Reports

Summit Firn Caves, Mount Rainier, Washington

Abstract. *Heat and steam from the crater fumaroles have melted over 5700 feet (1737 meters) of cave passage in the ice-filled east crater of Mount Rainier. The caves are in approximate balance with the present geothermal heat release. Future changes in the thermal activity of the summit cone will cause corresponding changes in cave passage dimensions, location, and ceiling and wall ablation features.*

The twin summit craters of Mount Rainier in the Cascade Mountains of Washington (Fig. 1) may contain as much as 500 feet (152 m) of snow and ice. Melting at the bases of these ice masses by heat and steam emitted from the hot crater rocks has formed an extensive labyrinth of cave entrances and passages. To our knowledge no comparable system of steam-formed ice caves in a volcanic crater exists anywhere else in the world.

We have applied the term **firn cave** to the caves located within this ice mass because the ice density appears to be between 0.55 and 0.80 g/cm^3, the commonly accepted density of firn ice (*1*). No density measurements were made, but the estimated age of the ice as a few decades and the presence of abundant air bubbles in the ice suggests that true glacial ice is absent. The terms steam or ice cave seem inappropriate because steam occurs in other types of caves and ice cave usually refers to rock caves that contain ice that "persists through most or all of the summer and autumn" (*2*).

The summer of 1970 marked the first comprehensive investigations of the cave system since its discovery 100 years ago. In addition to our detailed studies, some reconnaissance work was accomplished by others (*3*).

Considerable attention is being focused on various aspects of the 14,400-foot (4,392-m) high volcano by scientists from several organizations. Earlier this year, steam vent temperature was relayed via a Nimbus 4 weather satellite to the Goddard Space Flight Center near Washington, D.C., for use by scientists of the National Aeronautics and Space Administration and the U.S. Geological Survey (*4*). Data on rock temperature at the summit surface were gathered during the summer of 1970 by D. Molenaar of the U.S. Geological Survey and by the staff of Project Crater sponsored by the National Geographic Society. In addition, U.S. Geological Survey seismometers recorded crustal disturbances in the Mount Rainier area during the summers of 1968 and 1969. Some of these projects were prompted by changes in thermal activity (*4*) recorded during the last 2 years by infrared surveys.

Should Mount Rainier become active again, the more than 1 billion gallons (3.8 billion liters) of water presently locked in the ice of the east crater could pose a threat to life and property (*5*). Although the crater ice volume is small compared with some of the debris flows and mudflows that have occurred on the mountain (*6*), the saturation of fresh and altered rocks with water derived from the melting crater ice or the sudden release of a crater lake could initiate a landslide or mudflow of tremendous proportions. F. G. Plummer (*7*) estimated that during an earthquake in 1870 a rockfall removed approximately 80 acres (32 hectares) from the southern edge of Liberty Cap, the northwestern peak of Mount Rainier. Many of the valleys that deeply dissect the mountain exhibit evidence of past mudflows and debris flows, some of which may have originated from the crater area. The extensively hydrothermally altered rocks in both summit craters would be highly susceptible to displacement during renewed volcanic activity, particularly if they became water saturated. Release of large quantities of warm or hot water could also cause surging, breakup, or other unusual behavior of the numerous glaciers on the mountain flanks.

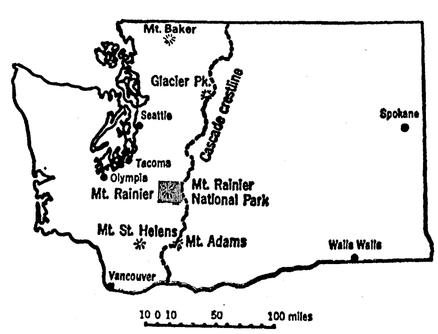

Fig. 1. Index map (State of Washington) (1 mile = 1.6 km).

Our detailed mapping and investigations of the cave system should furnish a more sensitive indicator of geothermal activity than is furnished by surface surveys. Periodic observations and resurveys of cave passages, in which changes in passage dimensions and location are noted, will enable the detection of heat-flow changes and of locations of volcanic emanation. Our initial expedition, conducted during August 1970, focused attention on the east summit crater, a nearly circular feature 1300 feet (396 m) across and over 600 feet (183 m) deep. The smaller and older western crater was explored but not mapped because of time limitations and because the cave system there is not so extensive. Because no published large-scale topographic map of the summit area exists and time did not permit us to construct one, we prepared a simple base map by using an engineer's compass and a resection survey method. Cave entrances and the results of our subsurface survey are plotted on the resulting base map (Fig. 2). The subsurface mapping was done with a steel tape and a tripod-mounted Brunton compass.

Three main entrances and numerous smaller ones at the upper crater margin lead down the 35- to 40-degree sloping crater walls and connect to a large perimeter passage that is 25 to 35 feet (7.6 to 10.6 m) across, 15 feet (4.6 m) high, and over 3000 feet (915 m) long. The passage winds three-quarters of the way around the crater. The combined length of all passages in the east crater exceeds 1 mile (1.6 km). The perimeter passage is surprisingly horizontal in its central part and lies about 200 feet (61 m) lower than the entrances. The horizontality may be controlled by localized thermal activity along an arcuate fault or other zone of structural weakness. If structural control were lacking, passage patterns should be more dendritic and follow the crater slope. An arcuate distribution of thermal anomalies as revealed by infrared imagery (*8*) also suggests the presence of arcuate structures.

Descending passages have vertical sides and ceilings that are convex upward (Fig. 3). Passages paralleling the slope contours (for instance, the large perimeter passage) are often shaped like right-angle triangles with the 90° angle located at the junction of the downslope ice wall and the ice ceiling. The floor slopes about 30° where mud to boulder-size volcanic rubble occurs and occasionally over 40° where bedrock is exposed. Only near some of the entrances and in one small area within the cave was the floor ice-covered.

The average free air temperature, except near entrances, is 4°C. Rock and steam temperature, however, is considerably higher. The highest ground temperature recorded was 86°C, and the highest steam temperature was 56°C. Sulfurous fumes occur locally in the west crater caves but are absent in the east crater. Hundreds of small fumaroles emit considerable quantities of steam that frequently impair visibility in the firn caves and make mapping, photography, and other observations difficult. Some of these fumaroles make audible hissing and gurgling noises. Although the rising heat and steam cause the ice walls and ceilings to drip constantly, no appreciable quantities of standing or flowing water were observed. The dripping water infiltrates into the floor and percolates toward the crater center. A small body of water could exist beneath the ice at the crater bottom, but these areas are presently inaccessible. Saluskin, a Yakima Indian, guided two men to the base of the mountain around 1854 and reported that the two climbers claimed to see a lake in the summit crater (*9*). An ash eruption from Mount Rainier sometime between 1820 and 1854 (*10*) suggests that sufficient heat to form such a lake was available. Flett (*11*) reported that rocks thrown into one of the caves of the east crater made splashing noises and indicated that standing water was present.

In many places on the floor against or near the ice wall of the perimeter passage are ridgelike accumulations of rock debris. They range from 1 to 3 feet (0.3 to 0.9 m) high and parallel the sides of the passage. They are composed of unsorted, unstratified mud and rock debris derived from the upslope portion of the cave floor. In places they occur toward the center of the floor and in others closer to or in contact with the downslope ice wall. They probably represent talus formed against a downslope ice wall that advances and retreats in response to temperature fluctuations. The fluctuations could be due to normal seasonal changes or to changes in volcanic thermal activity.

The lowest point mapped [elevation

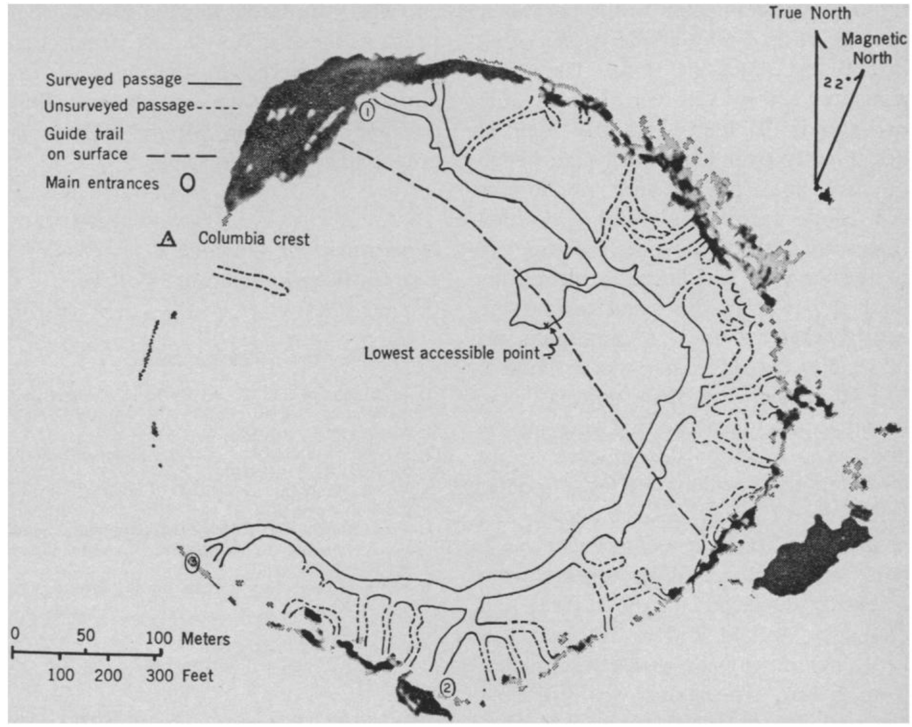

Fig. 2. Map of firn caves in the east crater of Mount Rainier, Washington [base map, National Park Service Air Photo MRNP-21-4 (16 September 1960)]. Columbia Crest represents the highest elevation at 14,410 feet (4,392 m). The elevation of the lowest accessible point is 13,870 feet (4,228 m).

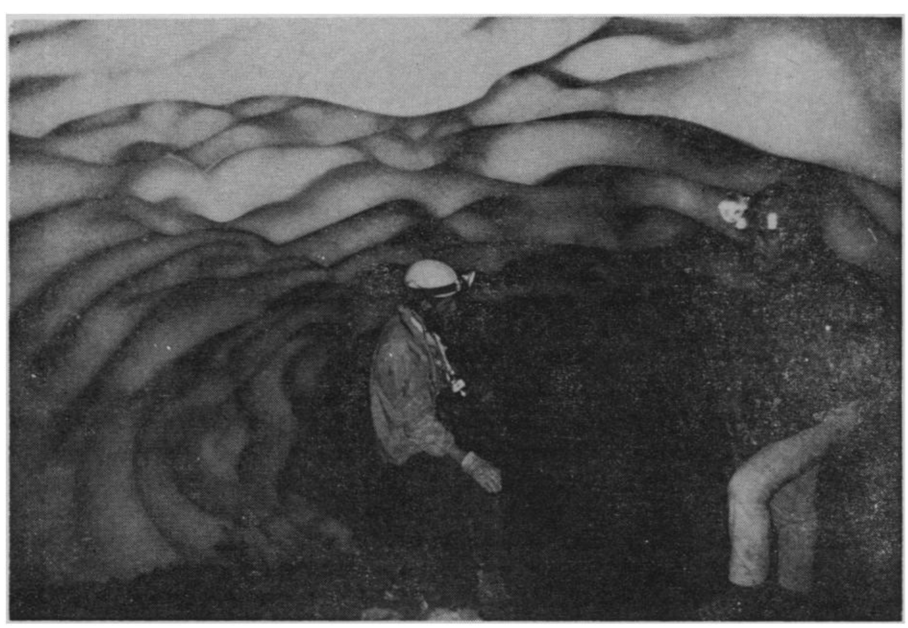

Fig. 3. View of passage descending from entrance 1 (see Fig. 2). The passage here is smaller than most, but the ceiling and wall fluting is typical.

13,870 feet (4,228 m)] is in a large room that is connected to the perimeter passage (Fig. 2) by a side passage that is 120 feet (36.6 m) long. The room measures 120 by 120 feet (36.6 by 36.6 m) and is 70 feet (21.3 m) high; it lies directly over a platform-like bench of rock that has a very precipitous downslope face. The crater wall continues to descend beyond the junction of the ice wall and floor. By projecting floor slopes from this point toward the nearby crater center, a maximum ice fill of 500 feet (152 m) was estimated.

Two rather unusual objects were found in this deep room. Lying on the floor was a badly decomposed shore bird, tentatively identified as a greater yellowlegs (*Totanus melanoleucus*), and protruding from the ceiling ice was a red woolen glove. Both objects were originally deposited on the surface and gradually worked 260 to 300 feet (79 to 91 m) downward as ice was melted from below. The glove was probably dropped less than 50 years ago by a climber, and the bird could have been a storm casualty. The frozen remains of a similar bird were found on the snow of the crater surface. The neck and head were missing from both animals, and we can offer no reasonable explanation for this.

We believe that an equilibrium exists between accumulation and melting of the crater ice. The ice above the big room probably melts at a rate of 5 to 6 feet (1.5 to 1.8 m) per year, and most of the crater ice is completely replaced every few decades. If the ice were stagnant and not actively subsiding, large ice flakes, similar to those found in the Paradise glacier caves (*12*), would develop on the cave ceiling. Flakes are large masses of ice that spall from the ceilings during periods of ice degeneration. The ice at deeper levels would also be expected to contain fewer air bubbles and be much denser if more time were available for recrystallization.

In places escaping steam has melted domelike grottoes into the ice. We call these features steam cups because of their resemblance to surface ablation features called sun cups by alpinists. The walls and ceilings of these steam cups are extremely smooth and broad, totally unlike the intricately fluted walls and ceilings of most passages (Fig. 3).

The presence of steam cups may mean that the ice mass at that point is moving downward too rapidly to allow fluted wall development or that new fumaroles have appeared. Each steam cup has a fumarole located directly beneath it. Because only a few steam cups were encountered in the mile of explored cave passage, we believe that thermal activity on Mount Rainier is not significantly increasing.

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13. We thank S. G. Chavet, W. Gates, R. Mack, J. Powell, and D. Sprague for their valuable assistance. The use of a McKinley expedition tent by Mountain Rescue Council, Tacoma, Washington, is greatly appreciated. The research was partially supported by a grant from Eastern Washington State College.

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Thermal Alteration of Silica Minerals: An Archeological Approach

Abstract. *Extensive experiments indicate that the application of heat to flint materials may have conferred an advantage to primitive man in the manufacture of chipped-stone implements. When Florida cherts are slowly heated to between 350° and 400°C and maintained at this temperature for sustained periods, a desirable change occurs in the fracture properties. This alteration takes place when the melting point of the impurities within the intercrystalline spaces is reached; thus the microcrystals of quartz are fitted closer together when materials other than quartz serve as fluxes.*

Crabtree and Butler (*1*) have suggested that thermal alteration may have played a role in facilitating the manufacture of chipped-stone implements by primitive man. Many projectile points as well as flint chipping debris from archeological sites in Florida exhibit the pinkish cast and vitreous luster indicative of thermal alteration. These objects differ markedly from materials found in outcrops. The research reported here was undertaken to test the hypothesis that the application of heat to flint materials may confer an advantage in the production of lithic tools (*2*).

A search of early historic accounts did not uncover any accurate description of the utilization of the technique of thermal alteration by aborigines (*3*). However, enough descriptions of the use of fire during some stage of stone tool manufacture were found to warrant the conclusion that primitive peoples realized that changes in siliceous materials occur when they are subjected to heat. One of the primary aims of the research reported here was to test the validity of recorded observations on the behavior of lithic materials when subjected to heating and cooling.

Most of the experiments were carried out on Florida cherts, but obsidian, English flint, Arkansas novaculite, and pure quartz were also tested. The conditions under which heating experiments were conducted were as follows: (i) the temperature was rapidly elevated, that is, the temperature was raised by 50°C increments and held approximately 1 hour at each succeeding increment until the testing temperature was reached (the length of time at the testing temperature varied); (ii) the temperatue was slowly elevated, that is, the temperature was raised by 50°C increments and held approximately 24 hours at each succeeding increment until the testing temperature was reached (the length of time at the testing temperature varied); (iii) the samples were immediately exposed to room temperature at the termination of the testing period; (iv) samples were cooled gradually in