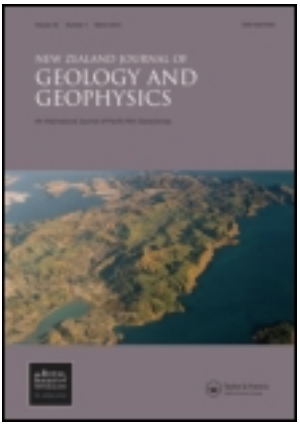

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GEOTHERMAL ICE CAVES ON MT EREBUS, ROSS ISLAND, ANTARCTICA

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ABSTRACT

A 400-m-long system of ice caverns forms the subsurface extension of one of the many fumarolic ice towers on the summit plateau of Mt Erebus. The cave system consists of a series of branching loops of passages that average 4 m high and wide and terminates in an ice cavern about 25 m high and wide with a floor about 60 m below the surface. Air temperatures within the cave varied from just below freezing to + 1.4°C. Zones of increased heat flow are considered to control the origin and the geometry of the cave system; the highest ground temperature measured at 15 cm depth was 16.8°C.

INTRODUCTION

The most conspicuous manifestations of thermal activity in the summit areas of the two active volcanoes, Mts Erebus and Melbourne, in Victoria Land, Antarctica, are the chimney-like ice formations termed fumarolic ice towers or ice pinnacles. They vary widely in shape and size; on Mt Erebus about two dozen reach a height above 5 m. Early visitors recognised these to be due to the condensation of thermal vapours (David & Priestley 1909; Holdsworth & Ugolini 1965). Lyon & Giggenbach (1974) discussed their distribution, their origin, and possible transport mechanisms for the water vapour required in the formation of these ice structures. The water vapour was considered to be derived through partial melting and evaporation of ice or snow by the residual heat supplied from cooling lava flows. For the resulting mixture of warm air and water vapour to reach the surface, the existence of a system of subsurface feeding channels was proposed.

In December 1972 an ice tower nearest to the camp (Fig. 1) was entered and was found to mark the highest point of an ice cavern about 10 m high and wide (Lyon & Giggenbach 1974). Partial exploration showed passages to slope downwards from the point of entry in directions both away from and towards the main crater. The associated cave system has been revisited in December 1974 and 1975 and is now fully explored; because it may be representative of the subsurface feeding channels for many of the other ice towers, it is described here in some detail. Preliminary inspection of other towers on the summit plateau of Mt Erebus indicates, however, that a wide variety in the extent and configuration of such subsurface cave systems can be expected.

SURVEY TECHNIQUES

Subsurface mapping of the cave system was carried out during December 1974 by employing a resection survey method with a 10-m-long string subdivided into 1 m sections and a simple protractor made from a cardboard

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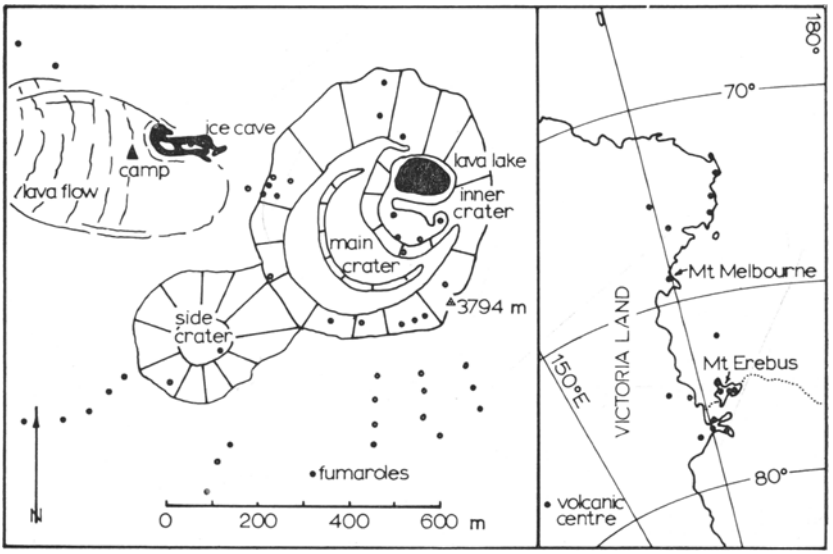

FIG. 1—Sketch map of summit area of Mt Erebus. Inset map shows location of Mt Erebus and surrounding volcanoes.

disc. Heights and widths of the cave were largely estimated and are accurate to about 20%, angles could be measured to within 3°. In spite of the primitive tools used, the closure error for the loop surveyed was only about 5 m. Air temperatures were measured with a calibrated whirling thermometer, and directions of air flow by observing the movement of exhaled breath; ground temperatures at 15 cm depth were obtained in December 1975 by use of calibrated mercury thermometers, allowing 15 min for equilibration.

DESCRIPTION OF THE CAVE SYSTEM

The ice cave described here closely resembles the one discovered on Mt Rainier (Kiver & Mumma 1971), except that the Erebus cave has only a single entrance, marked by an ice tower, about 4 m high. The overall shape of the cave system resembles a figure "8" with the longest axis in an east-west direction (Fig. 2). The passages are about 1 to 5 m wide and 3 to 5 m high; total passage length is about 400 m. The passage which extends about 60 m to the east and west of the entrance, with almost symmetric semi-circular cross sections, appears to follow the slope of some lava structure; the lower east–west passage clearly follows its elevation contours. The cross section here is strongly asymmetric: the downhill wall is close to vertical and the flat ice-roof meets the uphill lava slope at a sharp angle (Fig. 2C). The smaller loop of the figure "8" consists of a 50-m-long curving passage of close to uniform height (3 m) and width (5 m) that slopes down at 30°

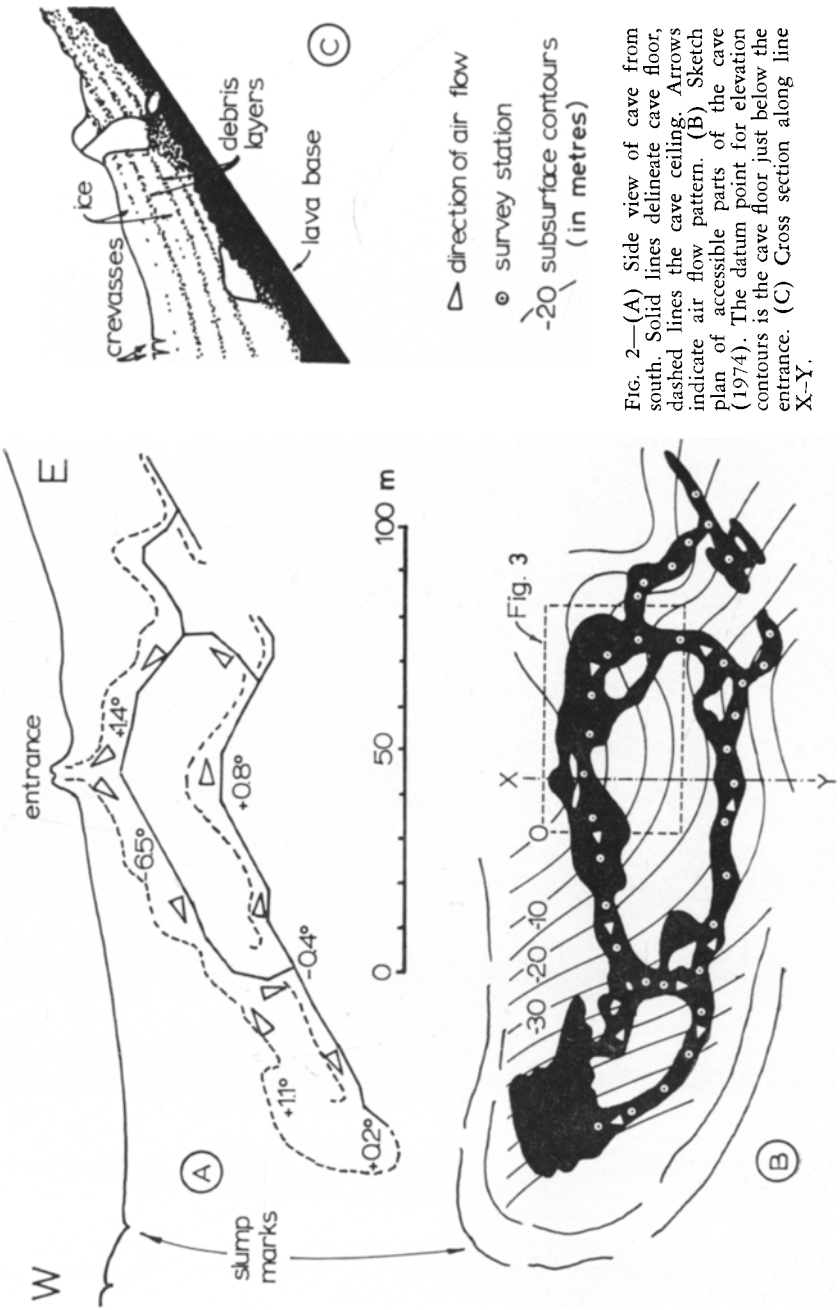

FIG. 2—(A) Side view of cave from south. Solid lines delineate cave floor, dashed lines the cave ceiling. Arrows indicate air flow pattern. (B) Sketch plan of accessible parts of the cave (1974). The datum point for elevation contours is the cave floor just below the entrance. (C) Cross section along line X–Y.

to a large cavern about 25 m wide and high. The western end marks the lowest point of the cave system, about 60 m below the surface. A passage on the upper end of the cavern closes the smaller loop. Most of the 30° sloping cavern floor is covered by blocks of ice and lava boulders up to 5 m diameter. In the upper part of the large cavern, however, and in passages close to the −30 m contour line, dense layers of lava are exposed. These steep rock cliffs appear to represent the front of a lava flow or possibly the inner wall of a crater-like depression. The contour lines shown in Fig. 2B delineate this lava subsurface believed to form the base for the cave system. There are no indications that further layers of ice occur beneath this surface.

As described earlier (Lyon & Giggenbach 1974), the cave walls near the entrance consist of 0·05 to 1-m-thick aternating sloping bands of ice and volcanic material, in which blocks up to several tens of centimeters in diameter are common. These volcanic debris layers are roughly parallel to the lava subsurface shown in Fig. 2B and are likely to represent material deposited during intermittent eruptions from the main crater while the depression accommodating the cave system filled with snow. Volcanic debris fallen from the ceiling covers most of the cave floor. Mounds of debris on the floor coincide with bands of volcanic debris in the cave ceiling; usually a raised ridge of debris runs along the centre of the passage floor. The main change observed for the 1974–75 period was the closure of several passages by either a rise in the amount of volcanic debris on the floor through slumping in the steeper parts of the cave or a lowering of the cave ceiling. Such downward movements of parts of the cave system have been documented for the Mt Rainier caves (Kiver & Steele 1975).

Farther away from the entrance the amount of volcanic debris interbedded in the ice decreases and only thin bands of ash or occasional blocks are observed. A thin wet layer of ash adheres to the cave walls; the underlying ice is opaque white and probably firn ice. Clear ice was only observed in small patches where melt water run-off from the walls had refrozen, e.g., on the floor below the entrance where dripping melt water led to the formation of ice stalagmites about 10–20 cm high; the ice tower forming the entrance also consisted largely of clear ice.

AIR MOVEMENT AND TEMPERATURES IN THE CAVE

The air temperatures measured during the 1974 exploration are indicated in Fig. 2A. The largest temperature gradient is found near the cave entrance, where cold outside air falls down the entrance dome and encounters warm moist air moving up largely from the eastern branch. The mixing of these two air flows causes the formation of thick layers of frost on the cave walls well down the western branch. Only minor frost adhered to the inner walls near the natural cave mouth at the top of the ice tower when the cave was first entered, before the sides of the ice tower were breached by investigating parties. However, thick layers of frost were observed to form rapidly around the edges of the artificial opening, and thus the air flow pattern described here may differ from that in the undisturbed cave. Cold air flowing down the western branch meets warmer moist air rising through the upper exit from

the big cavern causing the formation of persistent fog in the area around the cross over of the two main loops. The flow of air then splits, setting up two convecting loops. The temperature difference driving the convection current in the western loop is small; the air in the upper part of the big cavern is only 1·5°C warmer than that entering the big cavern (−0·4°C). The occurrence of deeply fluted curtains of clear ice, 1–2 m high, that end in horizontally surfaced pools of clear ice, indicates that liquid water is sometimes present in the lower parts of the big cavern. A somewhat higher temperature appears to be responsible for the air flow in the eastern loop; the temperature of the air shortly before escaping through the entrance was found to be + 1·4°C. No smell of suphurous gases could be detected.

POSSIBLE PROCESSES CONTROLLING THE SHAPE OF THE CAVE

If the shape of the cave system were simply controlled by melting and evaporation of ice through the rise of warm gases emanating from well defined vents, the channels could be expected to rise much more steeply or to follow the subsurface lava slopes. The largely horizontal extent of the cave system, however, suggests that the shape of the cave is mainly determined by the geometry of rather diffuse zones of heat release. Such zones of localised thermal activity were invoked to explain the horizontality of the Mt Rainier cave.

In December 1975 a survey was carried out of temperatures at 15 cm depth over the cave floor in the entrance area (Fig. 3). The highest temperature measured was 16·8°C. Higher temperatures possibly occur in areas beyond that surveyed. By use of relationships given by Dawson & Dickinson (1970) approximate values for the heat flow over the area surveyed can be calculated. Two heat transport mechanisms have to be considered: conduction and convection of heated air and water vapour. Where temperature differences between ambient air and at 15 cm depth are less than 12°C, conductive heat transport was found to predominate. Most of the area surveyed shows ground temperatures below this value; therefore, by use of a value of $1{\cdot}6 \times 10^{-3}$ cal cm^{-1} s^{-1} K^{-1} for the heat conductivity of loose volcanic soils (Dawson & Dickinson 1970) and the thermal gradients derived from the measured temperatures, the conductive heat flow is given by $H = 1{\cdot}07 \times 10^{-4} \times \Delta T$ cal cm^{-2} s^{-1}, where ΔT is the temperature difference between the measured ground temperature at 15 cm depth and the average air temperature in the cave of around + 1·0C. The areas between isotherms given in Fig. 3 were used to calculate the total amount of heat released over the area surveyed. The resulting value is close to 2000 cal s^{-1} or an average heat flow of $2{\cdot}7 \times 10^{-4}$ cal cm^{-2} s^{-1}.

Assuming this value to be representative for the entire cave floor (2800 m^2), the amount of heat supplied is found to be 7500 cal s^{-1}. Loss of heat by conduction through the ice ceiling, however, will reduce the amount of heat available for the melting or evaporation of ice. With the effective ceiling area taken to be twice the floor area, and at an average ice thickness of 20 m, the amount of heat lost through the ice to the outside atmosphere is calculated to be 5600 cal s^{-1}. The average outside air

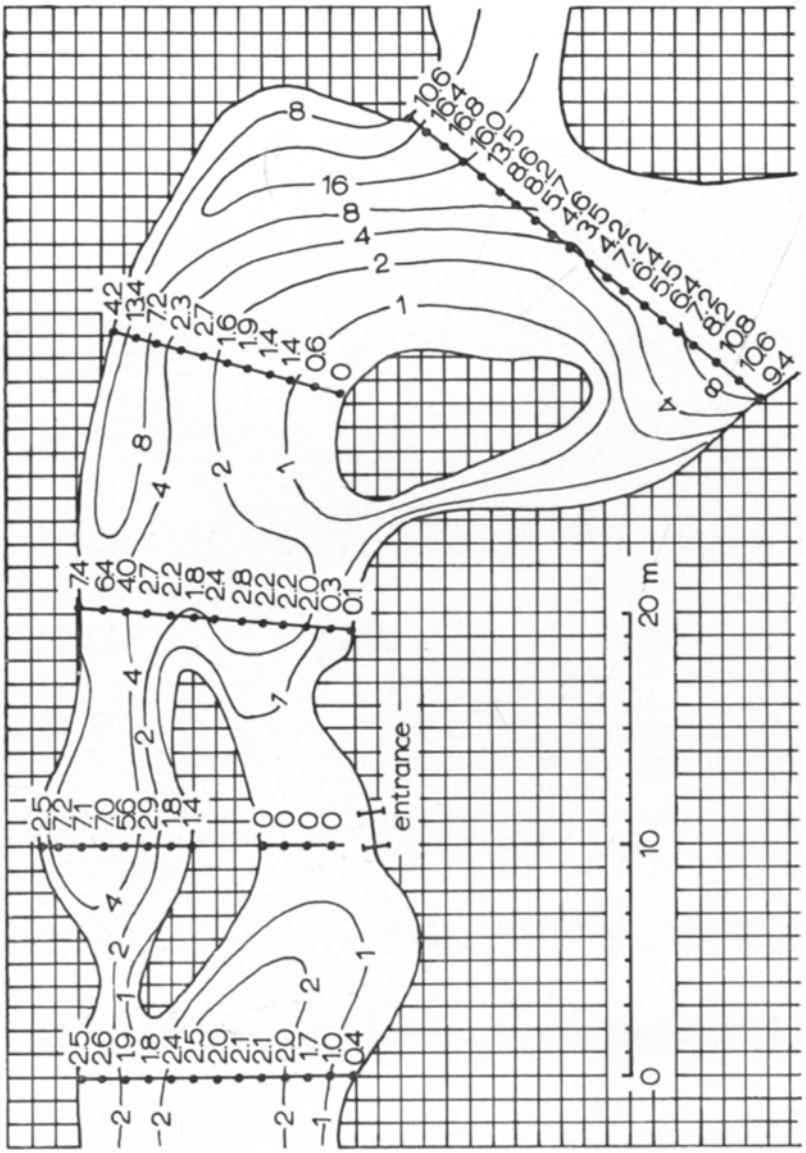

FIG. 3—Isotherms at 15 cm depth in the entrance area of cave.

temperature was taken to be $-40°$, and the thermal conductivity of ice to be 5×10^{-3} cal cm^{-1} s^{-1} K^{-1}. The value of 5600 cal s^{-1} is about three-quarters of the total heat supplied and suggests the dimensions of the cave to be controlled by a delicate balance between heat used up in the evaporation of ice and heat lost through conduction to the outside. An increase in evaporation giving rise to a reduction in the average thickness of the ice cover would be counteracted by increased loss of heat to the outside; on the other hand, increasing accumulation of insulating snow on the surface should allow the cave dimensions to increase.

The pattern of isotherms revealed by the temperature survey extends largely parallel to the main axis of the cave system which in turn lies in line with a chain of ice towers (Fig. 1) extending radially down from the main crater rim almost to the edge of the summit plateau (Lyon & Giggenbach 1974). The occurrence of such radially aligned chains of fumarolic ice towers is very common on Mt Erebus and appears to be due to increased heat flow along zones of structural weakness. These faults or other discontinuities allow warm gases to rise from deeper levels. Where they reach the surface, areas of warm ground or ground covered with thin ice roofs or low ice pinnacles are formed. In other areas, however, the warm gases encounter thicker layers of ice and a cavity may develop in the overlying ice. Convective rise of the warm vapours tends to increase the height of the cavity; the actual dimensions of the cave however, are likely to be also controlled by a dynamic equilibrium between ice removed as water vapour and ice replenished by downward movement of the ice mass. Indications for this movement towards the cave system are provided by the occurrence of subparallel slump marks on the surface. These ditches, sometimes tens of centimetres deep and 10–30 cm wide; are readily observed in the areas north and west of the cave system where volcanic material overlies the ice, and to the south where a semicircular pattern of crevasses outlines the cave below.

The mechanical stresses induced by these movements may also be responsible for the fall of large ice blocks, observed on the floor of the large cavern, by the spalling of chunks of ice from the cavern ceiling. The amount of ice fallen from the ceiling, leaving large patches of freshly exposed overlapping conchoidal dents, was estimated in 1975 to be several hundred tonnes. At present no values for the subsidence rate of the Erebus cave can be given; rates of 2–3 m $year^{-1}$ are reported by Kiver & Steele (1975) for the Mt Rainier cave.

No other evidence for major present-day thermal activity was observed within the cave system; however, in two places the occurrence of apparently thermally altered rock cliffs accompanied by efflorescences of salt indicates that stronger activity had once taken place. As already mentioned, the cave walls are usually covered with a wet layer of ash; frost was only observed in the western branch leading away from the entrance and in a small cavern near the end of the eastern-most branch (Fig. 2B). There, a thick layer of euhedral hexagonal ice crystals covers the entire wall. This may reflect a change in the heat-flow pattern affecting this section which has caused the temperature to drop below zero and thus reversed the tendency from melting and evaporation to recondensation.

Because of the convenient and nearly constant temperatures prevailing in the cave system, it is suitable for the installation of scientific equipment, in spite of the high relative humidity. During the 1974 expedition, a seismograph station was set up under an ice ledge in the entrance hall. The possible use of the cave for emergency shelter or intermediate temperature cool store for frost sensitive goods is also feasible.

Repeated temperature surveys of specified areas should detect subtle changes in the heat flow from the volcano which then may be related to changes in volcanic activity.

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