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ORIGIN OF GLACIER CAVES IN THE QUELCCAYA ICE CAP, PERU*

Lonnie G. Thompson *and* Garry D. McKenzie

Institute of Polar Studies, The Ohio State University, Columbus, Ohio 43210

ABSTRACT

The 5645 m-high Quelccaya Ice Cap of the Cordillera Oriental contains both obstruction- and crevasse-type glacier caves in several outlet glaciers. Reconnaissance observations on the obstruction caves, produced by deformation of ice around obstructions in the bed of the glacier, indicate that two distinct forms occur: (1) *single passages parallel to the ice-flow direction with a bedrock protuberance or boulder at the head, and* (2) *single passages perpendicular to ice flow and formed in the lee of bedrock ledges. The crevasse-type caves form from crevasse-wall collapse and roofing by snow and firn; they may occur at all angles to glacier flow. Speleothems observed in the caves include stalactities, stalagmites, columns, and cave coral; cave ceilings are usually fluted or striated.*

INTRODUCTION

In July 1974, 1976 and 1977, and January 1977, the first author observed several types of glacier caves in the Quelccaya Ice Cap, south central Andes, Peru during glaciological field work conducted under a cooperative program between the Institute of Polar Studies and the Peruvian Institute of Geology and Mining. The main objective of this research project is the development of a paleoclimatic record for an equatorial glacier (Thompson and Dansgaard, 1975), in a fashion similar to that previously accomplished for Greenland and for Antarctica

* Contribution No. 338 of the Institute of Polar Studies, The Ohio State University, Columbus, Ohio 43210.

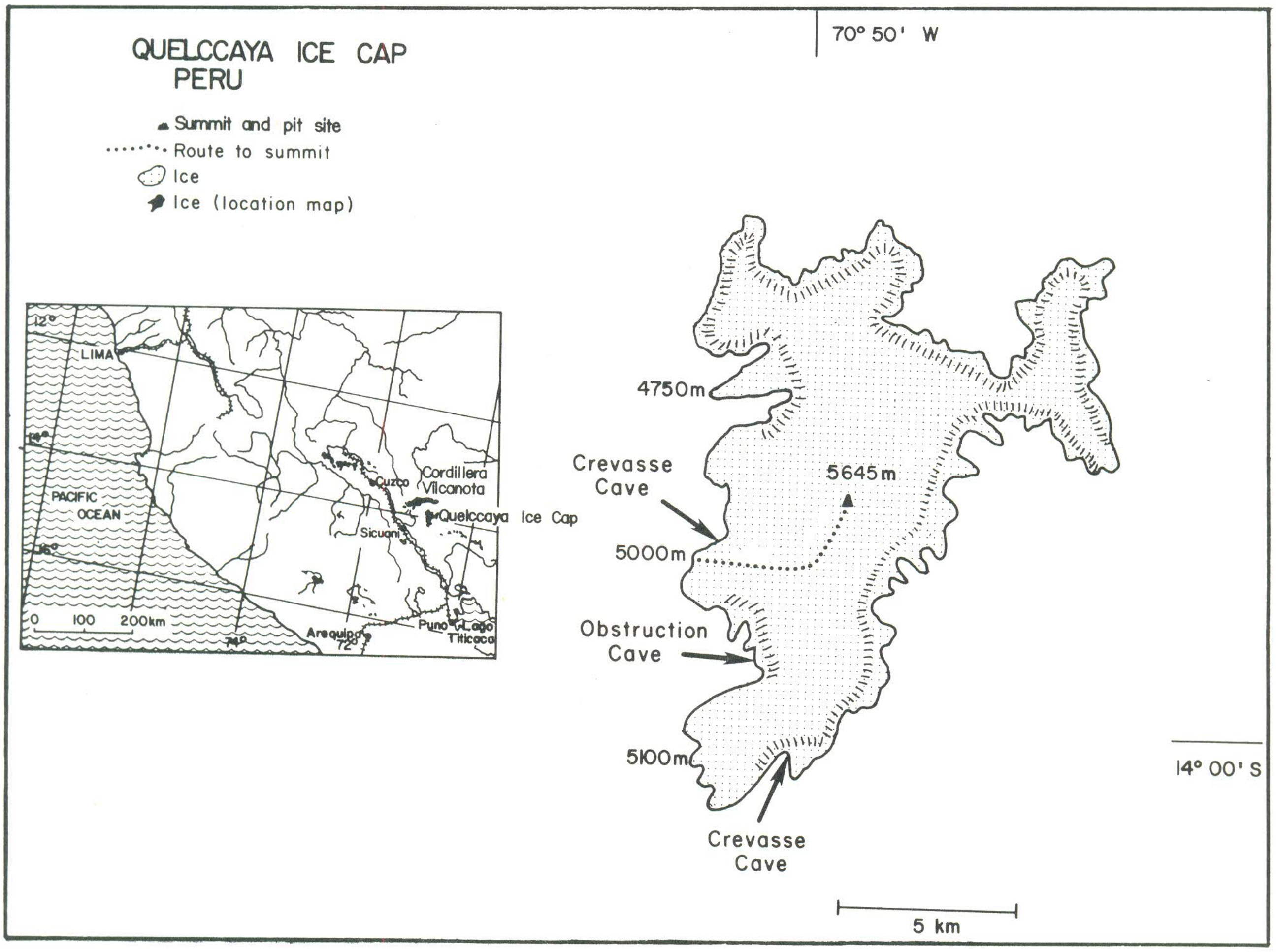


Figure 1. Map of Quelccaya Ice Cap, showing locations of some of the glacier caves.

(Dansgaard, *et al.*, 1969, 1971; Johnsen, *et al.*, 1972; Thompson, *et al.*, 1975; Thompson, 1975, 1977). Field work during these expeditions concentrated on establishing and maintaining an automatic recording meteorological station, snow pit studies, and ice coring for later particle, isotope, and β activity studies in the laboratory. A network of ablation and accumulation stakes was also established, to record changes in the glacier surface. The glacial history of the area has been studied by Mercer *et al.* (1975) and by Mercer and Palacios (1977). Hastenrath (1977, 1978) has reported on the meteorology and heat budget of the ice cap. Glaciospeleological field investigations have included observations on morphology, temperature, and speleothems; preliminary results have been reported by Thompson and McKenzie (1977).

THE QUELCCAYA ICE CAP

The Quelccaya Ice Cap (13°50'S, 70°50'W) is located in the Cordillera Oriental, 105 km east of Sicuani, Peru (Fig. 1). Except for small glaciers in New Guinea and on the Stanley Plateau in the Ruwenizori Range, Uganda, the Quelccaya Ice Cap is the only ice cap within the tropics. The ice cap covers an area of 70 km^2 and has four ice domes, the highest of which is 5645 m. Ice tongues on the eastern margin extend to 4900 m but, on the western side, outlet glaciers reach only to between 5000 and 5100 m. Approximately 90% of the margin exhibits steep ice cliffs. The glacier caves described here occur in several outlet glaciers on the western and southern margins of the ice cap; the perimeter has not been completely explored for glacier caves.

The ice cap is believed to be temperate. A temperature of 0°C was measured at a depth of 15 m during July, 1976 (Thompson, unpublished data). In July, the diurnal temperature range at the Summit is +6°C to -14°C; there is a 3°C difference in mean temperature between the winter and summer seasons. Most of the precipitation occurs during the southern summer; the dry season lasts from May to August. The mean annual accumulation of snow on the ice cap since 1969 is 2.08 m, or 1.14 m water equivalent (Thompson, unpublished data).

The 200 m-thick ice cap rests on a plateau of welded tuff. According to Mercer and Palacios (1977), the ice cap expanded during the height of the late Wisconsinan glaciation (between 28,000 and 14,000 B.P.), but only halfway to the limit of the maximum glaciation, the date of which is unknown. Readvances following the last glaciation occurred before 12,250 B.P. and about 11,000 B.P.; the Neoglacial advance culminated between 600 and 300 B.P.

GLACIER CAVES

Halliday (1976) has described glacier caves as caves formed within or at the base of a glacier. Such caves have been known for over a century; however, only within the last few decades has much attention been paid to them by glaciologists in their attempts to understand basal processes of glacier flow and by speleologists searching for new types of caves and speleothems. Developments in glaciospeleology—"a limitless new branch of speleology"—have been reviewed by Halliday and Anderson (1970) and more recently by Halliday (1976).

Peterson and McKenzie (1968) described an Alaskan glacier cave that had formed by the flow of ice around a bedrock protuberance and indicated that there was a second category of glacier cave formed by the ablative action of meltwater streams. In 1970, McKenzie re-defined these two types of glacier caves as obstruction caves and ablation caves. An obstruction cave is formed by interruption of the ice flow at the base of a glacier. A bedrock high or boulder in the ground moraine could initiate the formation of a cave that, in many cases, could lack an entrance for most of the year because of accumulated snow. The size of an obstruction cave depends on the rate of closure of the cave relative to the velocity of the ice. Obstruction caves usually have fluted or striated ceilings developed in a till/ice mixture carried at the base of the glacier. Speleothems may include sublimation crystals, hair ice, and till curls (Peterson and McKenzie, 1968).

An ablation cave is formed by moving air or water within or at the base of the glacier. These caves usually form near the terminus or margins, where meltwater streams flow. The walls and ceilings of these caves often have a scalloped appearance and are relatively debris-free. Stalactites and stalagmites may form in these caves during the ablation season.

Because most glacier caves are affected by temperature fluctuations, precipitation, and ice flow, they are part of dynamic systems and subject to change. Thus, some obstruction caves may undergo ablation during the late summer, and ablation caves may become closed in the winter and develop some of the speleothems normally found in drier obstruction caves.

In the investigations at Quelccaya, we have found two varieties of obstruction caves. Another type of cave, developed in crevasses, has been observed in the past associated with other glacier caves. They have never been found developed to the stage seen at Quelccaya, however.

OBSTRUCTION CAVES

About seven obstruction caves are known to occur on the western margin of the ice cap (Fig. 1). These caves occur in two morphologically distinct forms and are classified, according to tunnel orientation relative to ice flow direction, into parallel and perpendicular. Typical caves of these two types are described below.

The parallel obstruction caves (Fig. 2 and 3) are formed by ice flowing over a boulder or large bedrock protuberance which occurs at the upglacier end of the cave. The largest cave observed was at an elevation of 5100 m; it was 21 m long and had an opening 3 m wide and 2 m high. This cave showed little evidence of closure, having approximately the same dimensions at the point of origin—in this case a large boulder (Fig. 4)—as at the entrance. A 22 m long half-cave wall on the side of the glacier (Fig. 5) suggests that the cave was much longer in the past. The ceilings of this and other parallel obstruction caves often extend a few centimeters beyond the ice cliff as a 4 cm-thick ridge (Fig. 3). Because this glacier has very little basal debris where these resistant rims occur, it is thought that the rims may owe their stability to a different ice fabric developed by deformation at the base of the glacier.

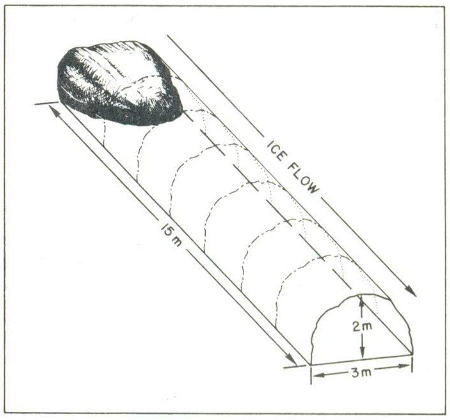
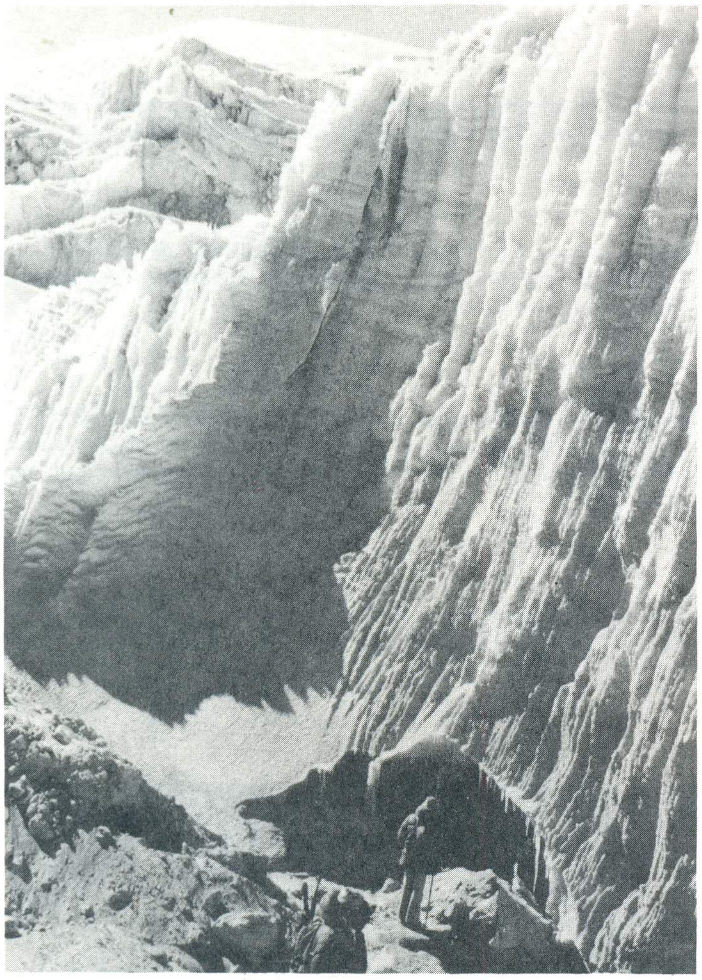


Figure 2. Diagram of a parallel obstruction cave, showing boulder at end.

Speleothems within the parallel obstruction caves are few. Although one might expect to see a till/ice mixture at the base of the glacier, this is visible only in some caves and is seldom more than 15 cm thick. In other caves, the till/ice layer is not present, because the ice is moving over a fairly clean bedrock surface. The walls and ceilings of these caves show a fluted surface (Fig. 6); the flute depth depends on the size of the irregularities in the subglacial surface, but no flutes deeper than 5 cm were seen. Till curls (Peterson and McKenzie, 1968) were present in several obstruction caves (Fig. 7). A few stalactites occur at the entrance to these caves (Fig. 6), but none was observed more than 2 m from the entrance unless the cave had been breached by a crevasse.

Obstruction caves of the perpendicular type are formed in the Quelccaya Ice Cap where the glacier leaves its bed as it passes over resistant bedrock ledges. Three of these caves were seen, although there no doubt are more in the area. Perpendicular caves do not have a single, direct passage that reaches the margin, as is the case with parallel obstruction caves, and entrance is gained through a crevasse that may be associated with glacier deformation over the plateau lip or in areas where the ice is not in contact with the bedrock downstream from the bedrock ledges. The caves ranged in length from 5 to 30 m and up to 4 m in height. Average dimensions of these



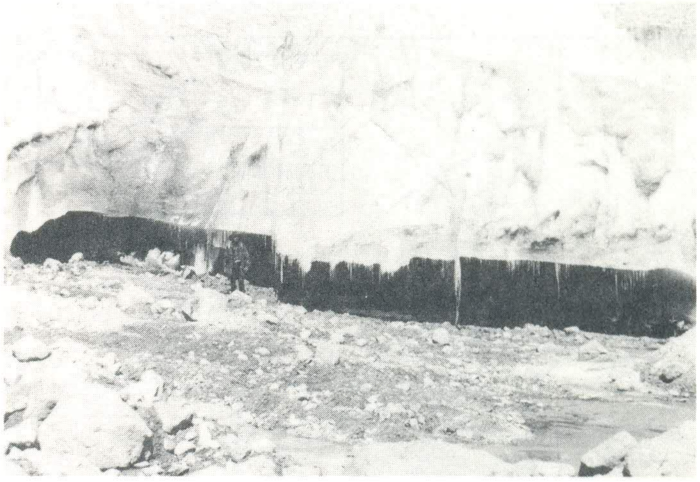
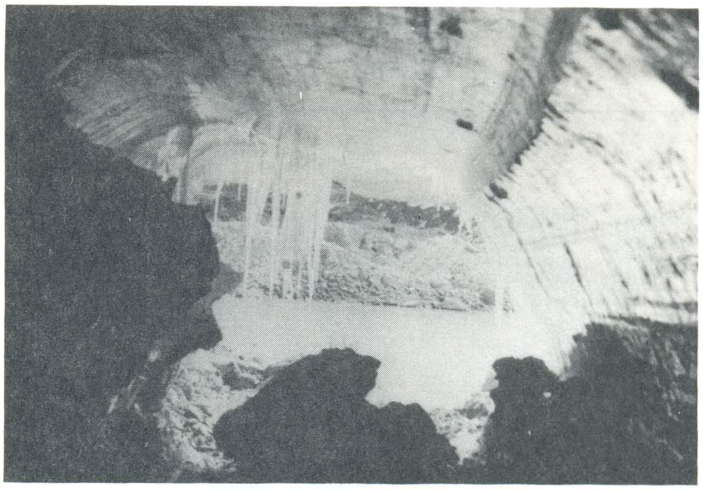


Figure 3. (above) Entrance to obstruction glacier cave on the west side of the Quelccaya Ice Cap. Ice cliff is about 30 m high. Around the cave entrance, there is a resistant rim of ceiling ice protruding several cm from the cliff face.

Figure 4. (top right) Three-meter wide boulder at the head of a 21 m-long obstruction tunnel of the parallel type.

Figure 5. (center right) Entrance to an obstruction cave extending 21 m under ice cap from far left. The 22 m-long half-tunnel shown here has been exposed by retreat of the ice cliff.

Figure 6. (bottom right) View out of a parallel obstruction cave. The cave ceiling is fluted and striated; the absence of scallops indicates minimal ablation. Ice stalactites form by refreezing of meltwater from the cliff face.



caves are indicated in the schematic diagrams (Figs. 8a and 8b). Figure 9 shows the interior of one of these caves, which contains stalactites, tilted stalactites, and deformed columns. The cave floor has a pebbly surface analogous to cave coral.

The ceilings of these caves are fluted, and the stalactites are associated with fractures in the ice ceiling.

CREVASSE CAVES

Crevasse caves have been investigated on the west and south margins of the ice cap (see Fig. 1). These caves measure more than 50 m in length, range between a fraction of a meter to 5 m in width, and have ceilings up to 20 m in height (Fig. 10). The crevasse caves form along areas of tensile stress in the ice and, also, on the slopes

Figure 7. (top left) Base of glacier in obstruction cave showing 5-cm thick debris/ice layer and a 15-cm high till curl. Glacier flow is from right to left.

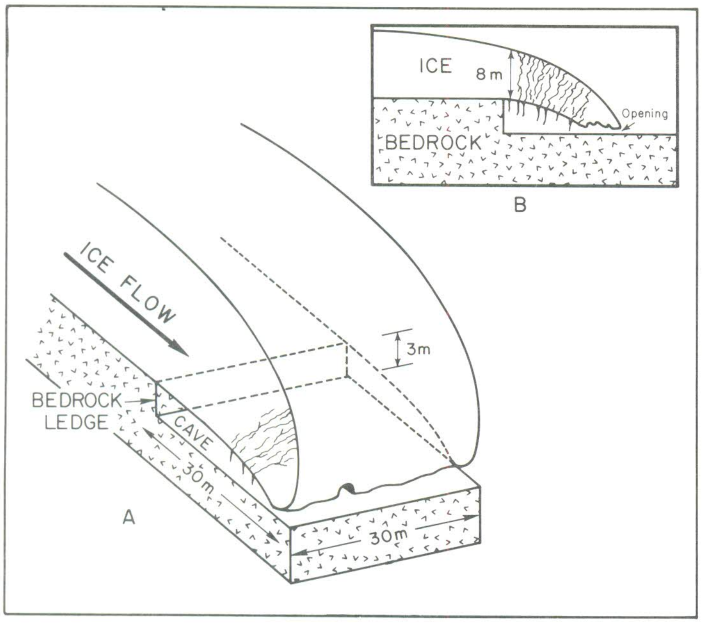
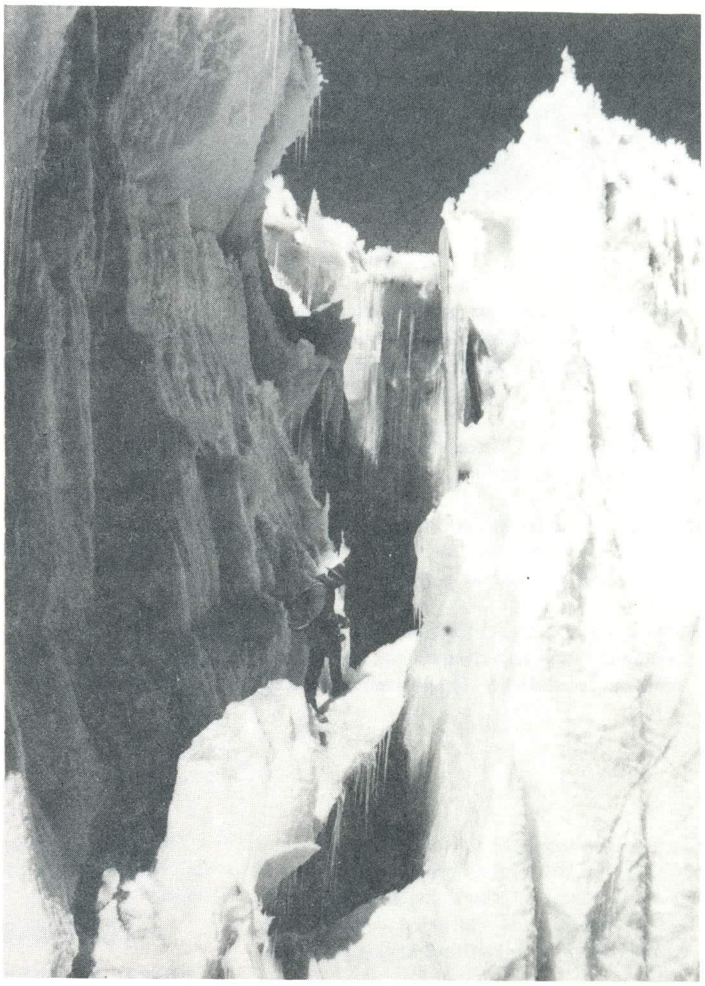


Figure 8. (center left) Diagrams of a perpendicular obstruction cave: (a) perpendicular cave showing bedrock ledge, (b) lateral view of perpendicular obstruction cave.

Figure 9. (bottom left) Perpendicular obstruction cave with deformed stalactites formed by meltwater penetrating from the glacier surface through fractures in the ceiling. Ice in the form of cave coral floors the cave.

Figure 11. (below) Entrance to crevasse cave on west side of Quelccaya Ice Cap. Snow and firn form ceiling. Ice speleothems often occur within these caves.



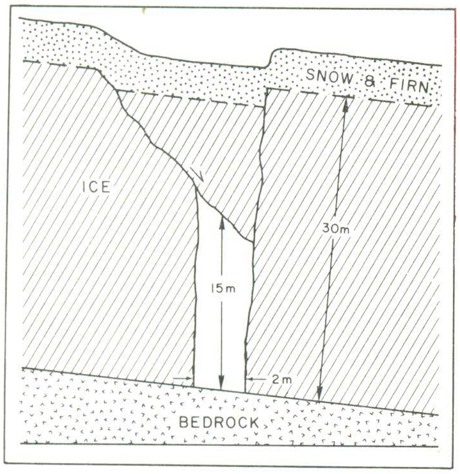


Figure 10. Diagram of a crevasse cave. The ceiling of the cave is formed by a collapsed crevasse wall covered by snow and firn.

below bedrock ledges over which the glacier has "calved," producing accumulations of large jumbled blocks on the slopes below. The ceilings of the crevasse caves are formed by snow and firn accumulation, partial crevasse filling by ice which has slumped from the crevasse wall, or a combination of these processes (Fig. 11). These caves contain stalactites and flowstone which build outward, perpendicular to the crevasse wall, and, in come cases, partition the crevasse cave. Although these caves receive meltwater from the surface and, in places, are open to the surface, only a small upper portion of any cave shows a scalloped surface indicating ablation. Floors of the caves often contain stalagmites and cave coral.

SUMMARY AND CONCLUSIONS

Two forms of obstruction-type glacier caves have been identified on the basis of tunnel orientation relative to ice-flow direction. Speleothems include (1) stalactites, (2) stalagmites, (3) columns, (4) cave coral, and (5) till curls. These cave features apparently persist throughout the year, as the caves do not pass through an ablation phase.

A further type of cave, formed by the roofing of a crevasse, has been defined. Although crevasse passages have been associated with other types of glacier caves, in the Quelccaya Ice Cap they are well-developed and distinctive forms that warrant a separate category in the classification of glacier caves.

Speleothems in the crevasse cave were primarily flowstone, stalactites and stalagmites. Scalloped surfaces were uncommon, suggesting little ablation of the walls of these caves.

Future work will include (1) observations on cave temperatures and changes in speleothems, (2) determination of glacier bed-flow rates, and (3) ice-fabric studies of the basal glacier ice. Further exploration of the ice-cap margin should reveal additional caves of each type, which would assist in developing a more complete understanding of their origin.

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