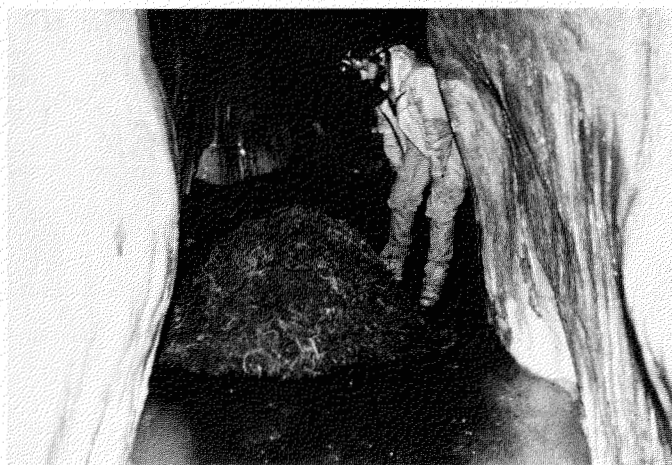


FIG. 8. Caverne Glacéé 85 — In the foreground, ice floor (10-15 cm); in the centre, ice mound covered with *Dryas* and *Cassiope* dating from  $1300 \pm 100$  B.P.; laterally, against the walls, ice concretions. (Photo taken in July 1985.)

#### THE ICE-FREE ZONE

Past the  $0^{\circ}\text{C}$  zone is a cold and dry zone (Fig. 3). The temperatures in Bear Cave and Tsi-tché-han were between  $-1^{\circ}\text{C}$  and  $-3.8^{\circ}\text{C}$  in that zone during the month of July in 1985 and 1987. In those same periods, the relative humidity was 60-65%. The dryness is explained by the fact that by passing through the  $0^{\circ}\text{C}$  zone, the atmosphere loses moisture through condensation on the walls. In winter, the temperature of this cold summer zone is actually higher than in the other parts of the cave. The ambient outside air entering the cave is very dry. In warming up as it progresses deeper into the cave, its relative humidity decreases to a point where the ground and the walls of the cave transfer moisture to the atmosphere, as described by Trombe (1965).

This drying out affects the whole cave environment, including the entire clastic material present, the wood pieces introduced by porcupines, as well as the remains of mammals, some of which are as old as 4270 B.P. (U.L. 257). The skeleton of small rodents are very well preserved in this zone. The dryness also explains the preservation of a red mark (perhaps a prehistoric drawing?) on a wall of the second room in Tsi-tché-han cave, as well as cracks in the ground clays of that same room.



The cold and dry zone was observed only in those cavities. In the other caves, an ice plug prevented access to that zone.

#### ICE PLUGS

In about ten caves, the ice blocking the passages is more or less transparent (Fig. 9). It forms a vertical wall from the ceiling to the ground. The details of its accumulation are not yet

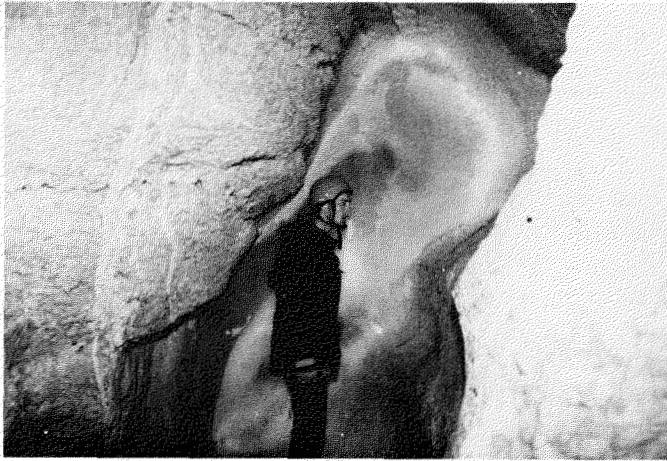


FIG. 9. Ice plug. (Photo taken in July 1987.)

determined, but it closely resembles the concretion ice. The most probable hypothesis implies the development on both ceiling and floor of concretion ice to the point where they join, thus producing an ice blockage or ice plug.

A second type of ice plug is formed by an accumulation of ice crystals. The best example is located in Grande Caverne. The walls, from a distance of 30 m on in the cave, are covered with hoar frost. This accumulation thickens on the walls as one progresses deeper into the cave. At the end of the cave, 70 m from the entrance, the passage is blocked by a wall measuring 4 m wide and 2.5 m high (Fig. 10). A water cascade situated at the



FIG. 10. Grande Caverne — In the background, ice accumulation blocking the passage; in the foreground, ice floor (over 1 m thick) overlain with small ice stalagmites; on the ceiling, ice crystals covering the rocky wall by a few centimetres. (Photo taken in July 1987.)

entrance of the cave is certainly one of the factors explaining this abundance of ice crystals. This waterfall humidifies the atmosphere entering the cave during spring and summer.

The third type of ice plug constitutes a mass of stratified ice undergoing a melting process. It was observed in Caverne Glacée 85, where the stratified ice wall is situated at 40 m inside the cave (Figs. 11 and 12). This 4 m high wall has an inclined surface and is dirtied by silt freed from the ice layers. The warm air moving near the ceiling creates a more rapid melting of the upper part of the wall. Schroeder (1977), in the cave of the

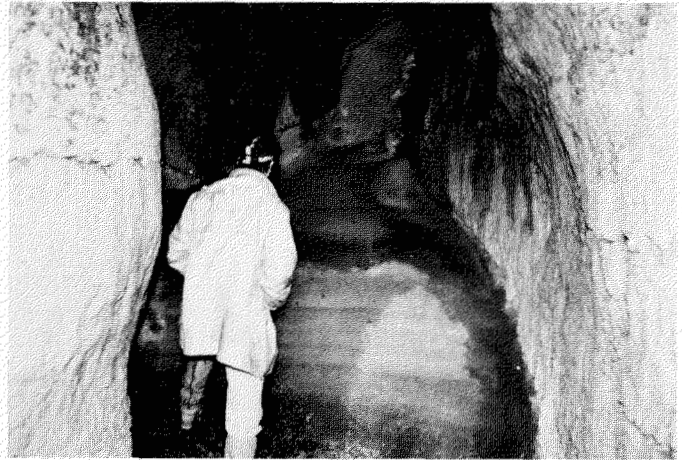


FIG. 11. Caverne Glacée 85 — Stratified ice wall. (Photo taken in July 1985.)

Nahanni, and Marshall and Brown (1974), in the Coulthard caves, observed the same phenomenon.

Also in Caverne Glacée 85, a mound 1 m high and 1.5 m wide is found (Fig. 8) formed of ice very rich in air bubbles, similar to the ice blocking the passage at the end of that cave. Its existence is due to a 5 cm thick cover of herbaceous plants (*Dryas octopetala* and *Cassiope tetragona*), which provides thermal insulation.  $^{14}\text{C}$  dating indicates an age of  $1300 \pm 100$  B.P. (U.Q. 1282) for this herbaceous cover, which corresponds to an ancient nest of an animal living in the cave when a more important ice sheet covered the ground.

The stratified ice is the result of successive freezing of thin water layers formed in the summer on top of the previous winter ice. Deposits of silt between the ice layers and the numerous air bubbles in the ice are the principal indicators of this process. The presence of a stratified ice plug does not imply the presence of a rock block at the entrance of the cave, necessary for the retention of a water sheet that would ultimately freeze. If, however, this were the case, the ice in Caverne Glacée 85 would be very old, since the cave entrance is presently found on the slope of a ravine.

#### CONCLUSION

The dynamics of the ice encountered in the caves become integrated into an open system. The input is supplied by water carried into the caves by air circulation. In the caves, this water freezes and thaws many times, successively creating hoar frost, ice concretions, ice floors and stratified ice. Those various changes occur from the ceiling towards the ground in the cave passages. The output corresponds to the exit of water from the

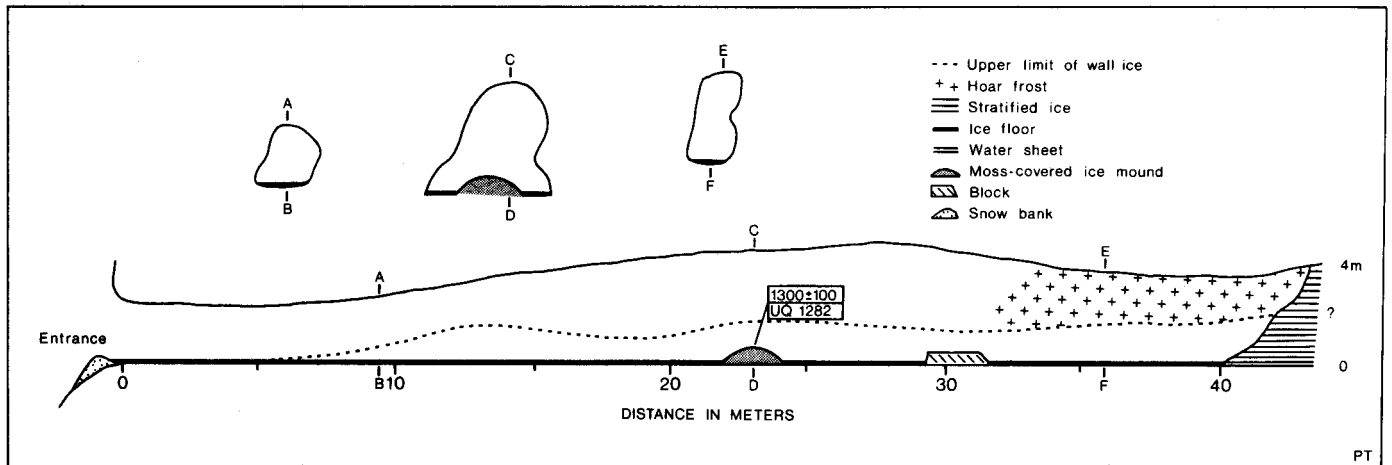


FIG. 12. Cross section of Caverne Glacée 85.

caves, either in a liquid or a vapor state. This water comes from the melting of ice in the summer and its sublimation in the winter. The volume of ice in the caves increases if the input is greater than the output and decreases in an inverse situation. Besides the annual variations, there are longer term variations, as indicated by a decrease in the volume of stratified ice since approximately 1200 B.P.

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