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# CRATER FIRN CAVES OF MOUNT ST. HELENS, WASHINGTON

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*Systematic observation, photo-reconnaissance, mapping, and sampling were performed in the crater firn caves of Mount St. Helens, Washington, from 1981 through 1996 by members of the International Glaciospeleological Survey in cooperation with the United States Forest Service and Mount St. Helens National Monument.*

*Mount St. Helens is an active dacitic volcano, which is currently in a semi-dormant state after a catastrophic explosive eruption in May 1980. A dacite dome occupies the crater and plugs the volcanic vent. The crater area has been progressively covered by a layer of snow, firn, and glacier ice since as early as 1986. Heat, steam, and volcanic gases from the crater fumaroles melted over 2415 meters of cave passage in the crater ice mass. The caves are in approximate balance with the present geothermal heat release. Future changes in the thermal activity will influence the dimensions, location, ceiling, wall, and wall ablation features of these caves. Cave passages are located above fumaroles and fractures in and adjacent to the crater lava dome. Cave passages gradually enlarge by ablation, caused by outside air circulation and by geothermal sources beneath the ice. The passages form a circumferential pattern around the dome, with entrance passages on the dome flanks. Passages grow laterally and vertically toward the surface, spawning ceiling collapse.*

*The crater ice body has been expanding since 1986 and its mean density increases each year. It possesses at least two active crevasses. Trends and changes in geothermal activity in the crater of Mount St. Helens have been noticeable through cave passage observation and re-mapping.*

This paper describes the crater firn caves of Mount St. Helens, Washington, a system of melt passages in firn ice in the crater of an active Pacific Rim volcano. Observations described were conducted from 1981 through 1996. Glaciologists have made mention of firn, crater, steam, and geothermal caves (Kiver & Mumma, 1975; Kiver & Steel, 1975), and sometimes have dealt with their origin to a limited degree. No one has provided timely observation of the evolution of geothermal ice cave systems in detail. International Glaciospeleological Survey (IGS) members are currently conducting these studies in the crater firn caves of Mount St. Helens, and have done so in an ongoing fashion throughout the development of the crater snowpack. This study documents an unique opportunity to capture data on the interaction of geothermal energy and alpine snowpack accumulation from its inception after the eruption of the volcano in 1980.

Crater reconnaissance in 1981 preceded annual surveys that began in 1982 with mapping, documention, and photography of cave passages, snow, firn, and glacier ice (Fig. 1). Several years of observations and data have been collected, but they have not been systematically interpreted at this point. We have examined temporal relationships of the behavior of the system in terms of cause and effect. Our conclusions are based on preliminary results and qualitative interpretation. We intend to offer what explanation we can for the trend of development observed in crater firn caves at Mount St. Helens.

**Figure 1. One of the crater firn caves of Mt. St. Helens. Photo courtesy of Rob Huff.**

## GEOLOGIC SETTING

### LAVA DOME AND CRATER

Pringle (1993) summarized the geology of Mount St. Helens. The Lava Dome consists of dacite. The west crater wall exposes a good cross-section of the volcano before the 1980 eruption. The lower section of the crater wall consists of a dacite dome of Pine Creek age (~3000-2500 yrs B.P.). This dacite dome is cut by dikes of the Castle Creek age

**Figure 2. Photo showing a cross section of the volcano before the 1980 eruption and the 330 m high lava dome in the crater of Mt. St. Helens. Photo by Charles H. Anderson, Jr.**

(~2500-1500 yrs B.P.), some of the feeder dikes for the Cave Basalt Eruption that formed Ape Cave. Above the Cave Basalt is the dacite summit dome of Kalama Age (~500-200 yrs B.P.), the pre-1980 summit dome of Mount St. Helens (Fig. 2).

### ERUPTION HISTORY

Mount St. Helens is located in the southwest Cascade Mountains of Washington State, U.S.A. Mount St. Helens has been called the most violent, active volcano in the United States. It erupted at 8:32 a.m. on May 18, 1980, sending billowing columns of ash high into the atmosphere (Tilling et al., 1990). The eruption was preceded seconds earlier by a magnitude 5.1 earthquake, which caused a large portion of the north flank of the mountain to slide. Immediately afterward, an explosive lateral blast was directed northward through the still-moving slide block, closely followed by a summit eruption of ash and steam.

On May 19, 1980, when the extent of damage to the volcano was revealed, the entire north flank was gone. The greatly enlarged and deepened crater was horseshoe-shaped, open to the north with the south of the mountain then the highest part of the volcano at ~2502 m msl. The lip of the open crater on the north was estimated to be about 1890 m msl. Mount St. Helens remains a potentially active and dangerous volcano, though it now (1997) appears quiescent. In the last 515 years, it produced four major explosive eruptions and dozens of lesser eruptions.

On June 15, 1980, the formation of a small lava dome on the floor of the crater was evident. The ~185 m in diameter dome was less than 37 m high. By June 23, 1980, it had grown to be 200 m long and 60 m high. From May 1980 to October 1986, there have been a series of 16 dome-building eruptions, constructing the new 305 m (1,000 feet) high and 915 m wide lava dome in the crater formed by the May 18, 1980, eruption (Swanson & Holcomb, 1989). The nearly 1.6 km wide, 3.2 km long, 610 m deep crater is so large it makes the lava dome seem small (Fig. 2). The Washington Monument placed in the crater would only be half as high as the lava dome.

### EFFECTS ON PRE-EXISTING GLACIERS OF MOUNT ST. HELENS

From analysis of USGS topographic maps, the May 1980 eruption removed all of the Loowit and Leschi Glaciers and parts of the Ape, Forsyth, Nelson, Toutle, Shoestring, Smith and Wishbone Glaciers, more than 70% of the pre-eruption ice volume. Only two unnamed glaciers on the south side suffered no net volume loss of ice during the eruption. The eruption removed Forsyth and the Shoestring Glaciers zones of snow accumulation and ~75% of their volumes of glacier ice. As a result, the Shoestring Glacier has suffered significant ablation.

In 1981, following the great eruption, a surge occurred in Shoestring Glacier. Apparently, the weight of volcanic debris, added to a fairly heavy snow load in the winter of 1980-81, produced a sudden budget overbalance in spite of removal of a substantial portion of the original ice volume. The surge behavior was not repeated the following year.

### SNOW, FIRN, AND ICE IN MOUNT ST. HELENS CRATER

The shade from the high, steep crater walls to the south and west protects a large volume of the snow and ice that is presently accumulating in Mount St. Helens Crater. Crater ice volume increased from ~2.8 x $10^7$ $m^3$ of uncompacted snow and firn in 1988 to over 5.5 x $10^7$ $m^3$ in 1995. These figures are derived from published USGS figures modified by consideration of thickness data collected from direct cave observation. As of late 1996, the crater was estimated to have 5.85 x $10^7$ $m^3$ of ice, firn, and snow (Fig. 3).

During the winters since 1982, snow and ice avalanches from the crater walls contributed to the formation of a snow and ice field on the south (interior) side of the lava dome. The accumulation of avalanche material from the crater walls

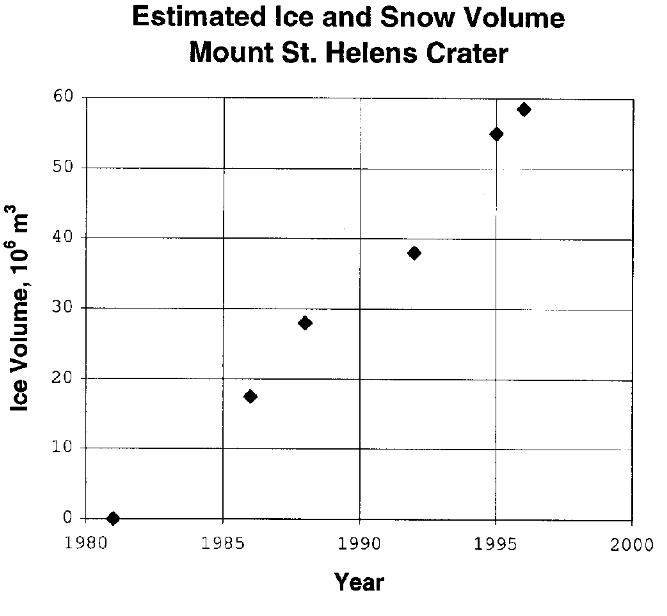



**Figure 3. Ice and snow volume in the crater of Mt. St. Helens.**

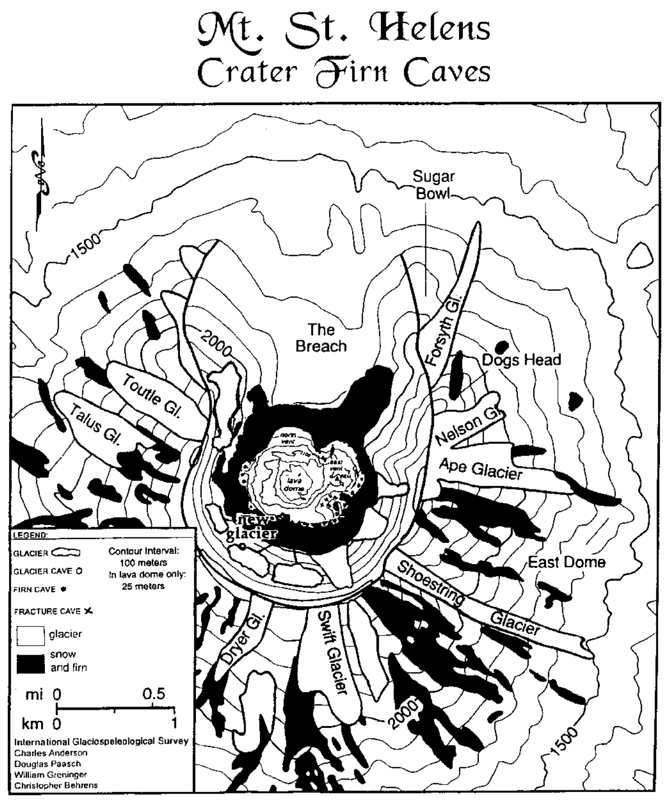
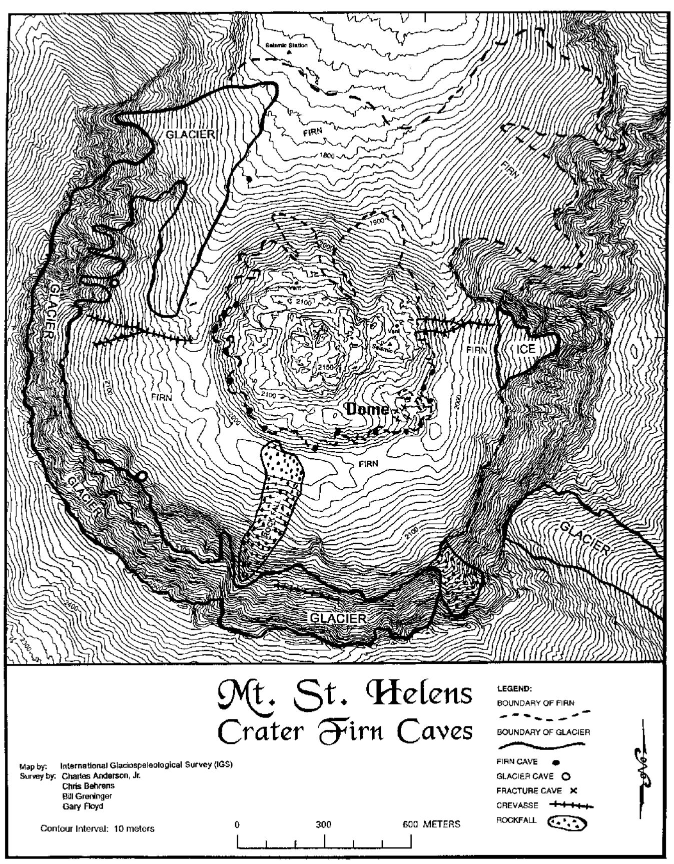



**Figure 4 (above) and Figure 5 (below).**




helped form an ice field ~60 m thick, based on crater firn cave surveys. The crater icefield is an incipient glacier that continues to grow.

The snow and ice on the south crater wall behind the lava dome have crevasses and flow features that show that a new glacier is forming (Fig. 4). The ice mass shows signs of ice flow around both sides of the lava dome and flowing out to the front of the dome. The rate of advance may be greater than any other glacier in the contiguous U.S. in recent centuries. The new glacier is forming between the south crater wall and the lava dome (Fig. 5). Snow stacking higher each year locally compresses the lower layers into glacial ice. There are at least two radial crevasses in the permanent ice field. One crevasse is located on the northwest side and another is on the northeast side of the crater, near the lava dome. Both crevasses penetrate through the lowermost layers of the permanent ice field. The crevasse on the northwest side was revealed when the roof of an ice cave collapsed, due possibly to thrust fault activity in the crater floor around September 1994. The ice density in

**Figure 6. The firn section of the ice mass in the crater of Mt. St. Helens showing a large crevasse. Crevasses are located at the northwest and northeast sides of the crater near the lava dome. Photo by Charles H. Anderson, Jr.**

September 1994 at the base of this crevasse was 0.85 g/cm$^3$. The ice density in the lowest cave passage was 0.86 g/cm$^3$ (September 1996; see Fig. 6). Density measurements were performed using a cylindrical saw, and by weighing and measuring the cut samples in the field.

### PROGRESSIVE RECRYSTALLIZATION

When winter's snowpack survives the summer and is buried by the following winter pack, the buried snow layer compacts and recrystallizes. New-fallen snow has a density of 0.06 to 0.08 g/cm$^3$. As water percolates through the snowpack and daily temperatures fluctuate, individual snowflakes metamorphose first to subspherical porous grains and later to granules of solid ice (corn snow). Density of the snowpack rises from ~0.1 to ~0.3 g/cm$^3$. When snow recrystallizes so that its density reaches an arbitrary value of 0.55, it becomes firn. As long as the firn has air pockets, the recrystallization process can increase its density. After 25 to 150 seasons, the density in a glacier reaches 0.88 g/cm$^3$ or more. Density of solid ice is ~0.92 g/cm$^3$. The process only continues if the confining pressure increases (Sharp, 1960).

Generally in the ice caves, firn is distinguished from recrystallized recent snow (corn snow) by stratigraphic relationships. Glacial ice forms from firn at a density of 0.82 g/cm$^3$, at which point the individual crystals become firmly interlocked with one another and the material possesses an inherent hardness (Sharp, 1960).

Multiple years of winter snowpacks were preserved between 1986 through 1997 and provided the pressure necessary to convert crater snowfall into a permanent firn field. As recrystallization continued in the deepest layers, the glacial ice formed a rigid fabric with limited permeability. From 1986 to 1996, gradual increases in basal ice densities were subjectively observed (though not measured) in cave passages, including the transition from snow to firn to ice. An apparently abrupt decrease in percolating water was noted in the final stage of this transition. We interpret this condition to result from bulk freezing in intergranular pores. Clearly, after a series of heavy winters and/or mild summers, there can be such a sequence of yearly net accumulations that it would take many years to degrade the body enough to remove them. In this way a "permanent" glacial core developed and is perpetuated in the Mount St. Helens crater.

### GEOTHERMAL ACTIVITY IN THE CRATER

The Mount St. Helens lava dome is the locus of the active volcanic vent. It, therefore, is a source of volcanic gas emissions. The caves are a primary result of the concentration of heat in an ice-and-snow covered terrain. They are localized at active fumaroles and form as conduits of escape for the heated gases. They are further modified by the drainage of heated surface water from the dome directly into the ice body.

Periodic observations and resurveys of cave passages, noting changes in passage dimensions and location, enabled the detection of heat-flow changes and of locations of volcanic emanations. Sulfurous fumes locally occur in the caves. 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 have been observed in the caves.

Gases from the numerous fumaroles and slowly circulating surface air mix throughout the cave passages. The degree of such mixing is most obviously recognized by the presence of breathable air throughout the known cave system. We have not observed stagnant or poisonous air compositions. Routine safety practice include carrying portable hydrogen sulfide and carbon monoxide detectors during new passage exploration. Many of the larger cave rooms provide a protected environment for monitoring volcanic gas composition. These rooms are ideal sites for prolonged monitoring of changes in volcanic emanations because they are relatively easy to find and their narrow connections with the upslope cave passages prevent rapid mixing with outside air.

If Mount St. Helens were to begin another eruptive phase, the first indications may be changes in the firn cave morphology (triggered by increased heat flow), together with increases in volcanic gas concentrations and microseismic activity. Passages may enlarge due to increases in the volume and temperature of steam and gas emissions from the fumaroles. Such observations might signal danger.

### CRATER FIRN CAVES OF MOUNT ST. HELENS

The crater firn caves are located in firn ice behind the lava dome of Mount St. Helens. The firn ice field is elongated east-to-west with a steep crater headwall rising up to 2550 m (8365 ft) on the south margin (Fig. 5). The firn ice field proper is

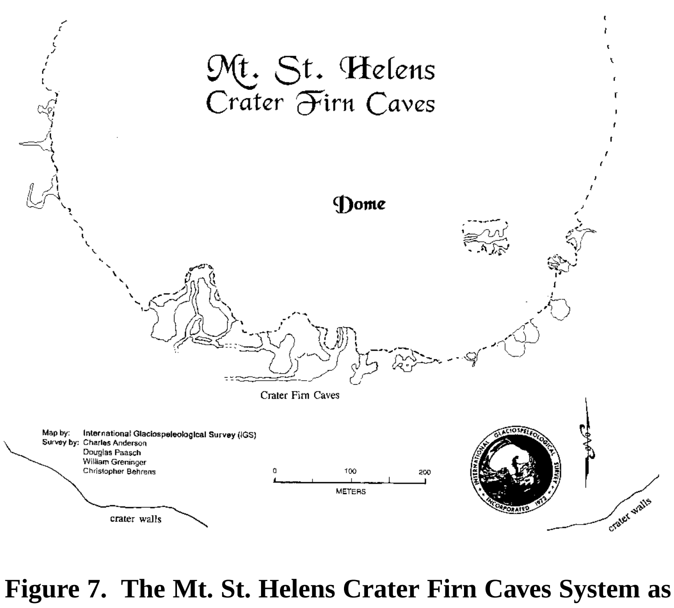



**Figure 7. The Mt. St. Helens Crater Firn Caves System as mapped in 1996.**

**Figure 8. One of the crater firn caves, looking up at scallops on the cave walls. Photo by Charles H. Anderson, Jr.**

**Figure 9. Ice stalagmite in the crater firn caves near the lowest passage. Photo by Charles H. Anderson, Jr.**

ice mass (Fig. 7). The caves are interpreted to be approximately in balance with the present geothermal heat release because they have reached an apparently stable morphology. Future changes in the thermal activity will influence the dimensions, location, ceiling, wall, and wall ablation features of these caves. Rapid enlargement forms "steam cups" (Kiver & Steel, 1975). Air circulation converts these to the typical scalloped ceiling and wall form ubiquitous in ice caves (Anderson et al., 1994).

Entrances to 15 firn caves have been identified around the perimeter of the lava dome. These caves were mapped in 1996 (Fig. 7). Some have spectacular large rooms. Most have small rooms and crawlways. Cave features include scalloped surfaces of ceilings and walls, moulins in the ceiling, multiple domes connected by crawlways, skylights, and, in winter, helictites, stalactites, and stalagmites of ice (Figs. 8 & 9). Room sizes in 1996 varied from 12 m x 24 m x 6 m high to 4.6 m x 4.6 m x 2.4 m high. The caves are generally associated with fumaroles. Other caves form on the crater and dome walls where melt water undermines the firn and glacial ice.

Six main entrances and numerous smaller ones behind the lava dome lead down the 40º sloping crater floor immediately adjacent to the dome (Fig. 10). The perimeter passage is surprisingly horizontal. The horizontality may be controlled by localized thermal activity along an arcuate fault or fracture zone within the lava dome. An arcuate distribution of thermal anomalies suggests that volcanic emanations are escaping around a plug-like lava body (the dome itself) in the vent and also suggests a circumferential trend. Descending passages have vertical sides and ceilings that are convex upward. Passages paralleling the slope contours are commonly shaped like right triangles with the 90º angle located at the junction of the downslope ice wall and the ice ceiling. The floor slopes are about 30º where mud to boulder-size volcanic rubble occur and occasionally over 40º where bedrock is

below the headwall on the southeast wall of the crater, rising to a maximum elevation of 1990 m (6520 ft) on the south side of the lava dome, and sloping downward to the northeast. Further to the northeast, the firn ice field rises gently to a saddle (1890 m or 6200 ft msl) adjacent to the crater wall.

The caves are called firn caves because ice density ranges from 0.55 to 0.82 g/cm$^3$. Sub-ice fumaroles and warm air currents form and maintain the cave passage beneath the ice field behind the lava dome. Heat and steam from the crater fumaroles melted over 2,415 m of cave passage in the crater

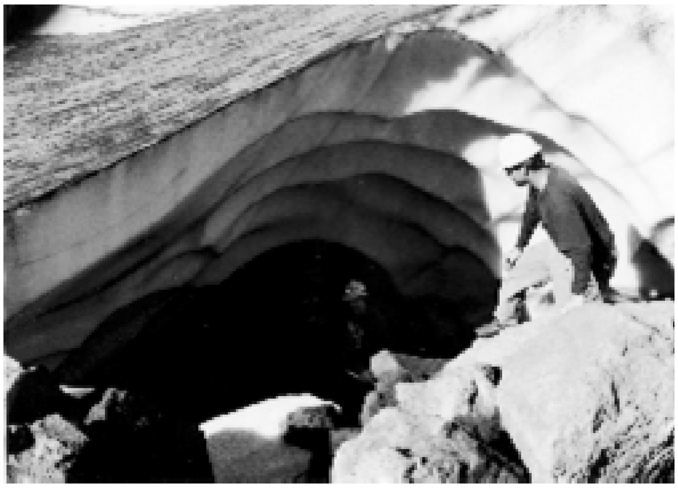


**Figure 10. Team members climbing down the lava dome to the entrance of the lowest passage which is parallel to the lava dome. Photo by Charles H. Anderson, Jr.**

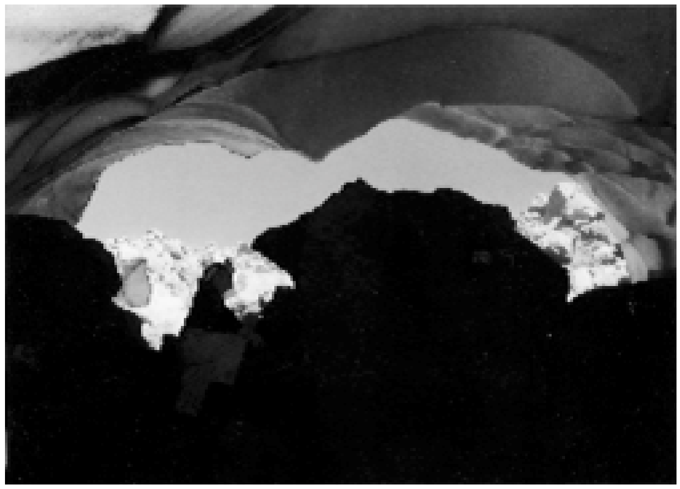


**Figure 11. Climbing from an ice cave entrance with the lava dome in the background. Photo by Charles H. Anderson, Jr.**

exposed (Fig. 11).

Ridge-like accumulations of rock debris from the lava dome occur in many places on the floor against or near the ice wall of the passage (Fig. 12). They are composed of unsorted, unstratified mud and rock debris derived from the upslope portion of the cave floor. They occur toward the center of the floor in some sites and in others closer to or in contact with the downslope ice wall. They probably represent talus formed against a downslope ice wall. This wall appears to retreat in response to temperature fluctuations. Fluctuation may be due to normal seasonal changes or to changes in volcanic thermal activity.

### Ablation Process

Evaporation/sublimation and heat conduction are the major active processes of ablation within the cave (Anderson et al., 1994). Since caves are sheltered from sunlight, radiation from the sun has no effect, but radiant heat from the heated ground and fumaroles may have an appreciable effect. The main control of cave ablation is the amount of air flow against the walls of the cave. Since the crater cave passage networks extend over vertical distances, convective circulation affects the ice cave system, especially volcanic heat sources. The flow rate is greatest in the least restrictive passage morphology. Since the ablation rate is faster where air flow is greatest, trunk passages will be initiated and become dominant.

### External Air Communication

As cave ablation and surface ablation continue through a summer season, the cave ceiling often approaches and intersects the ice surface over time. If the ice is fractured, or perhaps after winter snow adds weight to the ceiling, a cave passage may experience ceiling failure. In either case, the cave system suddenly gains a vent to outside air. The effect of venting in summer is to allow cold cave air out and warm outside air in. The effect is reversed in winter. Any superimposed restriction in the system, such as winter snow or rockfall blocking other entrances, exaggerates the importance of ablation vents. The vent entrance is a major means of communication with outside air. When all vents to the surface are closed, ordinary glacier caves become dormant. In crater firn caves that contain internal heat sources, the ablation process can continue by convection even when all external openings are blocked. The system is, therefore, less seasonally dependent and may evolve much faster than an ordinary glacier cave.

### Crater Access at Mount St. Helens

Crater access in the Mount St. Helens Administrative Closure Area is through a permit for scientific research issued to the International Glaciospeleological Survey by the United

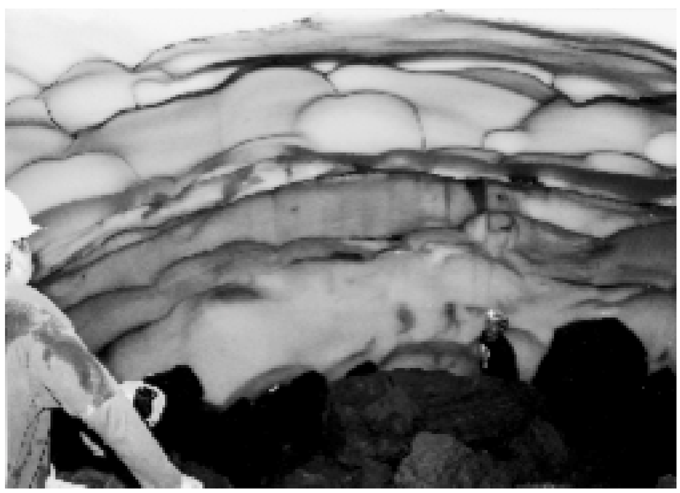


**Figure 12. The lowest cave passge where glacier ice is showing on September 29, 1996. Photo by Charles H. Anderson, Jr.**

States Forest Service. Specific application is required by the Forest Service for each crater visit. The crater is closed to public access, and anyone found without a crater permit within closed areas can be arrested and fined.

### HAZARDS OF CRATER CAVE STUDY

Since Mount St. Helens is active, there is an ever-present danger of volcanic eruption occurring while exploring the crater area (USGS, 1994). Since November 1986, Mount St. Helens has been relatively quiet except for occasional steam explosions and ash plumes reaching as high as 5.6 km msl (Swanson et al., 1987; Tilling et al., 1990). Even a small eruption of this type would be life threatening to anyone in the crater, if for no other reason than the poisonous nature of volcanic gases. Explosions have thrown rocks more than 1.0 km from the lava dome and have generated small pyroclastic flows in the crater. Although these explosions generated widespread public interest, they have been confined to the crater. In the recent geologic past, when pyroclastic flows encountered an abundant water supply (perhaps snow and ice), they generated volcanic debris flows (lahars) that have been traced more than 16 km from the crater down Mount St. Helens' north flank and connecting valleys (Wolfe & Pierson, 1995).

Inside the crater there are many rockfalls from the crater walls and the lava dome. These rockfalls pose a significant hazard to explorers entering the crater between August and November. In winter, snow avalanches off the crater walls and the lava dome has been large enough to flow out of the crater.

The ice caves themselves present a hazard in the snow field areas. These caves are changing each day and explorers must expect the entrances to collapse as cave passages grow internally by melting. At any time during the hottest time of the day from June through September, roof collapse can occur spontaneously. At any time, day or night, traverse over potentially thin roof ice is dangerous, and should be met with the same caution and preparation as for glacier traverse in the presence of hidden crevasses. Ice caves can also trap $SO_2$, $H_2S$, and $CO_2$ gas emitted by the volcanic fumaroles throughout the lava dome area. Breathable air is displaced by these gases, and people have died entering ice caves formed in these conditions on Mount Hood in Oregon (Kiver & Mumma, 1975).

## CONCLUSIONS

The results of this ongoing study will lead to a more thorough understanding of crater firn cave evolution at Mount St. Helens or any locale where ice accumulation interacts with geothermal energy. Cave formation was initiated above fumaroles located along fractures in and adjacent to the lava dome. Cave passages gradually enlarge by ablation, caused by outside air circulation and by geothermal sources beneath the ice. Passages grow laterally and vertically toward the surface, spawning ceiling collapse. The network of fumaroles have produced a ring of relatively horizontal passage connected to the surface by a number of ascending entrance passages.

An ice body is forming and expanding in the Mount St. Helens crater. Its mean density is increasing with each passing year, and the transition from snow to firn to glacier ice (with active crevasses) has been observed. Net budget balances have been positive in the crater since 1986, when the snowpack was first subjectively recognized to be growing.

Trends and changes in geothermal activity in the crater of Mount St. Helens have become noticeable through cave passage observation and remapping. Our detailed mapping and investigations of the crater cave system should furnish a more sensitive indicator of geothermal activity than is furnished by remote surveys.

## ACKNOWLEDGMENTS

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