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MONITORING THE DISAPPEARANCE OF A PERENNIAL ICE DEPOSIT IN MERRILL CAVE

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Abstract: Merrill Cave, part of a Pleistocene lava flow within Lava Beds National Monument, is the site of ice deposits that have fluctuated widely in volume between the Pleistocene and Holocene Epochs. Remnant mineral deposition from ice levels on the walls in the lower level of the cave provides insight into the depth of the ice during this time. The disappearance of a large perennial ice deposit in the lower level of the cave was tracked using historical photographs and modern photographic and ice-level monitoring techniques. A major change in airflow patterns and temperatures in an as yet unexplored lower level of the cave are suspected to have initiated the decline in ice levels. Measurements taken of the elevation of the surface of the ice deposit show a loss of over 1.25 m of ice in eight years. Surface and interior losses of ice from evaporation and/or sublimation have resulted in the near total loss of the large main perennial ice pond in the lower level of the cave. Photographs also document a drastic change in ice volume and levels during the same period of time. Several theories for the disappearance of ice have been suggested. One possible explanation for the loss of ice is related to a significant seismic event in the region in 1993 that may have caused rock fall in another, inaccessible section of the cave and precipitated the loss of ice in the accessible lower level. The dramatic loss of ice may also be the result of climate changes that, over time, indirectly influenced ice levels in Merrill Cave. Visitor impacts to the ice deposit after a large cavity breached the surface of the deposit contributed to the decline of ice conditions. Lastly, the presence of western juniper (*Juniperus occidentalis*) in the terrestrial environment above the cave may influence the hydrology of the cave environment.

Introduction

Lava Beds National Monument is located along the California–Oregon border. It is the site of scores of lava-tube caves and well preserved geologically young volcanic features. The lava flows in the park originated from a variety of vents and covered the entire park, leaving behind nine distinctive lava tube systems that stretch for up to 42 km under the Monument's landscape (Fig. 1). These flows extended to and under Tule Lake, an extensive, shallow Ice Age lake, before it was largely drained in the early 1900s. As these flows cooled, they left behind extensive networks of lava tubes, jumbled aa lava flows, lava lakes, sag basins and inflation plateaus. The basaltic lava flows that created the caves were erupted over 10,000 years ago in the late Pleistocene (Donnelly-Nolan and Champion, 1987; Waters, et al., 1990; U.S. National Park Service, 2003). As of December 2005, field reconnaissance has located 502 caves and other lava tube features within the monument that total over 45 km of underground passage.

The surrounding high elevation desert environment on the northern flank of the Medicine Lake Volcano, a southern Cascade Mountain Range volcano covering approximately 2300 km^2, supports a patchwork of bunchgrass, sage, and juniper in the lower lying areas, while in the higher elevations, ponderosa and lodge pole pine communities predominate. This diverse region of northern California encompasses an awe-inspiring landscape. It lies at the junction of the Sierra-Klamath, Great Basin, and Cascades geographic regions.

Background

Water is a scarce natural resource in this semiarid environment. No surface water sources are present within Lava Beds National Monument. However, ice caves within the Monument, replenished by seasonal rains and winter snow melt, provide critical sources of water for wildlife. Ice levels in these caves have been tracked annually since 1990 to monitor the fluctuation of the ice from season to season and year to year.

Merrill Cave, a historically notable cave, was explored by visitors to the Monument in the early 1900s who passed by it on the first wagon road into the area. Although known to prehistoric Indians living in the area, the first documentation made of the cave was in 1888 by a trapper named Tom Durham. It was named after the Merrill Family of Klamath Falls, Oregon. In 1917 Charles H. Merrill homesteaded 160 acres of land in the area that included Merrill Cave. He operated a resort near the cave for four years. The land was donated by the Merrill family to the National Park Service in 1938 (Larson and Larson, 1990).

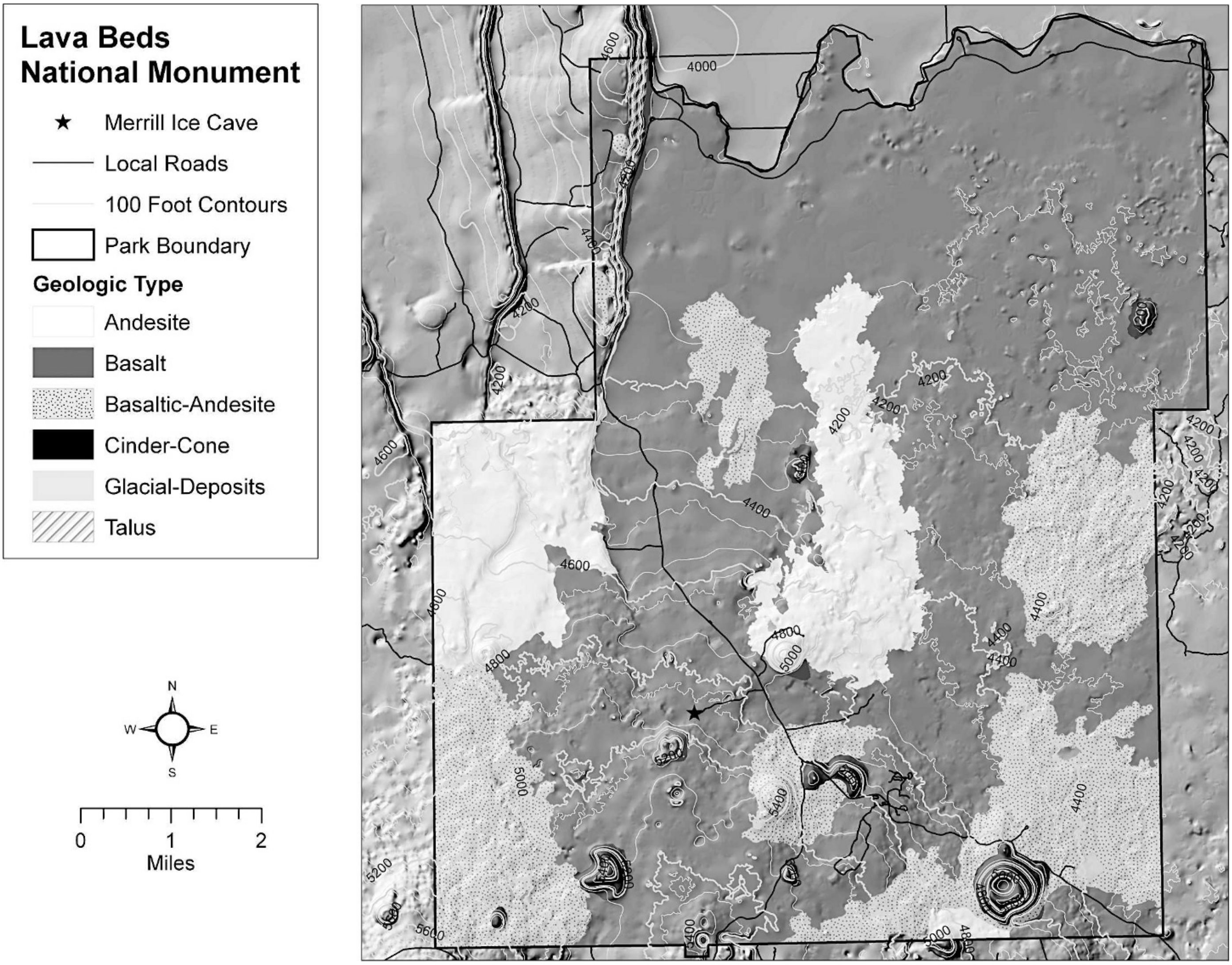

Figure 1. Lava Beds National Monument topographic and geologic map. NPS map by Jason Mateljak.

Merrill/Skull Lava Tube

Merrill Cave (Fig. 2), with an entrance elevation of 1488 m and a total length of 198 m, contains two levels of a master tube known as the Merrill/Skull distributary. The lava flow in which Merrill Cave is found traverses 16 km of the Monument beginning at Modoc Crater and terminating near the pre-settlement shoreline of Tule Lake. The lower level of the cave contains a main ice deposit. Ice caves form in lava tubes when dense colder air settles into a lower level during the winter months and is trapped. Caves with cold-traps may have temperatures around 10 °C below what would be expected at the latitude and altitude where they are found (Moore and Sullivan, 1978). Yonge (2004) discusses seasonal and permanent ice in caves as a result of physical and environmental mechanisms. Water from surface precipitation events is continually deposited in this lower section of Merrill Cave and freezes, forming a perennial ice deposit. The upstream and downstream passages leading to the pond in the lower level also have shallow ice deposits and fluctuate markedly from season to season, dependant upon local precipitation patterns. The main ice pond surface has been fed from these two smaller ice deposits in the lower passage. Developments in the cave that included two stairways leading down to the lower level, walkways on the upper and lower levels, and a catwalk platform over the ice deposit in the lower level were added during the era of the Civilian Conservation Corps in the early 1930s, and improved by the National Park Service in 1957. In 2003, the catwalk platform was removed because its footings were compromised by the receding ice. It was replaced by a viewing platform at the north end of the deposit.

History

There is evidence that the large main ice deposit in the lower 110 m-long passage of the cave has fluctuated dramatically over several thousand years. The climate, and thus the ice, was influenced by Pleistocene glacial

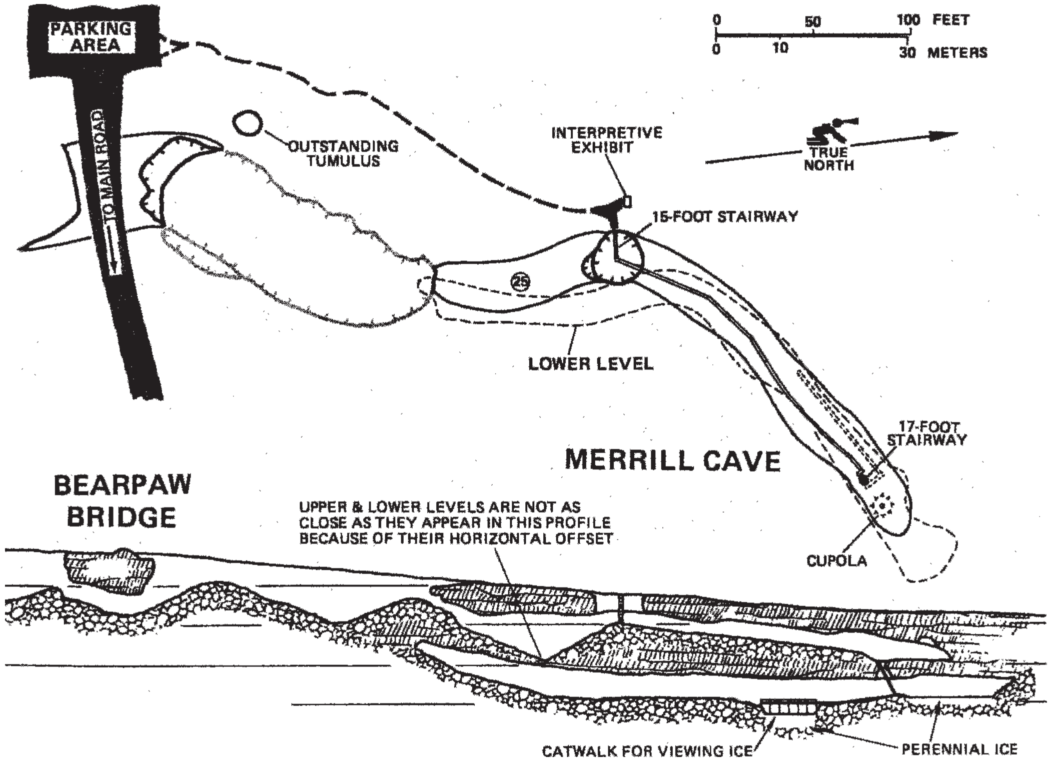

Figure 2. Merrill Cave map showing the upper and lower levels of the cave with cross section and top views (Larson and Larson, 1990).

advances and retreats during the Wisconsin Period 70,000 to 10,000 years ago. Well-defined ice horizon marks in the lower level of the cave, formed by minerals deposited in the ice and seasonal melt water interface, indicate that ice filled most of the lower master tube for an extended period of time in the past (Fig. 3). Over much of the past 40 years, until 1998, photo documentation of the ice has revealed that ice levels have increased. Feeder ice flows at either end of the main ice deposit in Merrill Cave remained relatively constant.

In the spring of 1997, a group of National Park Service employees and Cave Research Foundation (CRF) members noticed a pocket of air beneath the surface of the ice. In November 1997, CRF volunteers taking ice level measurements recorded a small 0.3 m diameter hole that had appeared on the surface of the ice deposit (Sowers and Devereaux, 2000). Below the surface, a large cavity had developed in the ice deposit and a very strong current of air blew out of the hole. The flow of air from beneath the hole, coupled with acts of vandalism, caused the hole to expand rapidly. In addition to the expansion of the cavity in the ice, large amounts of debris had begun to accumulate on the ice. The source of this debris was unknown. One scenario suggested the source of the debris was fallen material from the cave ceiling or reemerged material buried in the ice deposit. Another scenario suggested that visitors to the cave were throwing rocks from breakdown debris deposits onto the floor in an attempt to enlarge the size of the hole by collapsing the edges of it. Precautionary measures were taken to protect cave visitors as well as cave resources. Merrill Cave was closed to all visitors in spring of 1999 for public safety and resource protection purposes. It was reopened in 2003, after the safety issues were resolved and the catwalk platform over the ice deposit was relocated.

Monitoring of the lower level ice deposit was deemed necessary to record the processes taking place, identify the source of rock fall, and investigate safety concerns. Regular photo monitoring of the ice in Merrill Cave began in 1990. In addition, other monitoring activities included rock fall, ice level, and temperature/relative humidity. This report is a summary of the results of these monitoring activities and what has been learned.

A complex relationship of environmental conditions and geological processes is present in Merrill Cave, but not fully understood. The development of a large subsurface ice cavity in the perennial ice deposit and the subsequent near-total disappearance of the ice are perhaps part of a long term cycle of ice recurrence in the cave. However, current speculation explaining the cavity formation in the deposit suggests that airflow from beneath the ice deposit has changed, allowing warmer air to slowly sublimate and evaporate the ice from the base of the deposit. This change of airflow could have been the result of the movement of rocks in a lower, inaccessible level of the cave. However,

Figure 3. Ice level mineral deposits. Field of view is approximately 2.5 m in height. The white mineral stains (indicated with arrows) reveal a history of extensive ice levels in the lower level of the cave.

definite evidence is presently unobtainable because the lower reaches of the passage are blocked with rubble.

Methods

A long term, multi-purpose monitoring program was developed for Merrill Cave by the CRF and the NPS that was cost effective and efficient. All ice level measurements were taken from a pre-established monitoring datum on the cave wall identified by a metal screw (zero line on Fig. 4) installed into the cave wall. This method was implemented by the CRF to monitor and track changes in ice levels in selected caves within Lava Beds National Monument over an extended period of time. Fluctuation in the distances between the datum and the ice deposit indicated increasing or decreasing ice levels. The accuracy of this methodology can be influenced by conditions within the cave such as air flow patterns, temperature changes, and rates of evaporation/sublimation; and extrinsically through the movement of water from the surface through soil substrates and into the cave and the location of the deposition of this water onto the ice. However, for monitoring purposes, this method can provide a useful reference of ice levels over time.

Historical photographs in park archives provided views of the Merrill Cave main ice deposit in the 1960s. The cave photo monitoring program was established by the CRF to provide documentation of changes in cave

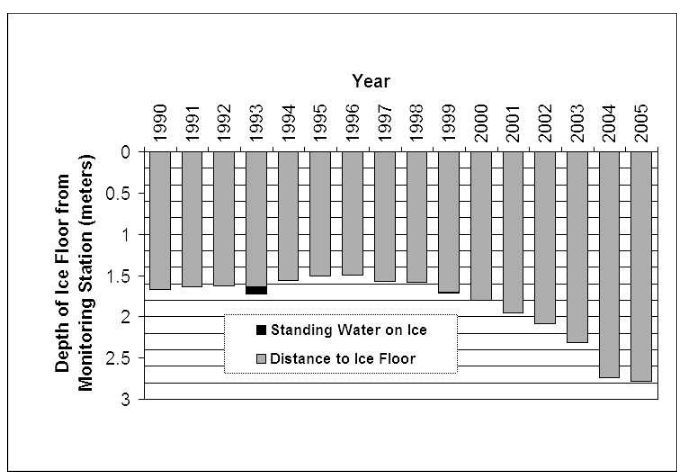

Figure 4. Ice levels of the main perennial ice deposit in Merrill Cave.

environments over time as influenced by natural processes and human activity. Beginning in 1990, the photo monitoring program established a photo point at the down-flow edge of the ice deposit. Photos were to be retaken every five years from the same locations. This schedule was not adhered to until 1998 when additional NPS personnel were available to carry out a regular monitoring schedule. Annual photos were taken after the ice cavity was discovered in Merrill Cave to closely monitor the process and document changes. Photo monitoring points were selected to cover a variety of views of the main ice deposit in the lower level of the cave. Photo monitoring stations were initially set up by the CRF and located by identifying a representative view of the ice floor, measuring from the camera to significant features such as cave walls, marked by plastic survey flagging. All information was recorded on a photo monitoring data form in addition to a sketch of the photo point location. Additional photo monitoring stations were established later by the author using the same methodology. Photos were taken using a Nikon FM 2 35 mm camera with a 28–80 mm lens, 200 ASA film, and remote electronic flash. A Nikon D100 digital SLR camera with a 28–80 mm lens was used to take the 2005 photo from the recently constructed viewing platform.

After rock material began appearing on the surface of the ice deposit, NPS staff deemed it necessary to identify where the material was originating. Initial theories included falling ceiling material, reappearance of rock material from within the ice that had been deposited on the ice floor in the past or moved up through the floor from the bottom of the deposit, and vandalism. A 3 × 9 m rock fall monitoring station was established in 1999 on the ice below the catwalk over the floor using plastic survey flagging. Photographs were taken of the ice floor within this monitoring station for two years to measure quantities of rock fall and changes in surface ice conditions.

During the Summer of 2001 and Spring of 2002 Hobo brand data loggers from Onset, Inc. were used to measure short-term fluctuations in environmental conditions inside the ice cavity and on the surface of the ice deposit in the lower level of the cave. Loggers were set to record temperature and relative humidity conditions every hour in the two locations for eight months.

MONITORING RESULTS

Ice-level monitoring of the ice pond from 1990 to 2005 (Fig. 4) showed increasing ice levels of the ice deposit until sometime between September and November 1997 when the cavity in the ice appeared and measurements revealed a decreasing ice level. Several different methods of monitoring were employed to learn about the processes involved.

Figure 5. Photograph of ice deposit taken in 1962 looking up-flow in the cave. Note fairly low ice level, exposing several large blocks of lava rubble, also called breakdown. Several large, apparently stable blocks are labeled A through E for reference in succeeding photographs. Also note the wooden walkway at the right edge of the photograph constructed in Merrill Cave. In the mid-1960s these structures were replaced by steel and aluminum walkways. Dark colored areas are shallow pools of melt-water in the clear ice; covered blocks of lava can faintly be seen under the clear ice at left. Milky color of the balance of the ice surface is due to minute bubbles of air and fractures in the ice. Also note high water/ice marks on intact tube wall at upper center and extensive mineral covering on walls and ceiling in background.

PHOTOGRAPHIC MONITORING

Photographs show the effects of natural processes and human impacts on the ice in Merrill Cave from 1962–2005. They provide a valuable overview of the changes that took place in ice deposit conditions and the decrease in ice levels in the late 1990s and early 2000s. Historical photographs may be used as a historical reference and monitoring tool (Leutscher, et al., 2005).

Historical photos were taken of the ice floor including a 1962 photo showing the surface of the ice floor (Fig. 5). Dedicated photo monitoring of the ice deposit surface was initiated in 1990 when the floor was unaltered by current conditions. Photographs from early in this time period

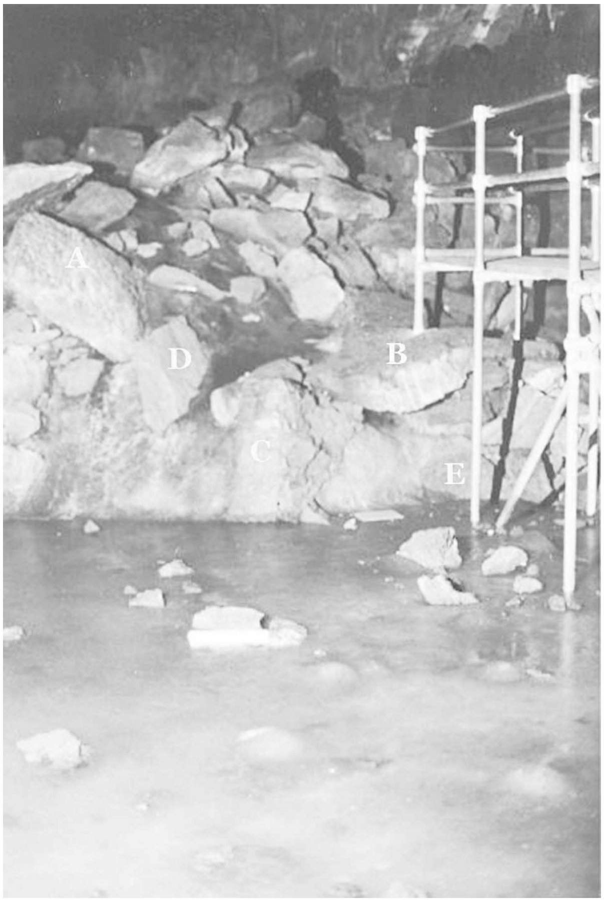

Figure 6. View of ice deposit and upstream ice cascade in Merrill Cave taken in 1990. The ice surface is relatively clear as submerged lava blocks can be seen under its surface; lower ice levels are milky white due to trapped air bubbles and fractures in ice. The large breakdown blocks are partly cemented in a thick ice cascade. Note the bottom of the walkway supports have been engulfed in ice about 20 cm since it was installed in the mid-1960s. White scale bar at center of photo is 30 cm wide. Blocks labeled A through E are the same as those shown in previous photograph.

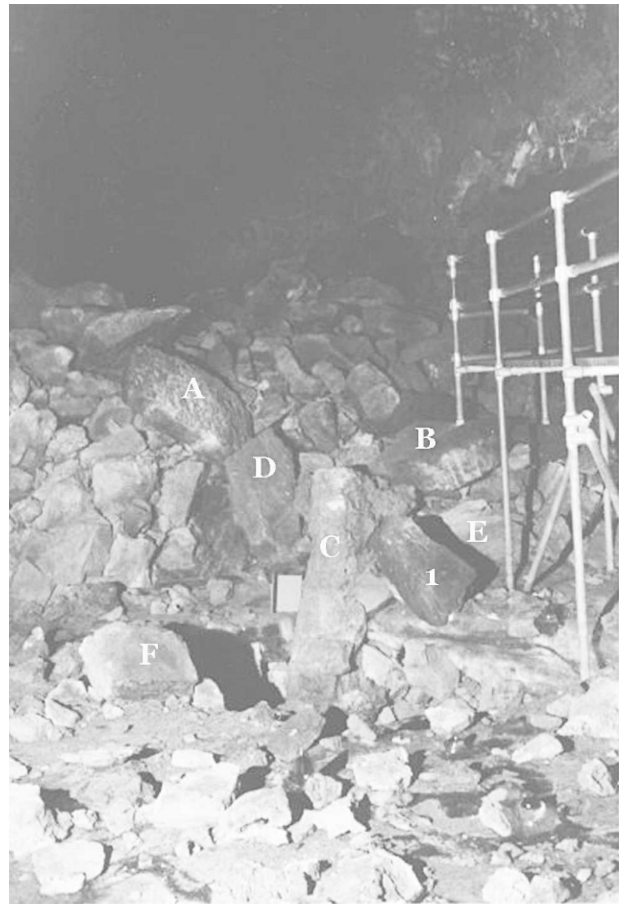

Figure 7. Photograph of the ice deposit in Merrill Cave taken in April of 1999. Note that the ice level has dropped further, exposing more of the upstream rubble pile. Block 1 makes a brief appearance. The origin of this block is unknown. It may have slid down on the pile of rubble above or been moved by visitors from somewhere on the upstream breakdown pile.

reveal a solid ice floor that has very little debris on its surface (Fig. 6). Compared with the 1962 photo, the ice level had risen by 1990.

The same photo retaken in 1999 and 2000 (Figs. 7 and 8) reveals a drastic change in the quality of the ice. Excessive amounts of debris had accumulated on the surface, in addition to the appearance and expansion of a hole in the ice.

The visible degradation of the ice in Merrill Cave began in November 1997 when a small hole appeared in the surface of the ice that grew quickly to 116 cm × 55 cm by March of 1998 (Fig. 9). Beneath this surface hole, a large cavity had formed in the ice deposit. Given the initial diameter of the cavity beneath the surface when it was discovered (4.6 m), the subsurface melting/sublimation phenomenon had probably been at work for an extended period of time. Photo monitoring recorded the changes in the size of the hole in the Merrill Cave ice deposit between March, 1998 and November, 2000. When measured in November of 2000, the size of the hole had grown to 4.4 m × 4.3 m (Fig. 10). As of October, 2005 most of the main ice deposit in Merrill Cave has been claimed by the natural forces at work, with the exception of a 1 m high bench along the east wall and a narrow fissure fill on the northwest corner of the ice pond (Fig. 11).

Rock Fall Monitoring

The accumulation of rock on the ice deposit was a concern because of the potential hazards associated with rock fall. This debris could have originated from: (1) rock fall from the ceiling of the cave; (2) sublimated material re-emerging from beneath the ice in combination with evaporation of ice from the surface; or (3) visitors

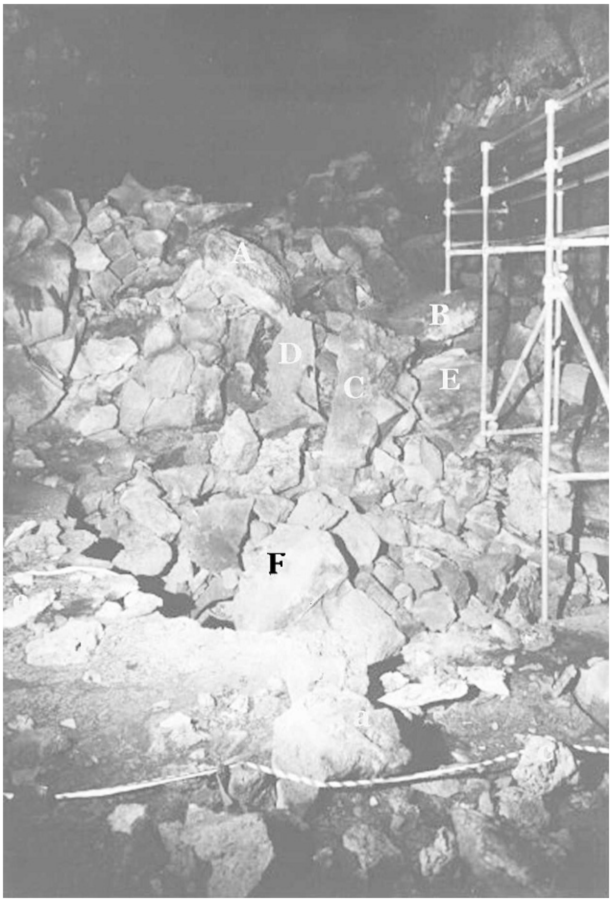

Figure 8. In this photograph taken in November of 2000 note that the ice deposit has substantially melted further. Block F has slipped and/or rolled further down into the cavity. Block 1 has disappeared down into the rubble cavity as well. Smaller boulders near the downstream edge of the ice surface are labeled lower case a to e. Striped plastic tape delineates the reference area for a concurrent rock fall study.

Figure 9. Merrill Cave ice deposit cavity breach, March, 1998.

depositing rocks onto the ice in an attempt to enlarge the cavity hole in the floor or create new holes.

A gate was constructed at the entrance and the cave was closed to the public to provide for public safety, prevent possible further resource damage by vandalism, and give resource managers a chance to study the phenomenon at work. A rock fall monitoring plot, which can be seen in Figure 10, was marked off and cleared on the top of the ice to observe the amount of rock accumulation from natural causes. Observations of the monitoring plot and photo documentation over a period of 17 months (June 1999–November 2000) revealed no natural rock fall on the ice deposit. Based on these observations, the changes in the accumulation of debris material appear to be the result of ice sublimation and evaporation processes. Various sizes of basalt rock material were identified embedded in the cavity walls. Part of the initial deposition of material was apparently the result of visitors throwing rocks onto the ice deposit attempting to increase the size of the cavity hole.

The accumulation of debris before closure of the cave to visitors is therefore attributed to a combination of vandalism and reemergence of submerged material due to loss of ice from sublimation processes and evaporation. Sublimation processes take place very slowly. More rocks and debris material continued to emerge from the ice deposit as the ice evaporated.

ENVIRONMENTAL MONITORING

Temperature and relative humidity probes were installed to monitor conditions and obtain an accurate record of environmental fluctuations both inside the expanding hole and on the surface of the main ice deposit in the lower level of the cave. Conditions on the surface of the ice deposit followed seasonal patterns in terrestrial heating and cooling (Fig. 12). In September 1993, a magnitude 6.0 earthquake with an epicenter 22 km west-northwest of Klamath Falls, Oregon (Washington State University, 2006) may have initiated a shift of cave rubble in the lower levels of the lava tube beneath the perennial ice pond in Merrill Cave. A steady airflow from beneath the breakdown rubble affected the temperature and relative humidity conditions inside the cavity during the period of time monitoring took place (Fig. 13). These conditions included higher relative humidity (increased evaporation), and lower temperatures (higher air flow velocity). The location, quantity, and force of the airflow present suggested a source of air from outside the known passages of the cave. This airflow also may have dramatically increased the rate of evaporation of the ice that occurred over a short period of time and the size of the ice cavity when it was discovered. Ambient external terrestrial temperatures are recorded using a National Weather Service weather monitoring station at park headquarters. These data have been collected since 1946. Records show that the average annual high terrestrial temperatures have

Figure 10. Photograph of ice deposit hole in November, 2000, looking along the western wall. Large and small blocks labeled C, D, and F and a through e are labeled as in previous figures. Note stratified nature of ice deposit with clear and milky white, air bubble-filled layers.

increased 0.84 °C over the past 21 years in the local area that includes Merrill Cave (Fig. 14) (U.S. National Park Service, 2005). Average annual precipitation shows a declining trend since 1946 (Fig. 15). A combination of changing airflow patterns influenced by seismic activity, increased terrestrial temperatures and decreasing precipitation levels may be related to the disappearance of ice in Merrill Cave. Changes in cave ice levels can be influenced by climate changes (Luetscher et al., 2005).

Other Influences

Visitation

Visitation to Merrill Cave was measured from 1992 until the cave was closed in 1999 using a seismic trail sensor on the cave trail that monitored visitor traffic. These records from the cave are shown in Fig. 16. The highest visitation levels were recorded during the months June, July and August. A high of over 4,100 visitors was recorded in June of 1995. The cave had an average of 456 visitors per month before the cave was closed. The

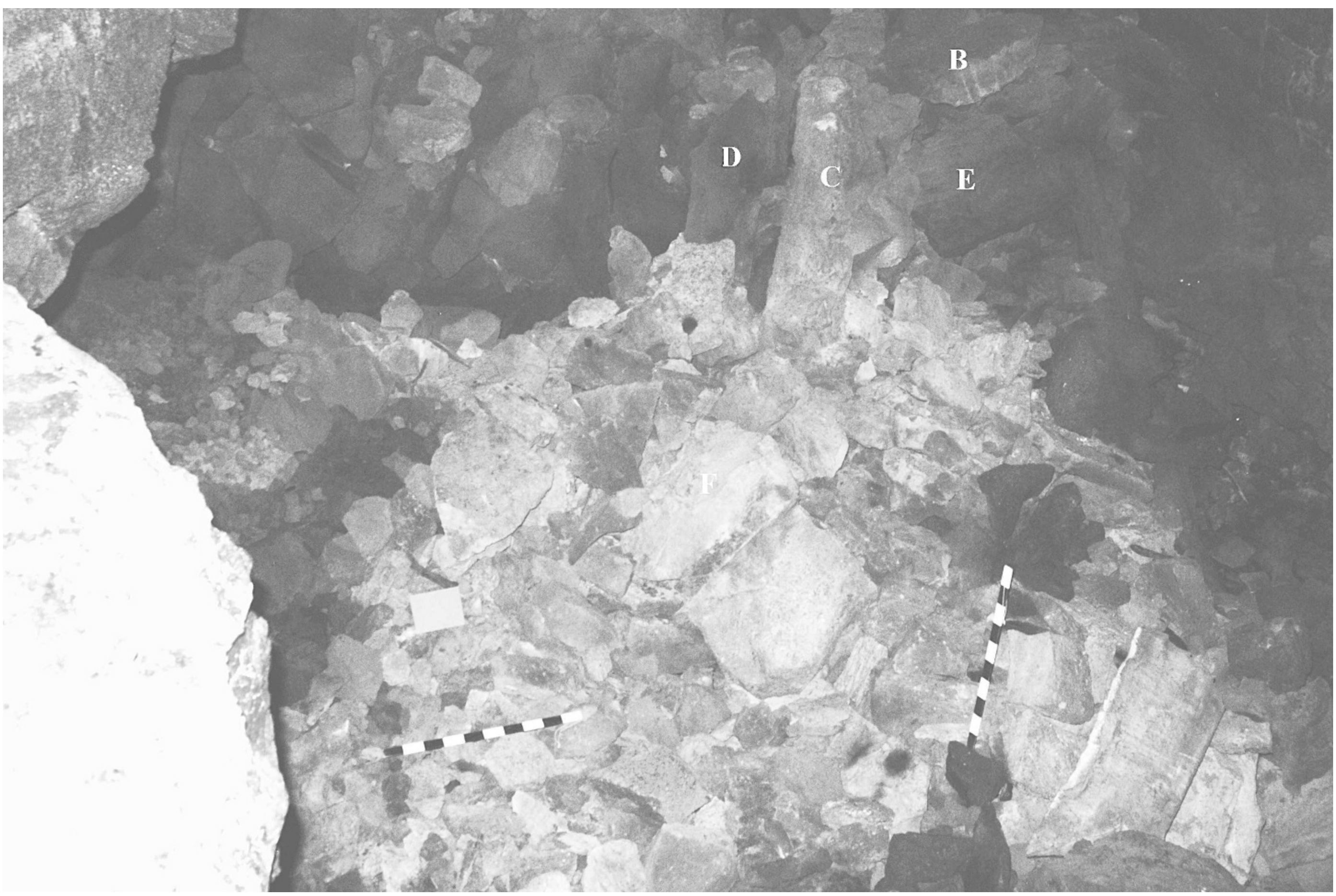

Figure 11. Merrill Cave Ice deposit, September 2005. The large ice pool has been entirely melted. The only visible basalt blocks still in place are B, C, D, E and F. The remaining blocks have fallen into the jumble of blocks on the floor of the lower section of the cave or shifted as a result of ice melting out of cavities between blocks. Note meter sticks and color board located on the breakdown floor of the former perennial ice deposit for scale.

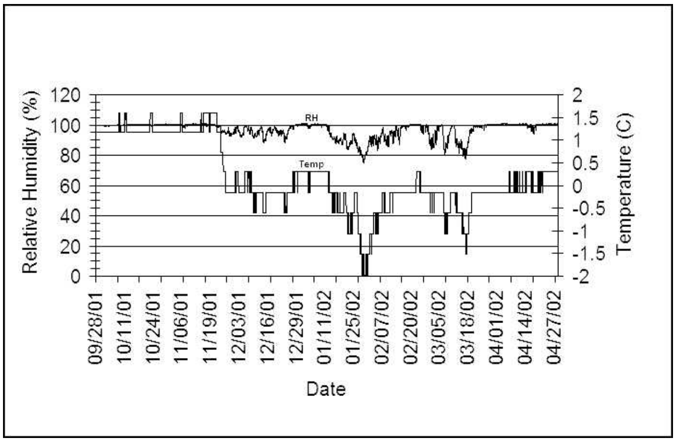

Figure 12. The relative humidity conditions on the surface of the ice pond are more variable with a lower average relative humidity (74.7% to 100.9%, average 96.7%) and temperatures slightly higher (−2 °C to 2 °C) because of exposure to the environmental influences in the lower level of the cave.

presence of visitors in the cave has had direct impacts on the ice deposit. The influences of visitation on the ice deposit include discarded trash, direct manipulation of the ice deposit, as well as potential influences of visitation on lower level cave temperatures by large numbers of visitors. Items discarded by visitors that included coins, 1970s era flash bulbs, glass bottles, tin cans, charred wood, etc. were found in different layers of the ice. Remnant catwalk platform materials were also found at lower levels in the ice deposit (Sowers and Devereaux, 2000). The results of deliberate attempts by cave visitors to enlarge the edges of the existing cavity in the ice with large rocks, and by

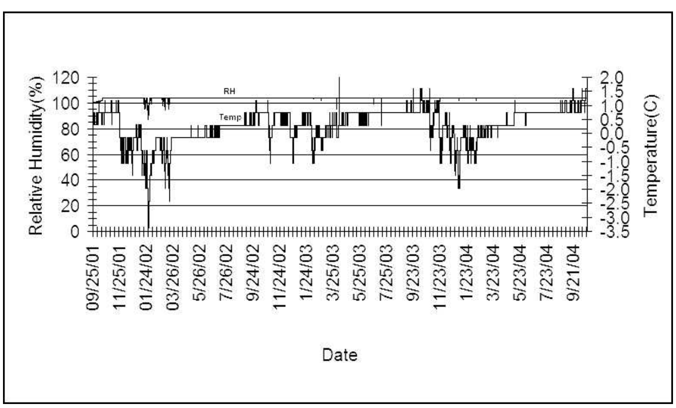

Figure 13. The recorded conditions inside the ice cavity from September 2001 through April 2002 show higher average and more stable relative humidity (86.9% to 103.7%, average 103%) and lower temperatures (−3 °C to 1 °C) for longer periods of time. This graph records a relative humidity that may be influenced by high evaporation rates of ice from inside the ice cavity.

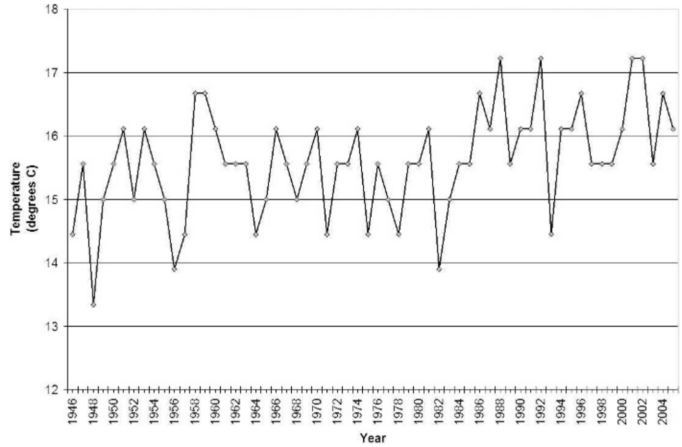

Figure 14. Average annual high temperatures (1946–2005) from the National Weather Service weather monitoring station at Indian Wells Headquarters reveal increasing ambient surface temperatures in the region of Lava Beds National Monument. This may directly affect the interior cave temperatures via interface with surface conditions through lava tube breakdown material.

physically kicking the edges to break off large chunks of ice, were observed by the author. These activities contributed to the premature enlargement of the cavity observed between 1998 and 2002. Visitor-level monitoring was reinitiated in 2004 after the cave was reopened.

Western Juniper Vegetation Community

The presence of western juniper (*Juniperus occidentalis*) is also worth mentioning in the context of this topic because of an indirect relationship in the surrounding terrestrial ecosystem above the cave. The expansion of western juniper in the region during the past 130 years has been cause for concern because of its impacts on plant communities and related components of affected ecosys-

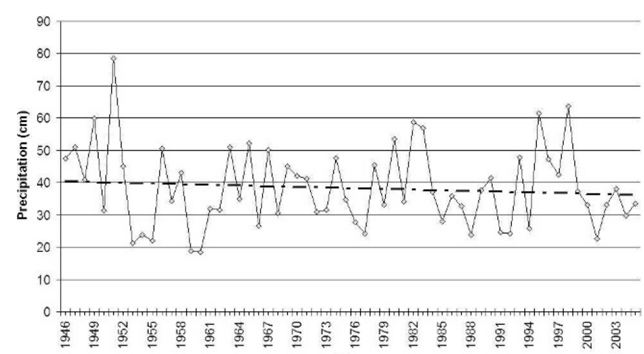

Figure 15. Average annual precipitation patterns (1946–2005) from the National Weather Service weather monitoring station.

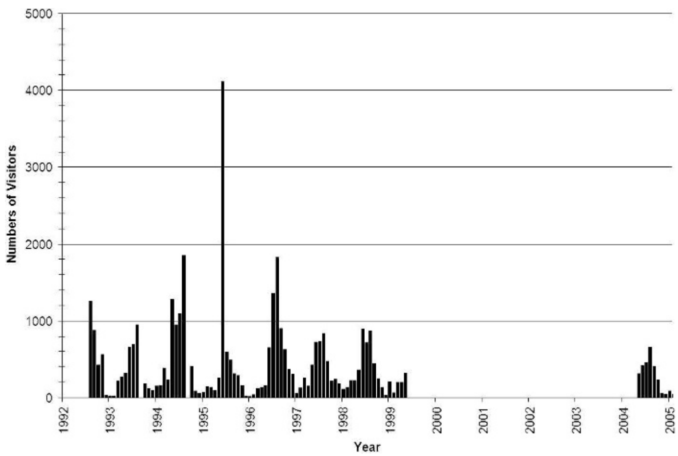

Figure 16. Visitation levels in Merrill Cave were recorded with a seismic trail sensor placed along the entrance/exit trail inside the cave.

tems (Miller et al., 2005). The abundance of western juniper in the high desert ecosystem on the surface above the cave may have an indirect effect on the hydrology of the cave environment. It is possible for a single mature western juniper to uptake approximately 35+ gallons of water per day during the summer months with extensive tap roots (personal communication, Richard F. Miller, Range Ecologist, Eastern Oregon Agricultural Research Center, Oregon State University, Corvalis, Oregon). This may influence the presence of water in the cave environment because it may relate directly to the number of mature junipers present and their proximity to Merrill Cave. The potential influence of the juniper community on the cave has not been investigated.

Conclusions

The current decline in the ice level in Merrill Cave is drastic and expected to continue until all the ice in the lower level of the cave is gone. Several explanations may independently, or in conjunction with one another, explain the cause of ice loss. Airflow from another section of the lava tube may have also contributed to forming the cavity in the ice deposit of the cave, which has subsequently expanded and consumed the entire deposit of ice. The loss of ice from evaporation indicates a change of air flow and a fluctuation in cave temperature.

Another explanation may be an increase in temperatures at a lower level of the master tube of which Merrill Cave is a part. The ice in this passage may have melted, and accelerated the melting of ice at the bottom of the ice pond. Thus, the ice cavity may have been the result of an opening of a smaller passage that had been filled with ice.

The ice may have possibly melted due to warmer temperatures outside the cave that exposed the base of the main ice deposit in the lower level of the cave to warmer air flow. Whatever the cause, the loss of ice by evaporation has consumed the majority of the ice present in the perennial ice deposits and feeder ice flows.

Future management of this cave will include environmental and ice-level monitoring of the lower level site that the main ice deposit once filled and new signed interpretation of the phenomenon at work for visitors to the cave. The presence of western junipers on the surface and the effect of this species on the hydrologic cycle of the cave require investigation. Future climate conditions and geological activity will determine the processes influencing this cave, which may, eventually, include the return of ice to its accessible lower level.

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